Quantitative Economics with Julia

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Contents

Part I

Getting Started with Julia

Chapter 1

Setting up Your Julia Environment

1.1 Contents

1.2 Overview

In this lecture we will cover how to get up and running with Julia.

There are a few different options for using Julia, including a local desktop installation and Jupyter hosted on the web.

If you have access to a web-based Jupyter and Julia setup, it is typically the most straightforward way to get started.

1.3 A Note on Jupyter

Like Python and R, and unlike products such as Matlab and Stata, there is a looser connection between Julia as a programming language and Julia as a specific development environment.

While you will eventually use other editors, there are some advantages to starting with the Jupyter environment while learning Julia.

- The ability to mix formatted text (including mathematical expressions) and code in a single document.
- Nicely formatted output including tables, figures, animation, video, etc.
- Conversion tools to generate PDF slides, static HTML, etc.
- Online Jupyter may be available, and requires no installation.

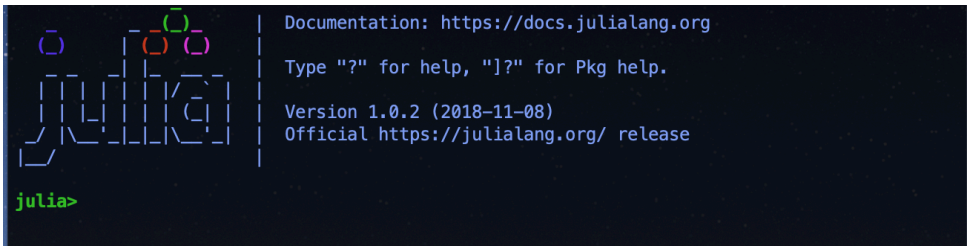
We'll discuss the workflow on these features in the next lecture.

1.4 Desktop Installation of Julia and Jupyter

If you want to install these tools locally on your machine

- Download and install Julia, from download page , accepting all default options.
  - We do **not** recommend JuliaPro.
- Open Julia, by either
  1. Navigating to Julia through your menus or desktop icons (Windows, Mac), or
  2. Opening a terminal and typing `julia` (Linux; to set this up on Mac, see end of section)

You should now be looking at something like this



This is called the JULIA *REPL* (Read-Evaluate-Print-Loop), which we discuss more later.

- In the Julia REPL, hit `]` to enter package mode and then enter.

```
add IJulia InstantiateFromURL
```

This adds packages for

- The `IJulia` kernel which links Julia to Jupyter (i.e., allows your browser to run Julia code, manage Julia packages, etc.).
- The `InstantiateFromURL` which is a tool written by the QE team to manage package dependencies for the lectures.

Note: To set up the Julia terminal command on Mac, open a terminal and run `sudo ln -s <where_julia_app_is>/Contents/Resources/julia/bin/julia /usr/local/bin/julia`.

The full command might look like `sudo ln -s /Applications/Julia-1.4.app/Contents/Resources/julia/bin/julia /usr/local/bin/julia`, if you placed the app in your `Applications` folder.

Note: To obtain the full set of packages we use, at this stage you can run the following (see the package setup section.)

```
using InstantiateFromURL
github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0", instant
```

1.4.1 Installing Jupyter

If you have previously installed Jupyter (e.g., installing Anaconda Python by downloading the binary `https://www.anaconda.com/download/`) then the `add IJulia` installs everything you need into your existing environment.

Otherwise - or in addition - you can install it directly from the Julia REPL

```
using IJulia; jupyterlab()
```

Choose the default, `y` if asked to install Jupyter and then JupyterLab via Conda.

After the installation, a JupyterLab tab should open in your browser.

(Optional) To enable launching JupyterLab from a terminal, use add Julia's Jupyter to your path.

1.4.2 Starting Jupyter

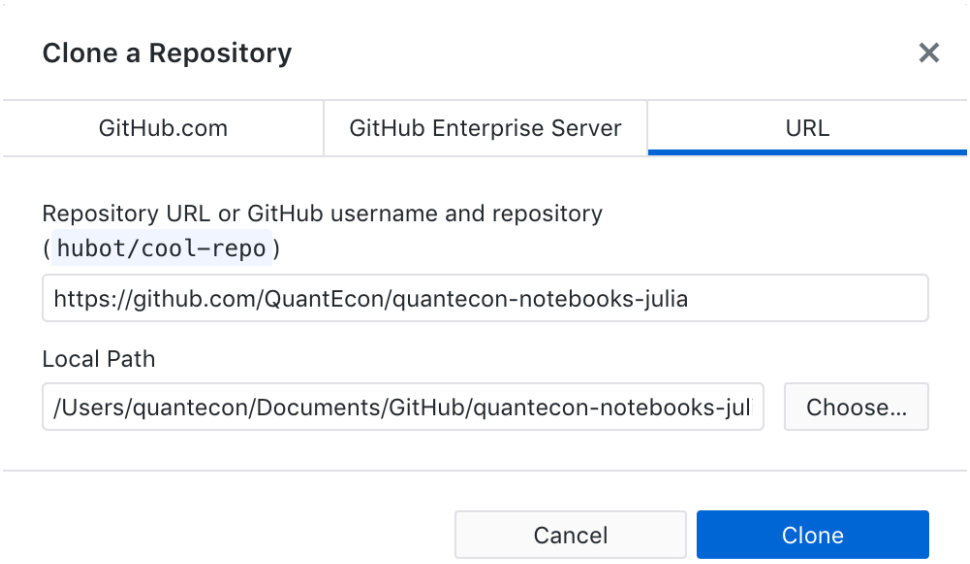
Next, let's install the QuantEcon lecture notes to our machine and run them (for more details on the tools we'll use, see our lecture on version control).

1. Install git.
2. (**Optional, but strongly recommended**) Install the GitHub Desktop.

GitHub Desktop Approach

After installing the Git Desktop application, click this link on your desktop computer to automatically install the notebooks.

It should open a window in the GitHub desktop app like this



Choose a path you like and clone the repo.

Note: the workflow will be easiest if you clone the repo to the default location relative to the home folder for your user.

From a Julia REPL, start JupyterLab by executing

```
using IJulia; jupyterlab()
```

Alternatively, if you installed Jupyter separately in Jupyter Installation or added Jupyter to your path then run `jupyter lab` in your terminal.

Navigate to the location you stored the lecture notes, and open the Interacting with Julia notebook to explore this interface and start writing code.

Git Command Line Approach

If you do not wish to install the GitHub Desktop, you can get the notebooks using the Git command-line tool.

Open a new terminal session and run

```
git clone https://github.com/quantecon/quantecon-notebooks-julia
```

This will download the repository with the notebooks in the working directory.

Then, `cd` to that location in your Mac, Linux, or Windows PowerShell terminal

```
cd quantecon-notebooks-julia
```

Then, either using the `using IJulia; jupyterlab()` or execute `jupyter lab` within your shell.

And open the Interacting With Julia lecture (the file `julia_environment.ipynb` in the list of notebooks in JupyterLab) to continue.

1.5 Using Julia on the Web

If you have access to an online Julia installation, it is the easiest way to get started.

Eventually, you will want to do a local installation in order to use other tools and editors such as Atom/Juno, but don't let the environment get in the way of learning the language.

1.5.1 Using Julia with JupyterHub

If you have access to a web-based solution for Jupyter, then that is typically a straightforward option

- Students: ask your department if these resources are available.
- Universities and workgroups: email [mailto:contact@quantecon.org"}{contact@quantecon.org} for help on setting up a shared JupyterHub instance with precompiled packages ready for these lecture notes.

Obtaining Notebooks

Your first step is to get a copy of the notebooks in your JupyterHub environment.

While you can individually download the notebooks from the website, the easiest way to access the notebooks is usually to clone the repository with Git into your JupyterHub environment.

JupyterHub installations have different methods for cloning repositories, with which you can use the url for the notebooks repository: `https://github.com/QuantEcon/quantecon-notebooks-julia`.

1.6 Installing Packages

After you have some of the notebooks available, as in above, these lectures depend on functionality (like packages for plotting, benchmarking, and statistics) that are not installed with every Jupyter installation on the web.

If your online Jupyter does not come with QuantEcon packages pre-installed, you can install the `InstantiateFromURL` package, which is a tool written by the QE team to manage package dependencies for the lectures.

To add this package, in an online Jupyter notebook run (typically with `<Shift-Enter>`)

```
In [1]: ] add InstantiateFromURL
```

Then, run

```
using InstantiateFromURL
github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0", instant
```

If your online Jupyter environment does not have the packages pre-installed, it may take 15-20 minutes for your first QuantEcon notebook to run.

After this step, open the downloaded Interacting with Julia notebook to begin writing code.

If the QuantEcon notebooks do not work after this installation step, you may need to speak to the JupyterHub administrator.

Chapter 2

Interacting with Julia

2.1 Contents

2.2 Overview

In this lecture we'll start examining different features of the Julia and Jupyter environments.

2.3 Using Jupyter

2.3.1 Getting Started

Recall that the easiest way to get started with these notebooks is to follow the cloning instructions earlier.

To summarize, if on a desktop you should clone the notebooks repository `https://github.com/quantecon/quantecon-notebooks-julia`, then in a Julia REPL type

```
using IJulia; jupyterlab()
```

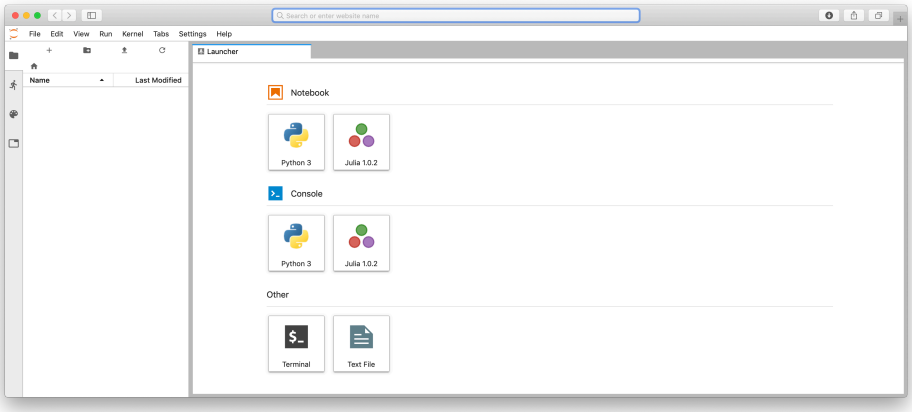
Hint: Julia will remember the last commands in the REPL, so you can use up-arrow to restart JupyterLab.

Alternatively, if you are using an online Jupyter, then you can directly open a new notebook.

Finally, if you installed Jupyter separately or have added added Jupyter to the Path then `cd` to the folder location in a terminal, and run

```
jupyter lab
```

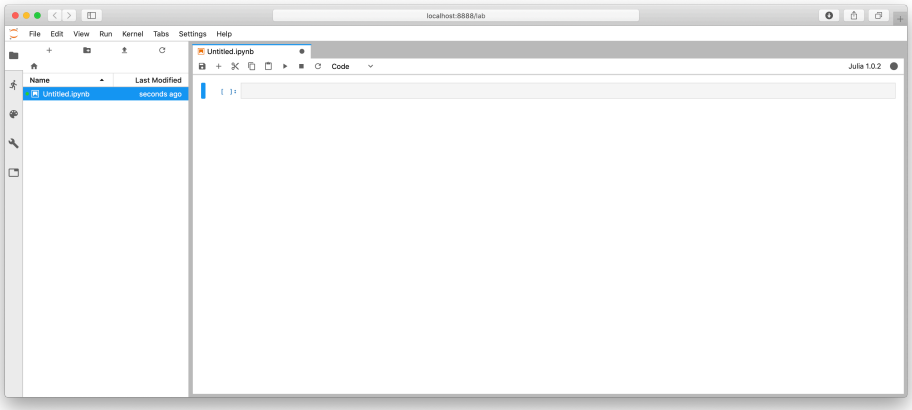
Regardless, your web browser should open to a page that looks something like this



The page you are looking at is called the "dashboard".

If you click on "Julia 1.x.x" you should have the option to start a Julia notebook.

Here's what your Julia notebook should look like



The notebook displays an *active cell*, into which you can type Julia commands.

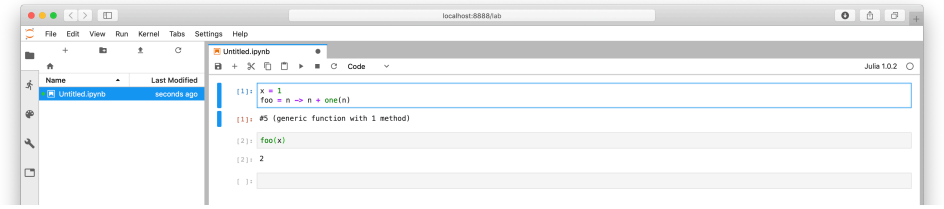
2.3.2 Notebook Basics

Notice that in the previous figure the cell is surrounded by a blue border.

This means that the cell is selected, and double-clicking will place it in edit mode.

As a result, you can type in Julia code and it will appear in the cell.

When you're ready to execute these commands, hit `Shift-Enter`



Modal Editing

The next thing to understand about the Jupyter notebook is that it uses a *modal* editing system.

This means that the effect of typing at the keyboard **depends on which mode you are in**.

The two modes are

1. Edit mode

- Indicated by a green border around one cell, as in the pictures above.
- Whatever you type appears as is in that cell.

1. Command mode

- The green border is replaced by a blue border.
- Key strokes are interpreted as commands — for example, typing b adds a new cell below the current one.

(To learn about other commands available in command mode, go to "Keyboard Shortcuts" in the "Help" menu)

Switching modes

- To switch to command mode from edit mode, hit the `Esc` key.
- To switch to edit mode from command mode, hit `Enter` or click in a cell.

The modal behavior of the Jupyter notebook is a little tricky at first but very efficient when you get used to it.

Working with Files

To run an existing Julia file using the notebook you can copy and paste the contents into a cell in the notebook.

If it's a long file, however, you have the alternative of

1. Saving the file in your **present working directory**.
2. Executing `include("filename")` in a cell.

The present working directory can be found by executing the command `pwd()`.

Plots

Note that if you're using a JupyterHub setup, you will need to first run

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

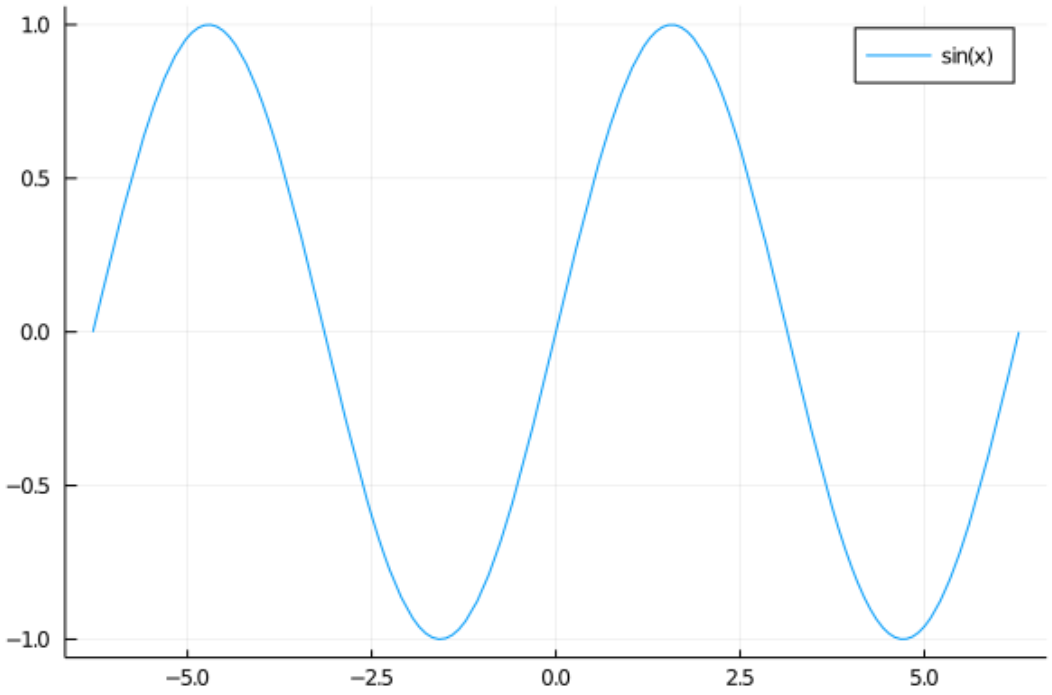
in a new cell (i.e., `Shift + Enter`).

This might take 15-20 minutes depending on your setup, as it installs a large set of packages for our use.

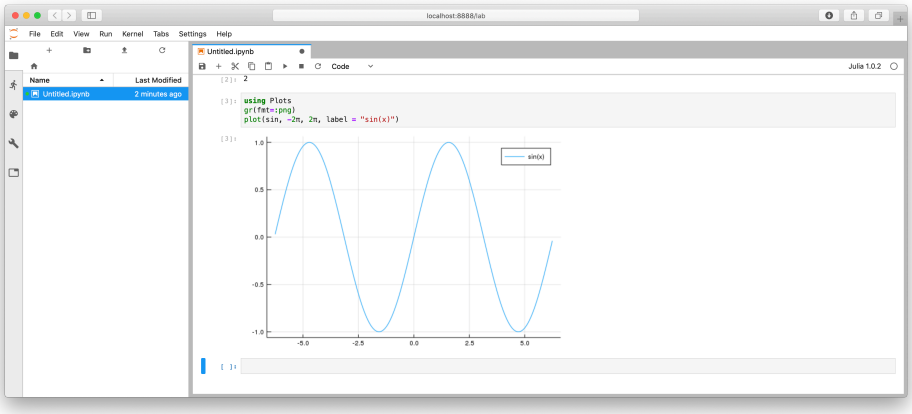
Run the following cell

```
In [2]: using Plots
        gr(fmt=:png);
        plot(sin, -2π, 2π, label="sin(x)")
```

Out[2]:



You'll see something like this (although the style of plot depends on your installation)



Note: The "time-to-first-plot" in Julia takes a while, since it needs to compile many functions - but is almost instantaneous the second time you run the cell.

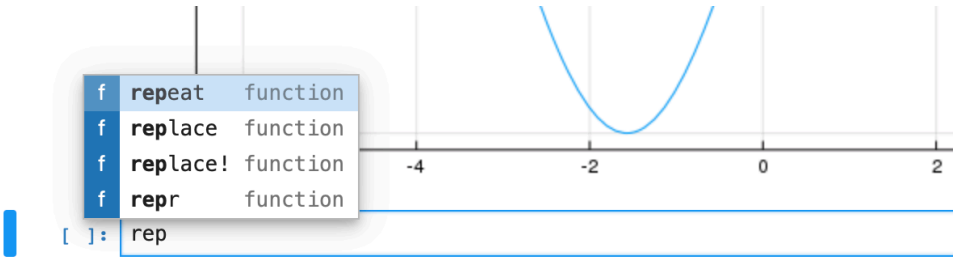
2.3.3 Working with the Notebook

Let's go over some more Jupyter notebook features — enough so that we can press ahead with programming.

Tab Completion

Tab completion in Jupyter makes it easy to find Julia commands and functions available.

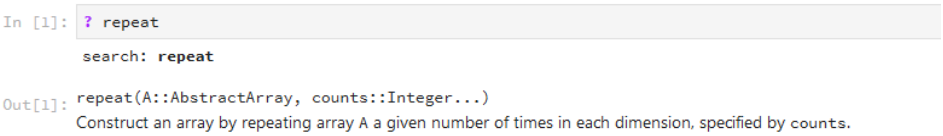
For example if you type `rep` and hit the tab key you'll get a list of all commands that start with `rep`



Getting Help

To get help on the Julia function such as `repeat`, enter `? repeat`.

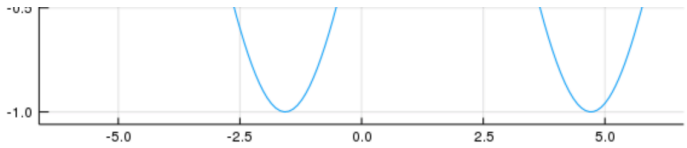
Documentation should now appear in the browser



Other Content

In addition to executing code, the Jupyter notebook allows you to embed text, equations, figures and even videos in the page.

For example, here we enter a mixture of plain text and LaTeX instead of code

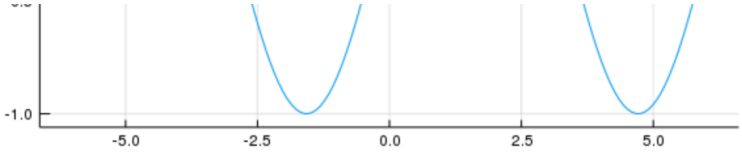



```
Euler found that

$$ \exp(i \pi) = -1 $$
```

Next we `Esc` to enter command mode and then type `m` to indicate that we are writing Markdown, a mark-up language similar to (but simpler than) LaTeX.

(You can also use your mouse to select `Markdown` from the `Code` drop-down box just below the list of menu items)

Now we `Shift + Enter` to produce this



Euler found that

$$\exp(i\pi) = -1$$

Inserting unicode (e.g. Greek letters)

Julia supports the use of unicode characters such as α and β in your code.

Unicode characters can be typed quickly in Jupyter using the `tab` key.

Try creating a new code cell and typing `\alpha`, then hitting the `tab` key on your keyboard.

Shell Commands

You can execute shell commands (system commands) in Jupyter by prepending a semicolon.

For example, `; ls` will execute the UNIX style shell command `ls`, which — at least for UNIX style operating systems — lists the contents of the current working directory.

These shell commands are handled by your default system shell and hence are platform specific.

Package Operations

You can execute package operations in the notebook by prepending a `]`.

For example, `] st` will give the status of installed packages in the current environment.

Note: Cells where you use `;` and `]` must not have any other instructions in them (i.e., they should be one-liners).

2.3.4 Sharing Notebooks

Notebook files are just text files structured in JSON and typically end with `.ipynb`.

A notebook can easily be saved and shared between users — you just need to pass around the `ipynb` file.

To open an existing `ipynb` file, import it from the dashboard (the first browser page that opens when you start Jupyter notebook) and run the cells or edit as discussed above.

The Jupyter organization has a site for sharing notebooks called nbviewer which provides a static HTML representations of notebooks.

QuantEcon also hosts the QuantEcon Notes website, where you can upload and share your notebooks with other economists and the QuantEcon community.

2.4 Using the REPL

As we saw in the desktop installation, the REPL is a Julia specific terminal.

It becomes increasingly important as you learn Julia, and you will find it to be a useful tool for interacting with Julia and installing packages.

As a reminder, to open the REPL on your desktop, either

1. Navigating to Julia through your menus or desktop icons (Windows, Mac), or
2. Opening a terminal and typing `julia` (Linux)

If you are using a JupyterHub installation, you can start the REPL in JupyterLab by choosing

1. Choose "New Launcher"
2. Choose a `Julia` Console

We examine the REPL and its different modes in more detail in the tools and editors lecture.

2.5 (Optional) Adding Jupyter to the Path

If you installed Jupyter using Julia, then you may find it convenient to add it to your system path in order to launch JupyterLab without running a Julia terminal.

The default location for the Jupyter binaries is relative to the `.julia` folder (e.g., `"C:\Users\USERNAME\.julia\conda\3\Scripts` on Windows).

You can find the directory in a Julia REPL using by executing

```
] add Conda
using Conda
Conda.SCRIPTDIR
```

On Linux/OSX, you could add that path to your `.bashrc`.

On Windows, to add directly to the path, type `;` to enter shell mode and then execute

```
setx PATH "$(Conda.SCRIPTDIR);%PATH%"
```

Chapter 3

Introductory Examples

3.1 Contents

3.2 Overview

We're now ready to start learning the Julia language itself.

3.2.1 Level

Our approach is aimed at those who already have at least some knowledge of programming — perhaps experience with Python, MATLAB, Fortran, C or similar.

In particular, we assume you have some familiarity with fundamental programming concepts such as

- variables
- arrays or vectors
- loops
- conditionals (if/else)

3.2.2 Approach

In this lecture we will write and then pick apart small Julia programs.

At this stage the objective is to introduce you to basic syntax and data structures.

Deeper concepts—how things work—will be covered in later lectures.

Since we are looking for simplicity the examples are a little contrived

In this lecture, we will often start with a direct MATLAB/FORTRAN approach which often is **poor coding style** in Julia, but then move towards more **elegant code** which is tightly

connected to the mathematics.

3.2.3 Set Up

We assume that you've worked your way through our getting started lecture already.

In particular, the easiest way to install and precompile all the Julia packages used in QuantEcon notes is to type `] add InstantiateFromURL` and then work in a Jupyter notebook, as described here.

3.2.4 Other References

The definitive reference is Julia's own documentation.

The manual is thoughtfully written but is also quite dense (and somewhat evangelical).

The presentation in this and our remaining lectures is more of a tutorial style based around examples.

3.3 Example: Plotting a White Noise Process

To begin, let's suppose that we want to simulate and plot the white noise process $\epsilon_0, \epsilon_1, \ldots, \epsilon_T$, where each draw ϵ_t is independent standard normal.

3.3.1 Introduction to Packages

The first step is to activate a project environment, which is encapsulated by `Project.toml` and `Manifest.toml` files.

There are three ways to install packages and versions (where the first two methods are discouraged, since they may lead to package versions out-of-sync with the notes)

1. `add` the packages directly into your global installation (e.g. `Pkg.add("MyPackage")` or `] add MyPackage`)
2. download an `Project.toml` and `Manifest.toml` file in the same directory as the notebook (i.e. from the `@__DIR__` argument), and then call `using Pkg; Pkg.activate(@__DIR__);`
3. use the `InstantiateFromURL` package

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

If you have never run this code on a particular computer, it is likely to take a long time as it downloads, installs, and compiles all dependent packages.

This code will download and install project files from the lecture repo.

We will discuss it more in Tools and Editors, but these files provide a listing of packages and versions used by the code.

This ensures that an environment for running code is **reproducible**, so that anyone can replicate the precise set of package and versions used in construction.

The careful selection of package versions is crucial for reproducibility, as otherwise your code can be broken by changes to packages out of your control.

After the installation and activation, `using` provides a way to say that a particular code or notebook will use the package.

```
In [2]: using LinearAlgebra, Statistics
```

3.3.2 Using Functions from a Package

Some functions are built into the base Julia, such as `randn`, which returns a single draw from a normal distibution with mean 0 and variance 1 if given no parameters.

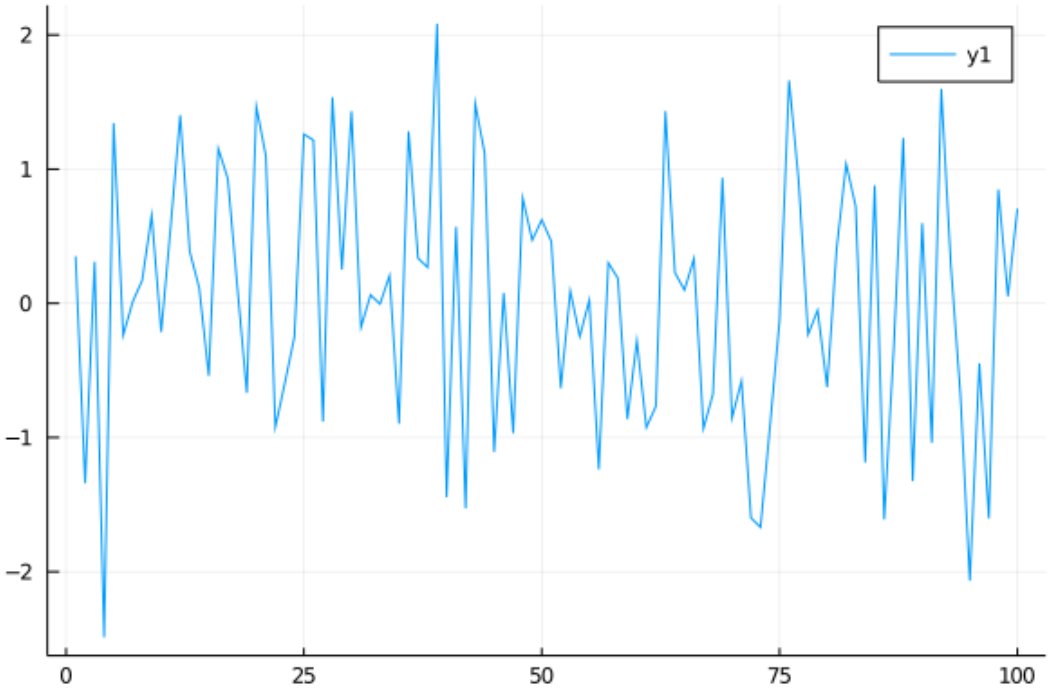
```
In [3]: randn()
```

```
Out[3]: 0.1340729773546092
```

Other functions require importing all of the names from an external library

```
In [4]: using Plots
        gr(fmt=:png); # setting for easier display in jupyter notebooks

        n = 100
        ϵ = randn(n)
        plot(1:n, ϵ)
```

```
Out[4]:
```



Let's break this down and see how it works.

The effect of the statement `using Plots` is to make all the names exported by the `Plots` module available.

Because we used `Pkg.activate` previously, it will use whatever version of `Plots.jl` that was specified in the `Project.toml` and `Manifest.toml` files.

The other packages `LinearAlgebra` and `Statistics` are base Julia libraries, but require an explicit using.

The arguments to `plot` are the numbers `1,2, ..., n` for the x-axis, a vector ϵ for the y-axis, and (optional) settings.

The function `randn(n)` returns a column vector `n` random draws from a normal distribution with mean 0 and variance 1.

3.3.3 Arrays

As a language intended for mathematical and scientific computing, Julia has strong support for using unicode characters.

In the above case, the ϵ and many other symbols can be typed in most Julia editor by providing the LaTeX and `<TAB>`, i.e. `\epsilon<TAB>`.

The return type is one of the most fundamental Julia data types: an array

```
In [5]: typeof(ϵ)
```

```
Out[5]: Array{Float64,1}
```

```
In [6]: ϵ[1:5]
```

```
Out[6]: 5-element Array{Float64,1}:
          0.3508933329262338
         -1.3417023907846528
          0.3098019819945068
         -2.4886691920076305
          1.3432653930816776
```

The information from `typeof()` tells us that ϵ is an array of 64 bit floating point values, of dimension 1.

In Julia, one-dimensional arrays are interpreted as column vectors for purposes of linear algebra.

The ϵ`[1:5]` returns an array of the first 5 elements of ϵ.

Notice from the above that

- array indices start at 1 (like MATLAB and Fortran, but unlike Python and C)
- array elements are referenced using square brackets (unlike MATLAB and Fortran)

To get **help and examples** in Jupyter or other julia editor, use the `?` before a function name or syntax.

```
?typeof

search: typeof typejoin TypeError

Get the concrete type of x.

Examples

julia> a = 1//2;

julia> typeof(a)
Rational{Int64}

julia> M = [1 2; 3.5 4];

julia> typeof(M)
Array{Float64,2}
```

3.3.4 For Loops

Although there's no need in terms of what we wanted to achieve with our program, for the sake of learning syntax let's rewrite our program to use a `for` loop for generating the data.

> **Note**
>
> In Julia v0.7 and up, the rules for variables accessed in `for` and `while` loops can be sensitive to how they are used (and variables can sometimes require a `global` as part of the declaration). We strongly advise you to avoid top level (i.e. in the REPL or outside of functions) `for` and `while` loops outside of Jupyter notebooks. This issue does not apply when used within functions.

Starting with the most direct version, and pretending we are in a world where `randn` can only return a single value

```
In [7]: # poor style
        n = 100
        ϵ = zeros(n)
        for i in 1:n
            ϵ[i] = randn()
        end
```

Here we first declared ϵ to be a vector of `n` numbers, initialized by the floating point `0.0`.

The `for` loop then populates this array by successive calls to `randn()`.

Like all code blocks in Julia, the end of the `for` loop code block (which is just one line here) is indicated by the keyword `end`.

The word `in` from the `for` loop can be replaced by either `∈` or `=`.

The index variable is looped over for all integers from `1:n` – but this does not actually create a vector of those indices.

Instead, it creates an **iterator** that is looped over – in this case the **range** of integers from `1` to `n`.

While this example successfully fills in ϵ with the correct values, it is very indirect as the connection between the index `i` and the ϵ vector is unclear.

To fix this, use `eachindex`

```
In [8]: # better style
        n = 100
        ϵ = zeros(n)
        for i in eachindex(ϵ)
            ϵ[i] = randn()
        end
```

Here, `eachindex(ϵ)` returns an iterator of indices which can be used to access ϵ.

While iterators are memory efficient because the elements are generated on the fly rather than stored in memory, the main benefit is (1) it can lead to code which is clearer and less prone to typos; and (2) it allows the compiler flexibility to creatively generate fast code.

In Julia you can also loop directly over arrays themselves, like so

```
In [9]: ϵ_sum = 0.0 # careful to use 0.0 here, instead of 0
        m = 5
        for ϵ_val in ϵ[1:m]
            ϵ_sum = ϵ_sum + ϵ_val
        end
        ϵ_mean = ϵ_sum / m
```

```
Out[9]: 0.12255423860142103
```

where `ϵ[1:m]` returns the elements of the vector at indices `1` to `m`.

Of course, in Julia there are built in functions to perform this calculation which we can compare against

```
In [10]: ϵ_mean ≈ mean(ϵ[1:m])
         ϵ_mean ≈ sum(ϵ[1:m]) / m
```

```
Out[10]: true
```

In these examples, note the use of `≈` to test equality, rather than `==`, which is appropriate for integers and other types.

Approximately equal, typed with `\approx<TAB>`, is the appropriate way to compare any floating point numbers due to the standard issues of floating point math.

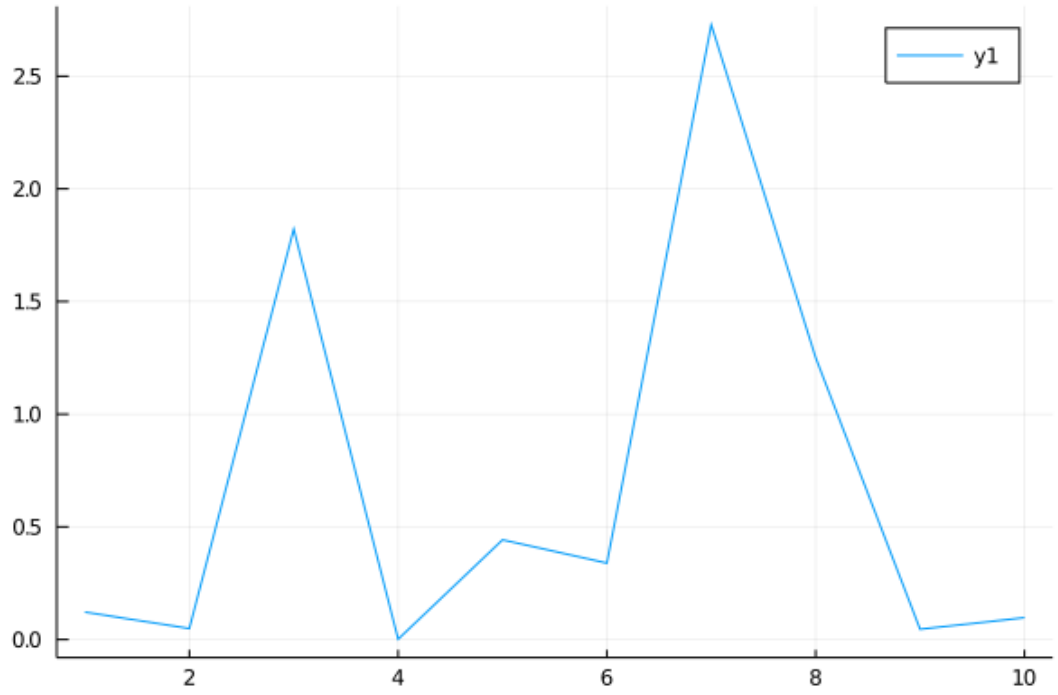
3.3.5 User-Defined Functions

For the sake of the exercise, let's go back to the `for` loop but restructure our program so that generation of random variables takes place within a user-defined function.

To make things more interesting, instead of directly plotting the draws from the distribution, let's plot the squares of these draws

In [11]:
```
# poor style
function generatedata(n)
    ϵ = zeros(n)
    for i in eachindex(ϵ)
        ϵ[i] = (randn())^2 # squaring the result
    end
    return ϵ
end

data = generatedata(10)
plot(data)
```

Out[11]:



Here

- `function` is a Julia keyword that indicates the start of a function definition
- `generatedata` is an arbitrary name for the function
- `return` is a keyword indicating the return value, as is often unnecessary

Let us make this example slightly better by "remembering" that `randn` can return a vectors.

In [12]:
```
# still poor style
function generatedata(n)
    ϵ = randn(n) # use built in function

    for i in eachindex(ϵ)
        ϵ[i] = ϵ[i]^2 # squaring the result
    end

    return ϵ
end
data = generatedata(5)
```

```
Out[12]: 5-element Array{Float64,1}:
          0.06974429927661173
          3.4619123178412163
          0.1462813968022536
          0.7638769909373935
          0.38175910849376604
```

While better, the looping over the `i` index to square the results is difficult to read.

Instead of looping, we can **broadcast** the `^2` square function over a vector using a `.`.

To be clear, unlike Python, R, and MATLAB (to a lesser extent), the reason to drop the `for` is **not** for performance reasons, but rather because of code clarity.

Loops of this sort are at least as efficient as vectorized approach in compiled languages like Julia, so use a for loop if you think it makes the code more clear.

```
In [13]: # better style
         function generatedata(n)
             ϵ = randn(n) # use built in function
             return ϵ.^2
          end
         data = generatedata(5)
```

```
Out[13]: 5-element Array{Float64,1}:
          1.4581291740342703
          1.8125501043209953
          0.24904149884873786
          0.04206678337831965
          3.0583819640808283
```

We can even drop the `function` if we define it on a single line.

```
In [14]: # good style
         generatedata(n) = randn(n).^2
         data = generatedata(5)
```

```
Out[14]: 5-element Array{Float64,1}:
          0.23661834702911036
          0.35774378676197877
          4.730500107602342
          0.05446363165615865
          0.7890340301810831
```

Finally, we can broadcast any function, where squaring is only a special case.

```
In [15]: # good style
         f(x) = x^2 # simple square function
         generatedata(n) = f.(randn(n)) # uses broadcast for some function `f`
         data = generatedata(5)
```

```
Out[15]: 5-element Array{Float64,1}:
          0.20883451157964544
          0.8296323684434822
          0.022319579049377283
          0.1644791401573571
          0.02347767867665137
```

As a final – abstract – approach, we can make the `generatedata` function able to generically apply to a function.

In [16]:
```
generatedata(n, gen) = gen.(randn(n)) # uses broadcast for some function `gen`

f(x) = x^2 # simple square function
data = generatedata(5, f) # applies f
```

Out[16]:
```
5-element Array{Float64,1}:
 0.10155073167168607
 2.2552140007754518
 0.7007155569314104
 6.311468975188948
 0.11904096398760988
```

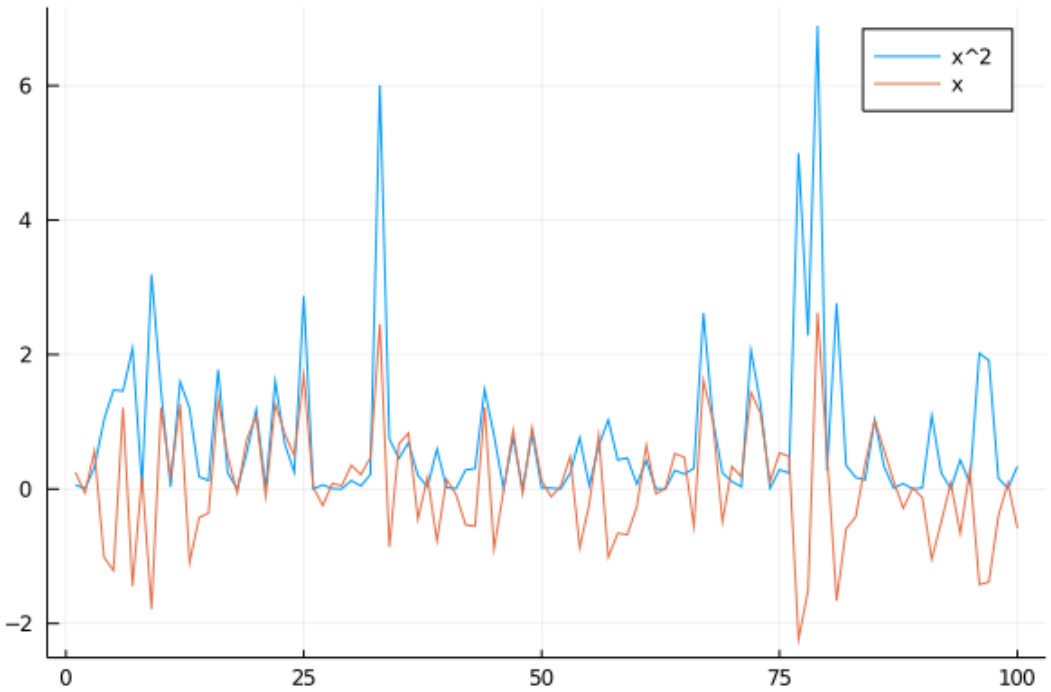
Whether this example is better or worse than the previous version depends on how it is used.

High degrees of abstraction and generality, e.g. passing in a function `f` in this case, can make code either clearer or more confusing, but Julia enables you to use these techniques **with no performance overhead**.

For this particular case, the clearest and most general solution is probably the simplest.

In [17]:
```
# direct solution with broadcasting, and small user-defined function
n = 100
f(x) = x^2

x = randn(n)
plot(f.(x), label="x^2")
plot!(x, label="x") # layer on the same plot
```

Out[17]:



While broadcasting above superficially looks like vectorizing functions in MATLAB, or Python ufuncs, it is much richer and built on core foundations of the language.

The other additional function `plot!` adds a graph to the existing plot.

This follows a general convention in Julia, where a function that modifies the arguments or a global state has a `!` at the end of its name.

A Slightly More Useful Function

Let's make a slightly more useful function.

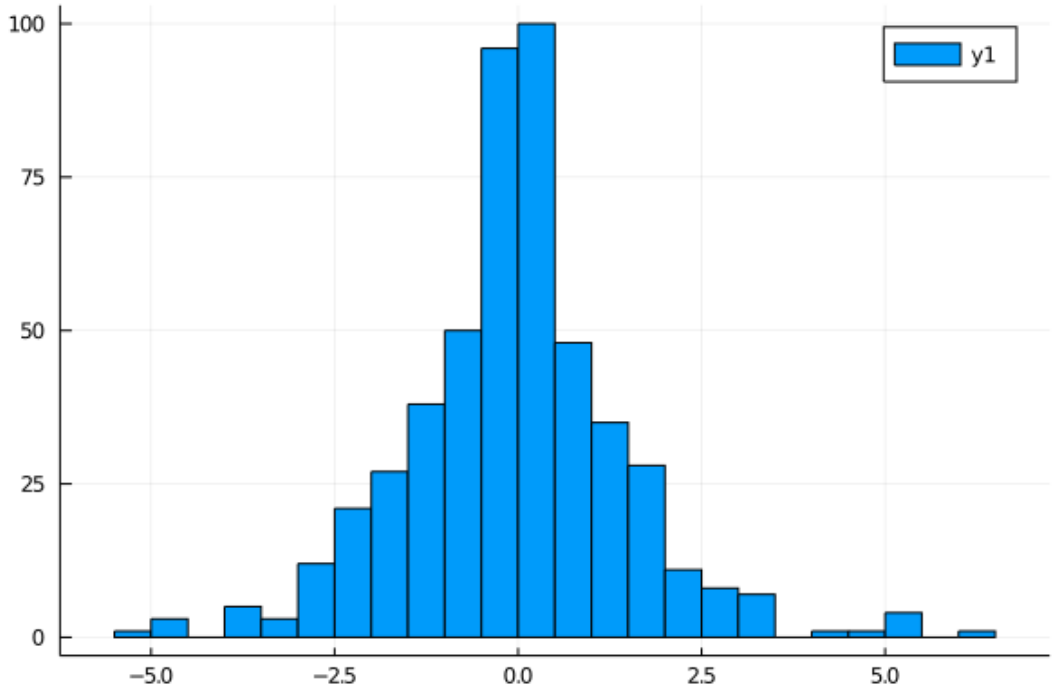
This function will be passed in a choice of probability distribution and respond by plotting a histogram of observations.

In doing so we'll make use of the `Distributions` package, which we assume was instantiated above with the project.

Here's the code

In [18]:
```
using Distributions

function plothistogram(distribution, n)
    ϵ = rand(distribution, n)  # n draws from distribution
    histogram(ϵ)
end

lp = Laplace()
plothistogram(lp, 500)
```

Out[18]:



Let's have a casual discussion of how all this works while leaving technical details for later in the lectures.

First, `lp = Laplace()` creates an instance of a data type defined in the `Distributions` module that represents the Laplace distribution.

The name `lp` is bound to this value.

When we make the function call `plothistogram(lp, 500)` the code in the body of the function `plothistogram` is run with

- the name `distribution` bound to the same value as `lp`
- the name `n` bound to the integer `500`

A Mystery

Now consider the function call `rand(distribution, n)`.

This looks like something of a mystery.

The function `rand()` is defined in the base library such that `rand(n)` returns `n` uniform random variables on $[0, 1)$.

```
In [19]: rand(3)
```

```
Out[19]: 3-element Array{Float64,1}:
          0.43077285177861757
          0.07691366276079359
          0.08457588208380429
```

On the other hand, `distribution` points to a data type representing the Laplace distribution that has been defined in a third party package.

So how can it be that `rand()` is able to take this kind of value as an argument and return the output that we want?

The answer in a nutshell is **multiple dispatch**, which Julia uses to implement **generic programming**.

This refers to the idea that functions in Julia can have different behavior depending on the particular arguments that they're passed.

Hence in Julia we can take an existing function and give it a new behavior by defining how it acts on a new type of value.

The compiler knows which function definition to apply to in a given setting by looking at the types of the values the function is called on.

In Julia these alternative versions of a function are called **methods**.

3.4 Example: Variations on Fixed Points

Take a mapping $f : X \to X$ for some set X.

If there exists an $x^* \in X$ such that $f(x^*) = x^*$, then x^*: is called a "fixed point" of f.

For our second example, we will start with a simple example of determining fixed points of a function.

The goal is to start with code in a MATLAB style, and move towards a more **Julian** style with high mathematical clarity.

3.4.1 Fixed Point Maps

Consider the simple equation, where the scalars p, β are given, and v is the scalar we wish to solve for

$$v = p + \beta v$$

Of course, in this simple example, with parameter restrictions this can be solved as $v = p/(1-\beta)$.

Rearrange the equation in terms of a map $f(x) : \mathbb{R} \to \mathbb{R}$

$$v = f(v) \tag{1}$$

where

$$f(v) := p + \beta v$$

Therefore, a fixed point v^* of $f(\cdot)$ is a solution to the above problem.

3.4.2 While Loops

One approach to finding a fixed point of (1) is to start with an initial value, and iterate the map

$$v^{n+1} = f(v^n) \tag{2}$$

For this exact `f` function, we can see the convergence to $v = p/(1-\beta)$ when $|\beta| < 1$ by iterating backwards and taking $n \to \infty$

$$v^{n+1} = p + \beta v^n = p + \beta p + \beta^2 v^{n-1} = p \sum_{i=0}^{n-1} \beta^i + \beta^n v_0$$

To implement the iteration in (2), we start by solving this problem with a `while` loop.

The syntax for the while loop contains no surprises, and looks nearly identical to a MATLAB implementation.

```
In [20]: # poor style
         p = 1.0 # note 1.0 rather than 1
         β = 0.9
         maxiter = 1000
         tolerance = 1.0E-7
         v_iv = 0.8 # initial condition
```

```
    # setup the algorithm
    v_old = v_iv
    normdiff = Inf
    iter = 1
    while normdiff > tolerance && iter <= maxiter
        v_new = p + β * v_old # the f(v) map
        normdiff = norm(v_new - v_old)

        # replace and continue
        v_old = v_new
        iter = iter + 1
    end
    println("Fixed point = $v_old, and |f(x) - x| = $normdiff in $iter
↪iterations")
```

```
Fixed point = 9.999999173706609, and |f(x) - x| = 9.181037796679448e-8 in 155
iterations
```

The `while` loop, like the `for` loop should only be used directly in Jupyter or the inside of a function.

Here, we have used the `norm` function (from the `LinearAlgebra` base library) to compare the values.

The other new function is the `println` with the string interpolation, which splices the value of an expression or variable prefixed by $ into a string.

An alternative approach is to use a `for` loop, and check for convergence in each iteration.

In [21]:
```
# setup the algorithm
v_old = v_iv
normdiff = Inf
iter = 1
for i in 1:maxiter
    v_new = p + β * v_old # the f(v) map
    normdiff = norm(v_new - v_old)
    if normdiff < tolerance # check convergence
        iter = i
        break # converged, exit loop
    end
    # replace and continue
    v_old = v_new
end
println("Fixed point = $v_old, and |f(x) - x| = $normdiff in $iter
↪iterations")
```

```
Fixed point = 9.999999081896231, and |f(x) - x| = 9.181037796679448e-8 in 154
iterations
```

The new feature there is `break` , which leaves a `for` or `while` loop.

3.4.3 Using a Function

The first problem with this setup is that it depends on being sequentially run – which can be easily remedied with a function.

```
In [22]: # better, but still poor style
         function v_fp(β, ρ, v_iv, tolerance, maxiter)
             # setup the algorithm
             v_old = v_iv
             normdiff = Inf
             iter = 1
             while normdiff > tolerance && iter <= maxiter
                 v_new = p + β * v_old # the f(v) map
                 normdiff = norm(v_new - v_old)

                 # replace and continue
                 v_old = v_new
                 iter = iter + 1
             end
             return (v_old, normdiff, iter) # returns a tuple
         end

         # some values
         p = 1.0 # note 1.0 rather than 1
         β = 0.9
         maxiter = 1000
         tolerance = 1.0E-7
         v_initial = 0.8 # initial condition

         v_star, normdiff, iter = v_fp(β, p, v_initial, tolerance, maxiter)
         println("Fixed point = $v_star, and |f(x) - x| = $normdiff in $iter
       ↪iterations")
```

```
Fixed point = 9.999999173706609, and |f(x) - x| = 9.181037796679448e-8 in 155
iterations
```

While better, there could still be improvements.

3.4.4 Passing a Function

The chief issue is that the algorithm (finding a fixed point) is reusable and generic, while the function we calculate `p + β * v` is specific to our problem.

A key feature of languages like Julia, is the ability to efficiently handle functions passed to other functions.

```
In [23]: # better style
         function fixedpointmap(f, iv, tolerance, maxiter)
             # setup the algorithm
             x_old = iv
             normdiff = Inf
             iter = 1
             while normdiff > tolerance && iter <= maxiter
                 x_new = f(x_old) # use the passed in map
```

```
            normdiff = norm(x_new - x_old)
            x_old = x_new
            iter = iter + 1
        end
        return (x_old, normdiff, iter)
    end

    # define a map and parameters
    p = 1.0
    β = 0.9
    f(v) = p + β * v # note that p and β are used in the function!

    maxiter = 1000
    tolerance = 1.0E-7
    v_initial = 0.8 # initial condition

    v_star, normdiff, iter = fixedpointmap(f, v_initial, tolerance, maxiter)
    println("Fixed point = $v_star, and |f(x) - x| = $normdiff in $iter
↪iterations")
```

```
Fixed point = 9.999999173706609, and |f(x) - x| = 9.181037796679448e-8 in 155
iterations
```

Much closer, but there are still hidden bugs if the user orders the settings or returns types wrong.

3.4.5 Named Arguments and Return Values

To enable this, Julia has two features: named function parameters, and named tuples

In [24]:
```
# good style
function fixedpointmap(f; iv, tolerance=1E-7, maxiter=1000)
    # setup the algorithm
    x_old = iv
    normdiff = Inf
    iter = 1
    while normdiff > tolerance && iter <= maxiter
        x_new = f(x_old) # use the passed in map
        normdiff = norm(x_new - x_old)
        x_old = x_new
        iter = iter + 1
    end
    return (value = x_old, normdiff=normdiff, iter=iter) # A named tuple
end

# define a map and parameters
p = 1.0
β = 0.9
f(v) = p + β * v # note that p and β are used in the function!

sol = fixedpointmap(f, iv=0.8, tolerance=1.0E-8) # don't need to pass
println("Fixed point = $(sol.value), and |f(x) - x| = $(sol.normdiff) in
↪$(sol.iter)"*
        " iterations")
```

```
    Fixed point = 9.999999918629035, and |f(x) - x| = 9.041219328764782e-9 in 177
iterations
```

In this example, all function parameters after the `;` in the list, must be called by name.

Furthermore, a default value may be enabled – so the named parameter `iv` is required while `tolerance` and `maxiter` have default values.

The return type of the function also has named fields, `value, normdiff,` and `iter` – all accessed intuitively using `..`

To show the flexibilty of this code, we can use it to find a fixed point of the non-linear logistic equation, $x = f(x)$ where $f(x) := rx(1-x)$.

```
In [25]: r = 2.0
         f(x) = r * x * (1 - x)

         sol = fixedpointmap(f, iv=0.8)
         println("Fixed point = $(sol.value), and |f(x) - x| = $(sol.normdiff) in
 ↪$(sol.iter)
         iterations")
```

```
    Fixed point = 0.4999999999999968, and |f(x) - x| = 3.979330237546819e-8 in 7
iterations
```

3.4.6 Using a Package

But best of all is to avoid writing code altogether.

```
In [26]: # best style
         using NLsolve

         p = 1.0
         β = 0.9
         f(v) = p .+ β * v # broadcast the +
         sol = fixedpoint(f, [0.8])
         println("Fixed point = $(sol.zero), and |f(x) - x| = $(norm(f(sol.zero) -
 ↪sol.zero)) in
         " *
                 "$(sol.iterations) iterations")
```

```
    Fixed point = [9.999999999999973], and |f(x) - x| = 3.552713678800501e-15 in 3
iterations
```

The `fixedpoint` function from the `NLsolve.jl` library implements the simple fixed point iteration scheme above.

Since the `NLsolve` library only accepts vector based inputs, we needed to make the `f(v)` function broadcast on the `+` sign, and pass in the initial condition as a vector of length 1 with `[0.8]`.

While a key benefit of using a package is that the code is clearer, and the implementation is tested, by using an orthogonal library we also enable performance improvements.

```
In [27]: # best style
         p = 1.0
         β = 0.9
         iv = [0.8]
         sol = fixedpoint(v -> p .+ β * v, iv)
         println("Fixed point = $(sol.zero), and |f(x) - x| = $(norm(f(sol.zero) -
 ↪sol.zero)) in
         " *
                 "$(sol.iterations) iterations")
```

```
Fixed point = [9.999999999999973], and |f(x) - x| = 3.552713678800501e-15 in 3
iterations
```

Note that this completes in `3` iterations vs `177` for the naive fixed point iteration algorithm.

Since Anderson iteration is doing more calculations in an iteration, whether it is faster or not would depend on the complexity of the `f` function.

But this demonstrates the value of keeping the math separate from the algorithm, since by decoupling the mathematical definition of the fixed point from the implementation in (2), we were able to exploit new algorithms for finding a fixed point.

The only other change in this function is the move from directly defining `f(v)` and using an **anonymous** function.

Similar to anonymous functions in MATLAB, and lambda functions in Python, Julia enables the creation of small functions without any names.

The code `v -> p .+ β * v` defines a function of a dummy argument, `v` with the same body as our `f(x)`.

3.4.7 Composing Packages

A key benefit of using Julia is that you can compose various packages, types, and techniques, without making changes to your underlying source.

As an example, consider if we want to solve the model with a higher-precision, as floating points cannot be distinguished beyond the machine epsilon for that type (recall that computers approximate real numbers to the nearest binary of a given precision; the *machine epsilon* is the smallest nonzero magnitude).

In Julia, this number can be calculated as

```
In [28]: eps()
```

```
Out[28]: 2.220446049250313e-16
```

For many cases, this is sufficient precision – but consider that in iterative algorithms applied millions of times, those small differences can add up.

The only change we will need to our model in order to use a different floating point type is to call the function with an arbitrary precision floating point, `BigFloat`, for the initial value.

```
In [29]: # use arbitrary precision floating points
         p = 1.0
```

```
β = 0.9
iv = [BigFloat(0.8)] # higher precision

# otherwise identical
sol = fixedpoint(v -> p .+ β * v, iv)
println("Fixed point = $(sol.zero), and |f(x) - x| = $(norm(f(sol.zero) -
↪sol.zero)) in
" *
        "$(sol.iterations) iterations")
```

```
  Fixed point = BigFloat[10.
↪000000000000002220446049250313573885329099314128483772878678
09936811555686155], and |f(x) - x| = 0.0 in 3 iterations
```

Here, the literal `BigFloat(0.8)` takes the number `0.8` and changes it to an arbitrary precision number.

The result is that the residual is now **exactly** `0.0` since it is able to use arbitrary precision in the calculations, and the solution has a finite-precision solution with those parameters.

3.4.8 Multivariate Fixed Point Maps

The above example can be extended to multivariate maps without any modifications to the fixed point iteration code.

Using our own, homegrown iteration and simply passing in a bivariate map:

```
In [30]: p = [1.0, 2.0]
         β = 0.9
         iv = [0.8, 2.0]
         f(v) = p .+ β * v # note that p and β are used in the function!

         sol = fixedpointmap(f, iv = iv, tolerance = 1.0E-8)
         println("Fixed point = $(sol.value), and |f(x) - x| = $(sol.normdiff) in
       ↪$(sol.iter)"*
         "iterations")
```

```
  Fixed point = [9.999999961080519, 19.999999923853192], and |f(x) - x| =
9.501826248250528e-9 in 184iterations
```

This also works without any modifications with the `fixedpoint` library function.

```
In [31]: using NLsolve

         p = [1.0, 2.0, 0.1]
         β = 0.9
         iv =[0.8, 2.0, 51.0]
         f(v) = p .+ β * v

         sol = fixedpoint(v -> p .+ β * v, iv)
         println("Fixed point = $(sol.zero), and |f(x) - x| = $(norm(f(sol.zero) -
       ↪sol.zero)) in
         " *
                 "$(sol.iterations) iterations")
```

```
    Fixed point = [10.0, 20.000000000000004, 0.9999999999999929], and |f(x) - x| =
6.661338147750939e-16 in 3 iterations
```

Finally, to demonstrate the importance of composing different libraries, use a `StaticArrays.jl` type, which provides an efficient implementation for small arrays and matrices.

```
In [32]: using NLsolve, StaticArrays
         p = @SVector [1.0, 2.0, 0.1]
         β = 0.9
         iv = [0.8, 2.0, 51.0]
         f(v) = p .+ β * v

         sol = fixedpoint(v -> p .+ β * v, iv)
         println("Fixed point = $(sol.zero), and |f(x) - x| = $(norm(f(sol.zero) -
↪sol.zero)) in
         " *
                "$(sol.iterations) iterations")
```

```
    Fixed point = [10.0, 20.000000000000004, 0.9999999999999929], and |f(x) - x| =
6.661338147750939e-16 in 3 iterations
```

The `@SVector` in front of the `[1.0, 2.0, 0.1]` is a macro for turning a vector literal into a static vector.

All macros in Julia are prefixed by `@` in the name, and manipulate the code prior to compilation.

We will see a variety of macros, and discuss the "metaprogramming" behind them in a later lecture.

3.5 Exercises

3.5.1 Exercise 1

Recall that $n!$ is read as "n factorial" and defined as $n! = n \times (n-1) \times \cdots \times 2 \times 1$.

In Julia you can compute this value with `factorial(n)`.

Write your own version of this function, called `factorial2`, using a `for` loop.

3.5.2 Exercise 2

The binomial random variable $Y \sim Bin(n, p)$ represents

- number of successes in n binary trials
- each trial succeeds with probability p

Using only `rand()` from the set of Julia's built-in random number generators (not the `Distributions` package), write a function `binomial_rv` such that `binomial_rv(n, p)` generates one draw of Y.

Hint: If U is uniform on $(0, 1)$ and $p \in (0, 1)$, then the expression `U < p` evaluates to `true` with probability p.

3.5.3 Exercise 3

Compute an approximation to π using Monte Carlo.

For random number generation use only `rand()`.

Your hints are as follows:

- If U is a bivariate uniform random variable on the unit square $(0, 1)^2$, then the probability that U lies in a subset B of $(0, 1)^2$ is equal to the area of B.
- If $U_1, \ldots, U_n$ are iid copies of U, then, as n gets larger, the fraction that falls in B converges to the probability of landing in B.
- For a circle, area = π * $radius^2$.

3.5.4 Exercise 4

Write a program that prints one realization of the following random device:

- Flip an unbiased coin 10 times.
- If 3 consecutive heads occur one or more times within this sequence, pay one dollar.
- If not, pay nothing.

Once again use only `rand()` as your random number generator.

3.5.5 Exercise 5

Simulate and plot the correlated time series

$$x_{t+1} = \alpha\, x_t + \epsilon_{t+1} \quad \text{where} \quad x_0 = 0 \quad \text{and} \quad t = 0, \ldots, n$$

The sequence of shocks $\{\epsilon_t\}$ is assumed to be iid and standard normal.

Set $n = 200$ and $\alpha = 0.9$.

3.5.6 Exercise 6

Plot three simulated time series, one for each of the cases $\alpha = 0$, $\alpha = 0.8$ and $\alpha = 0.98$.

(The figure will illustrate how time series with the same one-step-ahead conditional volatilities, as these three processes have, can have very different unconditional volatilities)

3.5.7 Exercise 7

This exercise is more challenging.

Take a random walk, starting from $x_0 = 1$

$$x_{t+1} = \alpha\, x_t + \sigma\, \epsilon_{t+1} \quad \text{where} \quad x_0 = 1 \quad \text{and} \quad t = 0, \ldots, t_{\max}$$

- Furthermore, assume that the $x_{t_{\max}} = 0$ (i.e. at $t_{\max}$, the value drops to zero, regardless of its current state).
- The sequence of shocks $\{\epsilon_t\}$ is assumed to be iid and standard normal.
- For a given path $\{x_t\}$ define a **first-passage time** as $T_a = \min\{t \,|\, x_t \leq a\}$, where by the assumption of the process $T_a \leq t_{\max}$.

Start with $\sigma = 0.2, \alpha = 1.0$

1. calculate the first-passage time, T_0, for 100 simulated random walks – to a $t_{\max} = 200$ and plot a histogram
2. plot the sample mean of T_0 from the simulation for $\alpha \in \{0.8, 1.0, 1.2\}$

3.5.8 Exercise 8(a)

This exercise is more challenging.

The root of a univariate function $f(\cdot)$ is an x such that $f(x) = 0$.

One solution method to find local roots of smooth functions is called Newton's method.

Starting with an x_0 guess, a function $f(\cdot)$ and the first-derivative $f'(\cdot)$, the algorithm is to repeat

$$x^{n+1} = x^n - \frac{f(x^n)}{f'(x^n)}$$

until $|x^{n+1} - x^n|$ is below a tolerance

1. Use a variation of the `fixedpointmap` code to implement Newton's method, where the function would accept arguments `f, f_prime, x_0, tolerance, maxiter`.
2. Test it with $f(x) = (x-1)^3$ and another function of your choice where you can analytically find the derivative.

3.5.9 Exercise 8(b)

For those impatient to use more advanced features of Julia, implement a version of Exercise 8(a) where `f_prime` is calculated with auto-differentiation.

In [33]:
```
using ForwardDiff

# operator to get the derivative of this function using AD
D(f) = x -> ForwardDiff.derivative(f, x)

# example usage: create a function and get the derivative
f(x) = x^2
f_prime = D(f)

f(0.1), f_prime(0.1)
```

Out[33]:
```
(0.010000000000000002, 0.2)
```

1. Using the `D(f)` operator definition above, implement a version of Newton's method that does not require the user to provide an analytical derivative.

2. Test the sorts of `f` functions which can be automatically integrated by `ForwardDff.jl`.

3.6 Solutions

3.6.1 Exercise 1

```
In [34]: function factorial2(n)
             k = 1
             for i in 1:n
                 k *= i  # or k = k * i
             end
             return k
         end

         factorial2(4)
```

```
Out[34]: 24
```

```
In [35]: factorial2(4) == factorial(4) # built-in function
```

```
Out[35]: true
```

3.6.2 Exercise 2

```
In [36]: function binomial_rv(n, p)
             count = 0
             U = rand(n)
             for i in 1:n
                 if U[i] < p
                     count += 1 # or count = count + 1
                 end
             end
             return count
         end

         for j in 1:25
             b = binomial_rv(10, 0.5)
             print("$b, ")
         end
```

```
5, 6, 4, 4, 7, 5, 6, 5, 6, 8, 7, 4, 4, 6, 5, 6, 5, 4, 3, 5, 5, 6, 6, 4, 3,
```

3.6.3 Exercise 3

Consider a circle with diameter 1 embedded in a unit square.

Let A be its area and let $r = 1/2$ be its radius.

If we know π then we can compute A via $A = \pi r^2$.

But the point here is to compute π, which we can do by $\pi = A/r^2$.

Summary: If we can estimate the area of the unit circle, then dividing by $r^2 = (1/2)^2 = 1/4$ gives an estimate of π.

We estimate the area by sampling bivariate uniforms and looking at the fraction that fall into the unit circle.

In [37]:
```
n = 1000000
count = 0
for i in 1:n
    u, v = rand(2)
    d = sqrt((u - 0.5)^2 + (v - 0.5)^2)  # distance from middle of square
    if d < 0.5
        count += 1
    end
end

area_estimate = count / n

print(area_estimate * 4)  # dividing by radius**2
```

```
3.143828
```

3.6.4 Exercise 4

In [38]:
```
payoff = 0
count = 0

print("Count = ")

for i in 1:10
    U = rand()
    if U < 0.5
        count += 1
    else
        count = 0
    end
    print(count)
    if count == 3
        payoff = 1
    end
end
println("\npayoff = $payoff")
```

```
   Count = 1201230100
payoff = 1
```

We can simplify this somewhat using the **ternary operator**. Here are some examples

In [39]:
```
a = 1  < 2 ? "foo" : "bar"
```

Out[39]:
```
"foo"
```

In [40]:
```
a = 1 > 2 ? "foo" : "bar"
```

Out[40]:
```
"bar"
```

Using this construction:

In [41]:
```
payoff = 0.0
count = 0.0

print("Count = ")

for i in 1:10
    U = rand()
    count = U < 0.5 ? count + 1 : 0
    print(count)
    if count == 3
        payoff = 1
    end
end
println("\npayoff = $payoff")
```

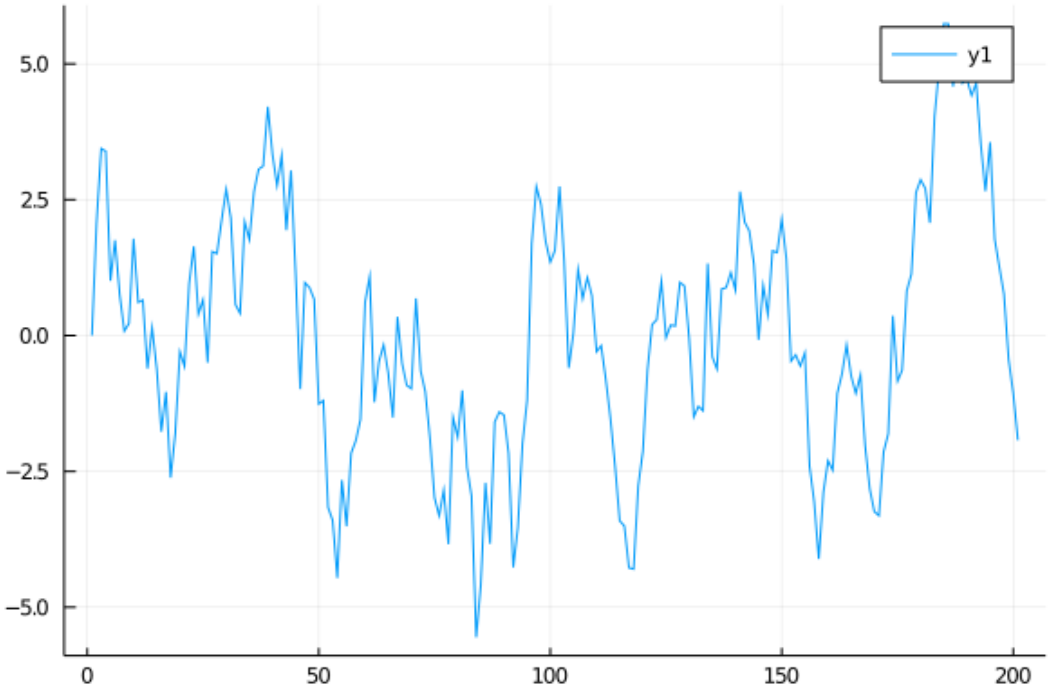
```
   Count = 1.0001230012
payoff = 1
```

3.6.5 Exercise 5

Here's one solution

In [42]:
```
using Plots
gr(fmt=:png); # setting for easier display in jupyter notebooks
α = 0.9
n = 200
x = zeros(n + 1)

for t in 1:n
    x[t+1] = α * x[t] + randn()
end
plot(x)
```

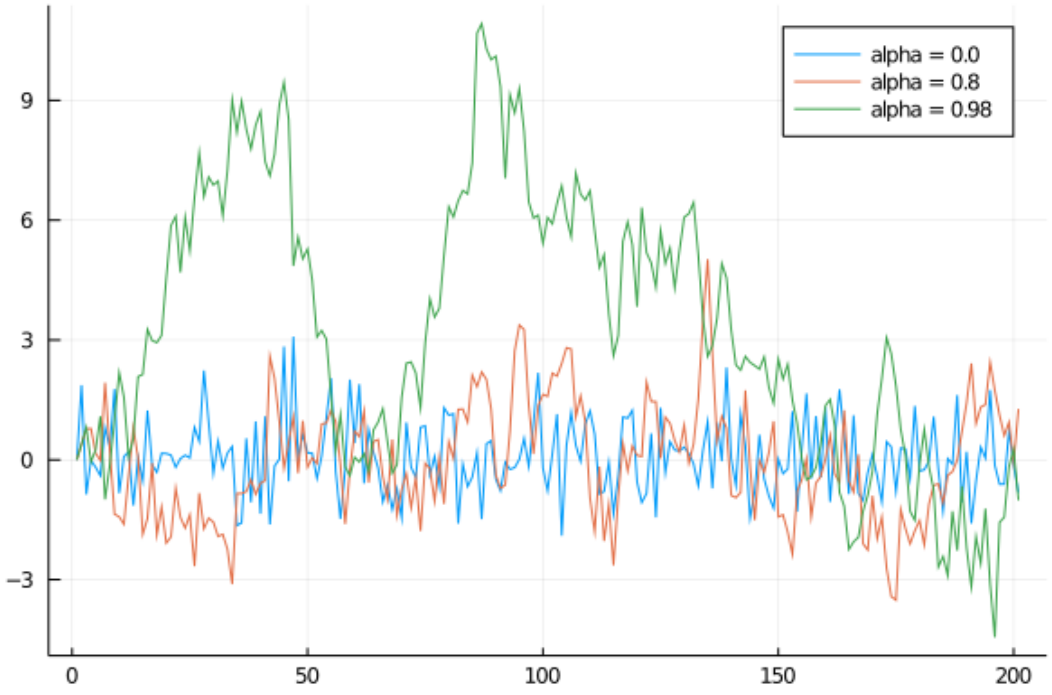
Out[42]:



3.6.6 Exercise 6

In [43]:
```
αs = [0.0, 0.8, 0.98]
n = 200
p = plot() # naming a plot to add to

for α in αs
    x = zeros(n + 1)
    x[1] = 0.0
    for t in 1:n
        x[t+1] = α * x[t] + randn()
    end
    plot!(p, x, label = "alpha = $α") # add to plot p
end
p # display plot
```

Out[43]:



3.6.7 Exercise 7: Hint

As a hint, notice the following pattern for finding the number of draws of a uniform random number until it is below a given threshold

```
In [44]: function drawsuntilthreshold(threshold; maxdraws=100)
             for i in 1:maxdraws
                 val = rand()
                 if val < threshold # checks threshold
                     return i # leaves function, returning draw number
                 end
             end
             return Inf # if here, reached maxdraws
         end

         draws = drawsuntilthreshold(0.2, maxdraws=100)
```

```
Out[44]: 2
```

Additionally, it is sometimes convenient to add to just push numbers onto an array without indexing it directly

```
In [45]: vals = zeros(0) # empty vector

         for i in 1:100
             val = rand()
             if val < 0.5
                 push!(vals, val)
             end
         end
         println("There were $(length(vals)) below 0.5")
```

```
There were 51 below 0.5
```

Chapter 4

Julia Essentials

4.1 Contents

Having covered a few examples, let's now turn to a more systematic exposition of the essential features of the language.

4.2 Overview

Topics:

- Common data types
- Iteration
- More on user-defined functions
- Comparisons and logic

4.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

4.3 Common Data Types

Like most languages, Julia language defines and provides functions for operating on standard data types such as

- integers
- floats
- strings
- arrays, etc…

Let's learn a bit more about them.

4.3.1 Primitive Data Types

A particularly simple data type is a Boolean value, which can be either `true` or `false`.

```
In [3]: x = true
```

```
Out[3]: true
```

```
In [4]: typeof(x)
```

```
Out[4]: Bool
```

```
In [5]: y = 1 > 2  # now y = false
```

```
Out[5]: false
```

The two most common data types used to represent numbers are integers and floats.

(Computers distinguish between floats and integers because arithmetic is handled in a different way)

```
In [6]: typeof(1.0)
```

```
Out[6]: Float64
```

```
In [7]: typeof(1)
```

```
Out[7]: Int64
```

If you're running a 32 bit system you'll still see `Float64`, but you will see `Int32` instead of `Int64` (see the section on Integer types from the Julia manual).

Arithmetic operations are fairly standard.

```
In [8]: x = 2; y = 1.0;
```

The `;` can be used to suppress output from a line of code, or to combine two lines of code together (as above), but is otherwise not necessary.

```
In [9]: x * y
```

```
Out[9]: 2.0
```

```
In [10]: x^2
```

```
Out[10]: 4
```

```
In [11]: y / x
```

```
Out[11]: 0.5
```

Although the `*` can be omitted for multiplication between a numeric literal and a variable.

```
In [12]: 2x - 3y
```

```
Out[12]: 1.0
```

A useful tool for displaying both expressions and code is to use the `@show` macro, which displays the text and the results.

```
In [13]: @show 2x - 3y
         @show x + y;
```

```
    2x - 3y = 1.0
x + y = 3.0
```

Here we have used `;` to suppress the output on the last line, which otherwise returns the results of `x + y`.

Complex numbers are another primitive data type, with the imaginary part being specified by `im`.

```
In [14]: x = 1 + 2im
```

```
Out[14]: 1 + 2im
```

```
In [15]: y = 1 - 2im
```

```
Out[15]: 1 - 2im
```

```
In [16]: x * y  # complex multiplication
```

```
Out[16]: 5 + 0im
```

There are several more primitive data types that we'll introduce as necessary.

4.3.2 Strings

A string is a data type for storing a sequence of characters.

In Julia, strings are created using double quotation marks (single quotations are reserved for the character type).

```
In [17]: x = "foobar"

Out[17]: "foobar"

In [18]: typeof(x)

Out[18]: String
```

You've already seen examples of Julia's simple string formatting operations.

```
In [19]: x = 10; y = 20

Out[19]: 20
```

The `\$` inside of a string is used to interpolate a variable.

```
In [20]: "x = $x"

Out[20]: "x = 10"
```

With parentheses, you can splice the results of expressions into strings as well.

```
In [21]: "x + y = $(x + y)"

Out[21]: "x + y = 30"
```

To concatenate strings use `*`

```
In [22]: "foo" * "bar"

Out[22]: "foobar"
```

Julia provides many functions for working with strings.

```
In [23]: s = "Charlie don't surf"

Out[23]: "Charlie don't surf"

In [24]: split(s)
```

```
Out[24]: 3-element Array{SubString{String},1}:
          "Charlie"
          "don't"
          "surf"

In [25]: replace(s, "surf" => "ski")

Out[25]: "Charlie don't ski"

In [26]: split("fee,fi,fo", ",")

Out[26]: 3-element Array{SubString{String},1}:
          "fee"
          "fi"
          "fo"

In [27]: strip(" foobar ")  # remove whitespace

Out[27]: "foobar"
```

Julia can also find and replace using regular expressions (see regular expressions documentation for more info).

```
In [28]: match(r"(\d+)", "Top 10")  # find digits in string

Out[28]: RegexMatch("10", 1="10")
```

4.3.3 Containers

Julia has several basic types for storing collections of data.

We have already discussed arrays.

A related data type is a **tuple**, which is immutable and can contain different types.

```
In [29]: x = ("foo", "bar")
         y = ("foo", 2)

Out[29]: ("foo", 2)

In [30]: typeof(x), typeof(y)

Out[30]: (Tuple{String,String}, Tuple{String,Int64})
```

An immutable value is one that cannot be altered once it resides in memory.

In particular, tuples do not support item assignment (i.e. `x[1] = "test"` would fail).

Tuples can be constructed with or without parentheses.

```
In [31]: x = "foo", 1
```

```
Out[31]: ("foo", 1)
```

```
In [32]: function f()
             return "foo", 1
         end
         f()
```

```
Out[32]: ("foo", 1)
```

Tuples can also be unpacked directly into variables.

```
In [33]: x = ("foo", 1)
```

```
Out[33]: ("foo", 1)
```

```
In [34]: word, val = x
         println("word = $word, val = $val")
```

```
word = foo, val = 1
```

Tuples can be created with a hanging `,` – this is useful to create a tuple with one element.

```
In [35]: x = ("foo", 1,)
         y = ("foo",)
         typeof(x), typeof(y)
```

```
Out[35]: (Tuple{String,Int64}, Tuple{String})
```

Referencing Items

The last element of a sequence type can be accessed with the keyword `end`.

```
In [36]: x = [10, 20, 30, 40]
```

```
Out[36]: 4-element Array{Int64,1}:
          10
          20
          30
          40
```

```
In [37]: x[end]
```

```
Out[37]: 40
```

```
In [38]: x[end-1]
```

```
Out[38]: 30
```

To access multiple elements of an array or tuple, you can use slice notation.

```
In [39]: x[1:3]

Out[39]: 3-element Array{Int64,1}:
          10
          20
          30

In [40]: x[2:end]

Out[40]: 3-element Array{Int64,1}:
          20
          30
          40
```

The same slice notation works on strings.

```
In [41]: "foobar"[3:end]

Out[41]: "obar"
```

Dictionaries

Another container type worth mentioning is dictionaries.

Dictionaries are like arrays except that the items are named instead of numbered.

```
In [42]: d = Dict("name" => "Frodo", "age" => 33)

Out[42]: Dict{String,Any} with 2 entries:
           "name" => "Frodo"
           "age"  => 33

In [43]: d["age"]

Out[43]: 33
```

The strings `name` and `age` are called the **keys**.

The keys are mapped to **values** (in this case `"Frodo"` and `33`).

They can be accessed via `keys(d)` and `values(d)` respectively.

Note Unlike in Python and some other dynamic languages, dictionaries are rarely the right approach (ie. often referred to as "the devil's datastructure").

The flexibility (i.e. can store anything and use anything as a key) frequently comes at the cost of performance if misused.

It is usually better to have collections of parameters and results in a named tuple, which both provide the compiler with more opportunities to optimize the performance, and also makes the code more safe.

4.4 Iterating

One of the most important tasks in computing is stepping through a sequence of data and performing a given action.

Julia provides neat and flexible tools for iteration as we now discuss.

4.4.1 Iterables

An iterable is something you can put on the right hand side of `for` and loop over.

These include sequence data types like arrays.

```
In [44]: actions = ["surf", "ski"]
         for action in actions
             println("Charlie doesn't $action")
         end
```

```
Charlie doesn't surf
Charlie doesn't ski
```

They also include so-called **iterators**.

You've already come across these types of values

```
In [45]: for i in 1:3
             print(i)
         end
```

```
123
```

If you ask for the keys of dictionary you get an iterator

```
In [46]: d = Dict("name" => "Frodo", "age" => 33)
```

```
Out[46]: Dict{String,Any} with 2 entries:
           "name" => "Frodo"
           "age"  => 33
```

```
In [47]: keys(d)
```

```
Out[47]: Base.KeySet for a Dict{String,Any} with 2 entries. Keys:
           "name"
           "age"
```

This makes sense, since the most common thing you want to do with keys is loop over them.

The benefit of providing an iterator rather than an array, say, is that the former is more memory efficient.

Should you need to transform an iterator into an array you can always use `collect()`.

```
In [48]: collect(keys(d))
```

```
Out[48]: 2-element Array{String,1}:
          "name"
          "age"
```

4.4.2 Looping without Indices

You can loop over sequences without explicit indexing, which often leads to neater code.

For example compare

```
In [49]: x_values = 1:5
```

```
Out[49]: 1:5
```

```
In [50]: for x in x_values
             println(x * x)
         end
```

```
1
4
9
16
25
```

```
In [51]: for i in eachindex(x_values)
             println(x_values[i] * x_values[i])
         end
```

```
1
4
9
16
25
```

Julia provides some functional-style helper functions (similar to Python and R) to facilitate looping without indices.

One is `zip()`, which is used for stepping through pairs from two sequences.

For example, try running the following code

```
In [52]: countries = ("Japan", "Korea", "China")
         cities = ("Tokyo", "Seoul", "Beijing")
         for (country, city) in zip(countries, cities)
             println("The capital of $country is $city")
         end
```

```
The capital of Japan is Tokyo
The capital of Korea is Seoul
The capital of China is Beijing
```

If we happen to need the index as well as the value, one option is to use `enumerate()`.

The following snippet will give you the idea

```
In [53]: countries = ("Japan", "Korea", "China")
         cities = ("Tokyo", "Seoul", "Beijing")
         for (i, country) in enumerate(countries)
             city = cities[i]
             println("The capital of $country is $city")
         end
```

```
   The capital of Japan is Tokyo
The capital of Korea is Seoul
The capital of China is Beijing
```

4.4.3 Comprehensions

(See comprehensions documentation)

Comprehensions are an elegant tool for creating new arrays, dictionaries, etc. from iterables.

Here are some examples

```
In [54]: doubles = [ 2i for i in 1:4 ]
```

```
Out[54]: 4-element Array{Int64,1}:
          2
          4
          6
          8
```

```
In [55]: animals = ["dog", "cat", "bird"];   # Semicolon suppresses output
```

```
In [56]: plurals = [ animal * "s" for animal in animals ]
```

```
Out[56]: 3-element Array{String,1}:
          "dogs"
          "cats"
          "birds"
```

```
In [57]: [ i + j for i in 1:3, j in 4:6 ]
```

```
Out[57]: 3×3 Array{Int64,2}:
          5  6  7
          6  7  8
          7  8  9
```

```
In [58]: [ i + j + k for i in 1:3, j in 4:6, k in 7:9 ]
```

```
Out[58]: 3×3×3 Array{Int64,3}:
         [:, :, 1] =
          12  13  14
```

```
 13  14  15
 14  15  16

[:, :, 2] =
 13  14  15
 14  15  16
 15  16  17

[:, :, 3] =
 14  15  16
 15  16  17
 16  17  18
```

Comprehensions can also create arrays of tuples or named tuples

```
In [59]: [ (i, j) for i in 1:2, j in animals]
```

```
Out[59]: 2×3 Array{Tuple{Int64,String},2}:
          (1, "dog")  (1, "cat")  (1, "bird")
          (2, "dog")  (2, "cat")  (2, "bird")
```

```
In [60]: [ (num = i, animal = j) for i in 1:2, j in animals]
```

```
Out[60]: 2×3 Array{NamedTuple{(:num, :animal),Tuple{Int64,String}},2}:
          (num = 1, animal = "dog")  …  (num = 1, animal = "bird")
          (num = 2, animal = "dog")     (num = 2, animal = "bird")
```

4.4.4 Generators

(See generator documentation)

In some cases, you may wish to use a comprehension to create an iterable list rather than actually making it a concrete array.

The benefit of this is that you can use functions which take general iterators rather than arrays without allocating and storing any temporary values.

For example, the following code generates a temporary array of size 10,000 and finds the sum.

```
In [61]: xs = 1:10000
         f(x) = x^2
         f_x = f.(xs)
         sum(f_x)
```

```
Out[61]: 333383335000
```

We could have created the temporary using a comprehension, or even done the comprehension within the `sum` function, but these all create temporary arrays.

```
In [62]: f_x2 = [f(x) for x in xs]
         @show sum(f_x2)
         @show sum([f(x) for x in xs]); # still allocates temporary
```

```
    sum(f_x2) = 333383335000
sum([f(x) for x = xs]) = 333383335000
```

Note, that if you were hand-code this, you would be able to calculate the sum by simply iterating to 10000, applying `f` to each number, and accumulating the results. No temporary vectors would be necessary.

A generator can emulate this behavior, leading to clear (and sometimes more efficient) code when used with any function that accepts iterators. All you need to do is drop the `]` brackets.

```
In [63]: sum(f(x) for x in xs)
```

```
Out[63]: 333383335000
```

We can use `BenchmarkTools` to investigate

```
In [64]: using BenchmarkTools
         @btime sum([f(x) for x in $xs])
         @btime sum(f.($xs))
         @btime sum(f(x) for x in $xs);
```

```
    10.138 μs (2 allocations: 78.20 KiB)
  9.508 μs (2 allocations: 78.20 KiB)
  4.725 ns (0 allocations: 0 bytes)
```

Notice that the first two cases are nearly identical, and allocate a temporary array, while the final case using generators has no allocations.

In this example you may see a speedup of over 1000x. Whether using generators leads to code that is faster or slower depends on the cirumstances, and you should (1) always profile rather than guess; and (2) worry about code clarify first, and performance second—if ever.

4.5 Comparisons and Logical Operators

4.5.1 Comparisons

As we saw earlier, when testing for equality we use `==`.

```
In [65]: x = 1
```

```
Out[65]: 1
```

```
In [66]: x == 2
```

```
Out[66]: false
```

For "not equal" use `!=` or `≠` (`\ne<TAB>`).

```
In [67]: x != 3
```

```
Out[67]: true
```

Julia can also test approximate equality with `≈` (`\approx<TAB>`).

```
In [68]: 1 + 1E-8 ≈ 1
```

```
Out[68]: true
```

Be careful when using this, however, as there are subtleties involving the scales of the quantities compared.

4.5.2 Combining Expressions

Here are the standard logical connectives (conjunction, disjunction)

```
In [69]: true && false
```

```
Out[69]: false
```

```
In [70]: true || false
```

```
Out[70]: true
```

Remember

- `P && Q` is `true` if both are `true`, otherwise it's `false`.
- `P || Q` is `false` if both are `false`, otherwise it's `true`.

4.6 User-Defined Functions

Let's talk a little more about user-defined functions.

User-defined functions are important for improving the clarity of your code by

- separating different strands of logic
- facilitating code reuse (writing the same thing twice is always a bad idea)

Julia functions are convenient:

- Any number of functions can be defined in a given file.
- Any "value" can be passed to a function as an argument, including other functions.
- Functions can be (and often are) defined inside other functions.
- A function can return any kind of value, including functions.

We'll see many examples of these structures in the following lectures.

For now let's just cover some of the different ways of defining functions.

4.6.1 Return Statement

In Julia, the `return` statement is optional, so that the following functions have identical behavior

```
In [71]: function f1(a, b)
             return a * b
         end

         function f2(a, b)
             a * b
         end
```

```
Out[71]: f2 (generic function with 1 method)
```

When no return statement is present, the last value obtained when executing the code block is returned.

Although some prefer the second option, we often favor the former on the basis that explicit is better than implicit.

A function can have arbitrarily many `return` statements, with execution terminating when the first return is hit.

You can see this in action when experimenting with the following function

```
In [72]: function foo(x)
             if x > 0
                 return "positive"
             end
             return "nonpositive"
         end
```

```
Out[72]: foo (generic function with 1 method)
```

4.6.2 Other Syntax for Defining Functions

For short function definitions Julia offers some attractive simplified syntax.

First, when the function body is a simple expression, it can be defined without the `function` keyword or `end`.

```
In [73]: f(x) = sin(1 / x)
```

```
Out[73]: f (generic function with 2 methods)
```

Let's check that it works

```
In [74]: f(1 / pi)
```

```
Out[74]: 1.2246467991473532e-16
```

Julia also allows you to define anonymous functions.

For example, to define `f(x) = sin(1 / x)` you can use `x -> sin(1 / x)`.

The difference is that the second function has no name bound to it.

How can you use a function with no name?

Typically it's as an argument to another function

```
In [75]: map(x -> sin(1 / x), randn(3))  # apply function to each element
```

```
Out[75]: 3-element Array{Float64,1}:
          -0.994378709150385
           0.7959953516509257
           0.7931544866509989
```

4.6.3 Optional and Keyword Arguments

(See keyword arguments documentation)

Function arguments can be given default values

```
In [76]: f(x, a = 1) = exp(cos(a * x))
```

```
Out[76]: f (generic function with 3 methods)
```

If the argument is not supplied, the default value is substituted.

```
In [77]: f(pi)
```

```
Out[77]: 0.36787944117144233
```

```
In [78]: f(pi, 2)
```

```
Out[78]: 2.718281828459045
```

Another option is to use **keyword** arguments.

The difference between keyword and standard (positional) arguments is that they are parsed and bounded by name rather than the order in the function call.

For example, in the call

```
In [79]: f(x; a = 1) = exp(cos(a * x))  # note the ; in the definition

         f(pi, a = 2) # calling with ; is usually optional and generally discouraged
```

```
Out[79]: 2.718281828459045
```

4.7 Broadcasting

(See broadcasting documentation)

A common scenario in computing is that

- we have a function `f` such that `f(x)` returns a number for any number `x`
- we wish to apply `f` to every element of an iterable `x_vec` to produce a new result `y_vec`

In Julia loops are fast and we can do this easily enough with a loop.

For example, suppose that we want to apply `sin` to `x_vec = [2.0, 4.0, 6.0, 8.0]`.

The following code will do the job

```
In [80]: x_vec = [2.0, 4.0, 6.0, 8.0]
         y_vec = similar(x_vec)
         for (i, x) in enumerate(x_vec)
             y_vec[i] = sin(x)
         end
```

But this is a bit unwieldy so Julia offers the alternative syntax

```
In [81]: y_vec = sin.(x_vec)
```

```
Out[81]: 4-element Array{Float64,1}:
           0.9092974268256817
          -0.7568024953079282
          -0.27941549819892586
           0.9893582466233818
```

More generally, if `f` is any Julia function, then `f.` references the broadcasted version.

Conveniently, this applies to user-defined functions as well.

To illustrate, let's write a function `chisq` such that `chisq(k)` returns a chi-squared random variable with `k` degrees of freedom when `k` is an integer.

In doing this we'll exploit the fact that, if we take `k` independent standard normals, square them all and sum, we get a chi-squared with `k` degrees of freedom.

```
In [82]: function chisq(k)
             @assert k > 0
             z = randn(k)
             return sum(z -> z^2, z)  # same as `sum(x^2 for x in z)`
         end
```

```
Out[82]: chisq (generic function with 1 method)
```

The macro `@assert` will check that the next expression evaluates to `true`, and will stop and display an error otherwise.

```
In [83]: chisq(3)
```

```
Out[83]: 1.7752187504987356
```

Note that calls with integers less than 1 will trigger an assertion failure inside the function body.

```
In [84]: chisq(-2)
```

```
AssertionError: k > 0


Stacktrace:

 [1] chisq(::Int64) at ./In[82]:2

 [2] top-level scope at In[84]:1
```

Let's try this out on an array of integers, adding the broadcast

```
In [85]: chisq.([2, 4, 6])

Out[85]: 3-element Array{Float64,1}:
          6.478871317138532
          5.419973596174483
          6.02040608718741
```

The broadcasting notation is not simply vectorization, as it is able to "fuse" multiple broadcasts together to generate efficient code.

```
In [86]: x = 1.0:1.0:5.0
         y = [2.0, 4.0, 5.0, 6.0, 8.0]
         z = similar(y)
         z .= x .+ y .- sin.(x) # generates efficient code instead of many
 ↪temporaries

Out[86]: 5-element Array{Float64,1}:
           2.1585290151921033
           5.090702573174318
           7.858879991940133
          10.756802495307928
          13.958924274663138
```

A convenience macro for adding broadcasting on every function call is `@.`

```
In [87]: @. z = x + y - sin(x)

Out[87]: 5-element Array{Float64,1}:
           2.1585290151921033
           5.090702573174318
           7.858879991940133
          10.756802495307928
          13.958924274663138
```

Since the `+, -, =` operators are functions, behind the scenes this is broadcasting against both the `x` and `y` vectors.

The compiler will fix anything which is a scalar, and otherwise iterate across every vector

```
In [88]: f(a, b) = a + b # bivariate function
         a = [1 2 3]
         b = [4 5 6]
         @show f.(a, b) # across both
         @show f.(a, 2); # fix scalar for second
```

```
f.(a, b) = [5 7 9]
f.(a, 2) = [3 4 5]
```

The compiler is only able to detect "scalar" values in this way for a limited number of types (e.g. integers, floating points, etc) and some packages (e.g. Distributions).

For other types, you will need to wrap any scalars in `Ref` to fix them, or else it will try to broadcast the value.

Another place that you may use a `Ref` is to fix a function parameter you do not want to broadcast over.

```
In [89]: f(x, y) = [1, 2, 3] ⋅ x + y   # "⋅" can be typed by \cdot<tab>
         f([3, 4, 5], 2)   # uses vector as first parameter
         f.(Ref([3, 4, 5]), [2, 3])   # broadcasting over 2nd parameter, fixing first
```

```
Out[89]: 2-element Array{Int64,1}:
          28
          29
```

4.8 Scoping and Closures

Since global variables are usually a bad idea, we will concentrate on understanding the role of good local scoping practice.

That said, while many of the variables in these Jupyter notebook are global, we have been careful to write the code so that the entire code could be copied inside of a function.

When copied inside a function, variables become local and functions become closures.

Warning.

For/while loops and global variables in Jupyter vs. the REPL: * In the current version of Julia, there is a distinction between the use of scope in an interactive Jupyter environment. * The description here of globals applies to Jupyter notebooks, and may also apply to the REPL and top-level scripts. * In general, you should be creating functions when working with .jl files, and the distinction generally won't apply.

For more information on using globals outside of Jupyter, (see variable scoping documentation), though these rules are likely to become consistent in a future version.

4.8.1 Functions

The scope of a variable name determines where it is valid to refer to it, and how clashes between names can occur.

Think of the scope as a list of all of the name bindings of relevant variables.

Different scopes could contain the same name but be assigned to different things.

An obvious place to start is to notice that functions introduce their own local names.

```
In [90]: f(x) = x^2  # local `x` in scope

         # x is not bound to anything in this outer scope
         y = 5
         f(y)
```

```
Out[90]: 25
```

This would be roughly equivalent to

```
In [91]: function g() # scope within the `g` function

             f(x) = x^2 # local `x` in scope

             # x is not bound to anything in this outer scope
             y = 5
             f(y)
         end
         g() # run the function
```

```
Out[91]: 25
```

This is also equivalent if the `y` was changed to `x`, since it is a different scope.

```
In [92]: f(x) = x^2  # local `x` in scope

         # x is not bound to anything in this outer scope
         x = 5   # a different `x` than the local variable name
         f(x)    # calling `f` with `x`
```

```
Out[92]: 25
```

The scoping also applies to named arguments in functions.

```
In [93]: f(x; y = 1) = x + y  # `x` and `y` are names local to the `f` function
         xval = 0.1
         yval = 2
         f(xval; y = yval)
```

```
Out[93]: 2.1
```

Due to scoping, you could write this as

```
In [94]: f(x; y = 1) = x + y  # `x` and `y` are names local to the `f` function
         x = 0.1
         y = 2
         f(x; y = y) # left hand `y` is the local name of the argument in the
 ↪function
```

```
Out[94]: 2.1
```

Similarly to named arguments, the local scope also works with named tuples.

```
In [95]: xval = 0.1
         yval = 2
         @show (x = xval, y = yval)  # named tuple with names `x` and `y`

         x = 0.1
         y = 2

         # create a named tuple with names `x` and `y` local to the tuple, bound
 ↪to the RHS `x`
         and `y`
         (x = x, y = y)
```

```
(x = xval, y = yval) = (x = 0.1, y = 2)
```

```
Out[95]: (x = 0.1, y = 2)
```

As you use Julia, you will find that scoping is very natural and that there is no reason to avoid using `x` and `y` in both places.

In fact, it frequently leads to clear code closer to the math when you don't need to specify intermediaries.

Another example is with broadcasting

```
In [96]: f(x) = x^2  # local `x` in scope

         x = 1:5     # not an integer

         f.(x)       # broadcasts the x^2 function over the vector
```

```
Out[96]: 5-element Array{Int64,1}:
           1
           4
           9
          16
          25
```

4.8.2 Closures

Frequently, you will want to have a function that calculates a value given some fixed parameters.

```
In [97]: f(x, a) = a * x^2

         f(1, 0.2)
```

```
Out[97]: 0.2
```

While the above was convenient, there are other times when you want to simply fix a variable or refer to something already calculated.

```
In [98]: a = 0.2
         f(x) = a * x^2     # refers to the `a` in the outer scope
         f(1)               # univariate function
```

```
Out[98]: 0.2
```

When the function `f` is parsed in Julia, it will look to see if any of the variables are already defined in the current scope.

In this case, it finds the `a` since it was defined previously, whereas if the code defines `a = 0.2` **after** the `f(x)` definition, it would fail.

This also works when embedded in other functions

```
In [99]: function g(a)
             f(x) = a * x^2  # refers to the `a` passed in the function
             f(1)            # univariate function
         end
         g(0.2)
```

```
Out[99]: 0.2
```

Comparing the two: the key here is not that `a` is a global variable, but rather that the `f` function is defined to capture a variable from an outer scope.

This is called a **closure**, and are used throughout the lectures.

It is generally bad practice to modify the captured variable in the function, but otherwise the code becomes very clear.

One place where this can be helpful is in a string of dependent calculations.

For example, if you wanted to calculate a `(a, b, c)` from $a = f(x), b = g(a), c = h(a, b)$ where $f(x) = x^2, g(a) = 2a, h(a, b) = a + b$

```
In [100]: function solvemodel(x)
              a = x^2
              b = 2 * a
              c = a + b
              return (a = a, b = b, c = c)  # note local scope of tuples!
          end

          solvemodel(0.1)
```

```
Out[100]: (a = 0.010000000000000002, b = 0.020000000000000004, c = 0.
          ↪030000000000000006)
```

4.8.3 Higher-Order Functions

One of the benefits of working with closures and functions is that you can return them from other functions.

This leads to some natural programming patterns we have already been using, where we can use **functions of functions** and **functions returning functions** (or closures).

To see a simple example, consider functions that accept other functions (including closures)

```
In [101]: twice(f, x) = f(f(x))  # applies f to itself twice
          f(x) = x^2
          @show twice(f, 2.0)

          twice(x -> x^2, 2.0)
          a = 5
          g(x) = a * x
          @show twice(g, 2.0);   # using a closure
```

```
    twice(f, 2.0) = 16.0
twice(g, 2.0) = 50.0
```

This pattern has already been used extensively in our code and is key to keeping things like interpolation, numerical integration, and plotting generic.

One example of using this in a library is Expectations.jl, where we can pass a function to the `expectation` function.

```
In [102]: using Expectations, Distributions

          @show d = Exponential(2.0)

          f(x) = x^2
          @show expectation(f, d);  # E(f(x))
```

```
    d = Exponential(2.0) = Exponential{Float64}(θ=2.0)
expectation(f, d) = 8.00000000000004
```

Another example is for a function that returns a closure itself.

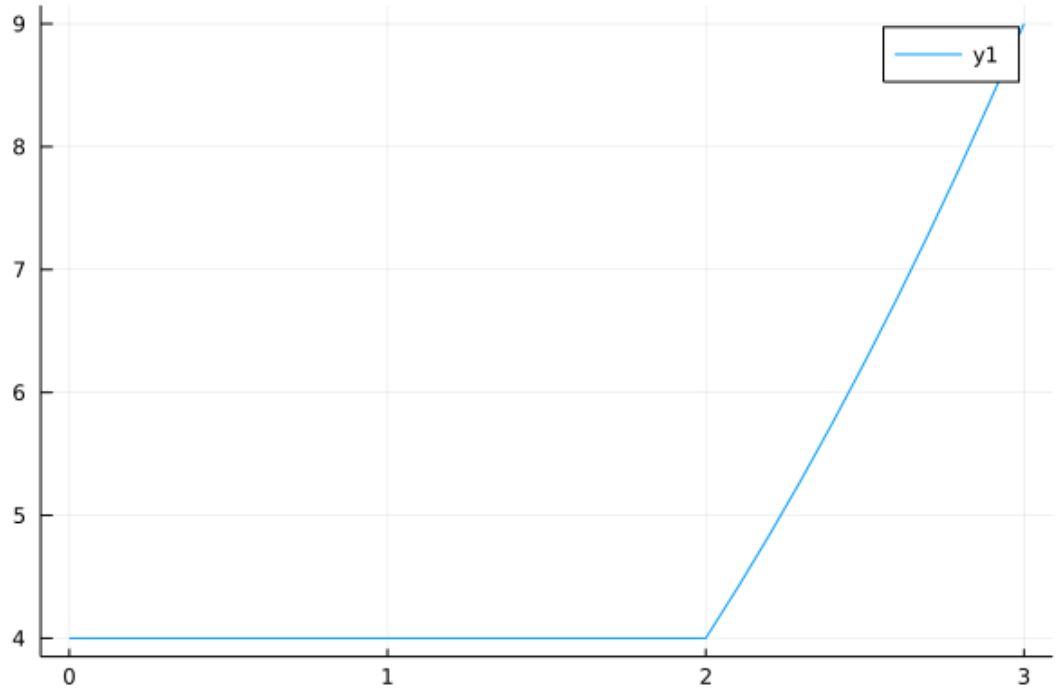
```
In [103]: function multiplyit(a, g)
              return x -> a * g(x)  # function with `g` used in the closure
          end

          f(x) = x^2
          h = multiplyit(2.0, f)    # use our quadratic, returns a new function
↪which doubles the
          result
          h(2)     # returned function is like any other function
```

```
Out[103]: 8.0
```

You can create and define using `function` as well

In [104]:
```
function snapabove(g, a)
    function f(x)
        if x > a         # "a" is captured in the closure f
            return g(x)
        else
            return g(a)
        end
    end
    return f    # closure with the embedded a
end

f(x) = x^2
h = snapabove(f, 2.0)

using Plots
gr(fmt=:png);
plot(h, 0.0:0.1:3.0)
```

Out[104]:



4.8.4 Loops

The `for` and `while` loops also introduce a local scope, and you can roughly reason about them the same way you would a function/closure.

In particular

In [105]:
```
for i in 1:2  # introduces local i
    dval1 = i
    println(i)
end
```

```
    # @show (i, dval1)  # would fail as neither exists in this scope

    for i in 1:2  # introduces a different local i
        println(i)
    end
```

```
 1
2
1
2
```

On the other hand just as with closures, if a variable is already defined it will be available in the inner scope.

```
In [106]: dval2 = 0  # introduces variables
          for i in 1:2   # introduces local i
              dval2 = i  # refers to outer variable
          end

          dval2 # still can't refer to `i`
```

```
Out[106]: 2
```

Similarly, for while loops

```
In [107]: val = 1.0
          tol = 0.002
          while val > tol
              old = val
              val = val / 2
              difference = val - old
          end

          @show val;
          # @show difference fails, not in scope
```

```
 val = 0.001953125
```

4.8.5 A Quick Check for Scoping Design

While we have argued against global variables as poor practice, you may have noticed that in Jupyter notebooks we have been using them throughout.

Here, global variables are used in an interactive editor because they are convenient, and not because they are essential to the design of functions.

A simple test of the difference is to take a segment of code and wrap it in a function, for example

```
In [108]: x = 2.0
          f(y) = x + y
```

```
z = f(4.0)

for i in 1:3
    z += i
end

println("z = $z")
```

```
 z = 12.0
```

Here, the `x` and `z` are global variables, the function `f` refers to the global variable `x`, and the global variable `z` is modified in the `for` loop.

However, you can simply wrap the entire code in a function

```
In [109]: function wrapped()
              x = 2.0
              f(y) = x + y
              z = f(4.0)

              for i in 1:3
                  z += i
              end

              println("z = $z")
          end

          wrapped()
```

```
 z = 12.0
```

Now, there are no global variables.

While it is convenient to skip wrapping our code throughout, in general you will want to wrap any performance sensitive code in this way.

4.9 Exercises

4.9.1 Exercise 1

Part 1: Given two numeric arrays or tuples `x_vals` and `y_vals` of equal length, compute their inner product using `zip()`.

Part 2: Using a comprehension, count the number of even numbers between 0 and 99.

- Hint: `iseven` returns `true` for even numbers and `false` for odds.

Part 3: Using a comprehension, take `pairs = ((2, 5), (4, 2), (9, 8), (12, 10))` and count the number of pairs `(a, b)` such that both `a` and `b` are even.

4.9.2 Exercise 2

Consider the polynomial

$$p(x) = a_0 + a_1 x + a_2 x^2 + \cdots a_n x^n = \sum_{i=0}^{n} a_i x^i \tag{1}$$

Using `enumerate()` in your loop, write a function `p` such that `p(x, coeff)` computes the value in (1) given a point `x` and an array of coefficients `coeff`.

4.9.3 Exercise 3

Write a function that takes a string as an argument and returns the number of capital letters in the string.

Hint: `uppercase("foo")` returns `"FOO"`.

4.9.4 Exercise 4

Write a function that takes two sequences `seq_a` and `seq_b` as arguments and returns `true` if every element in `seq_a` is also an element of `seq_b`, else `false`.

- By "sequence" we mean an array, tuple or string.

4.9.5 Exercise 5

The Julia libraries include functions for interpolation and approximation.

Nevertheless, let's write our own function approximation routine as an exercise.

In particular, write a function `linapprox` that takes as arguments

- A function `f` mapping some interval $[a, b]$ into $\mathbb{R}$.
- two scalars `a` and `b` providing the limits of this interval.
- An integer `n` determining the number of grid points.
- A number `x` satisfying `a ≤ x ≤ b`.

and returns the piecewise linear interpolation of `f` at `x`, based on `n` evenly spaced grid points `a = point[1] < point[2] < ... < point[n] = b`.

Aim for clarity, not efficiency.

Hint: use the function `range` to linearly space numbers.

4.9.6 Exercise 6

The following data lists US cities and their populations.

Copy this text into a text file called `us_cities.txt` and save it in your present working directory.

- That is, save it in the location Julia returns when you call `pwd()`.

This can also be achieved by running the following Julia code:

```
In [110]: open("us_cities.txt", "w") do f
            write(f,
          "new york: 8244910
```

```
    los angeles: 3819702
    chicago: 2707120
    houston: 2145146
    philadelphia: 1536471
    phoenix: 1469471
    san antonio: 1359758
    san diego: 1326179
    dallas: 1223229")
    end
```

```
Out[110]: 167
```

Write a program to calculate total population across these cities.

Hints:

- If `f` is a file type then `eachline(f)` provides an iterable that steps you through the lines in the file.
- `parse(Int, "100")` converts the string `"100"` into an integer.

4.9.7 Exercise 7

Redo Exercise 5 except

1. Pass in a range instead of the `a, b,` and `n`. Test with a range such as `nodes = -1.0:0.5:1.0`.
2. Instead of the `while` used in the solution to Exercise 5, find a better way to efficiently bracket the `x` in the nodes.

Hints: * Rather than the signature as `function linapprox(f, a, b, n, x)`, it should be called as `function linapprox(f, nodes, x)`. * `step(nodes)`, `length(nodes)`, `nodes[1]`, and `nodes[end]` may be useful. * Type `?÷` into jupyter to explore quotients from Euclidean division for more efficient bracketing.

4.10 Solutions

4.10.1 Exercise 1

Part 1 solution:

Here's one possible solution

```
In [111]: x_vals = [1, 2, 3]
          y_vals = [1, 1, 1]
          sum(x * y for (x, y) in zip(x_vals, y_vals))
```

```
Out[111]: 6
```

Part 2 solution:

One solution is

```
In [112]: sum(iseven, 0:99)
```

```
Out[112]: 50
```

Part 3 solution:

Here's one possibility

```
In [113]: pairs = ((2, 5), (4, 2), (9, 8), (12, 10))
          sum(xy -> all(iseven, xy), pairs)
```

```
Out[113]: 2
```

4.10.2 Exercise 2

```
In [114]: p(x, coeff) = sum(a * x^(i-1) for (i, a) in enumerate(coeff))
```

```
Out[114]: p (generic function with 1 method)
```

```
In [115]: p(1, (2, 4))
```

```
Out[115]: 6
```

4.10.3 Exercise 3

Here's one solutions:

```
In [116]: function f_ex3(string)
              count = 0
              for letter in string
                  if (letter == uppercase(letter)) && isletter(letter)
                      count += 1
                  end
              end
              return count
          end

          f_ex3("The Rain in Spain")
```

```
Out[116]: 3
```

4.10.4 Exercise 4

Here's one solutions:

```
In [117]: function f_ex4(seq_a, seq_b)
              is_subset = true
              for a in seq_a
                  if a  seq_b
                      is_subset = false
```

```
            end
        end
        return is_subset
    end

    # test
    println(f_ex4([1, 2], [1, 2, 3]))
    println(f_ex4([1, 2, 3], [1, 2]))
```

```
true
false
```

if we use the Set data type then the solution is easier

```
In [118]: f_ex4_2(seq_a, seq_b) = Set(seq_a) ⊆ Set(seq_b) # \subseteq (⊆) is
  ↪unicode for
          `issubset`

    println(f_ex4_2([1, 2], [1, 2, 3]))
    println(f_ex4_2([1, 2, 3], [1, 2]))
```

```
true
false
```

4.10.5 Exercise 5

```
In [119]: function linapprox(f, a, b, n, x)
              # evaluates the piecewise linear interpolant of f at x,
              # on the interval [a, b], with n evenly spaced grid points.

              length_of_interval = b - a
              num_subintervals = n - 1
              step = length_of_interval / num_subintervals

              # find first grid point larger than x
              point = a
              while point ≤ x
                  point += step
              end

              # x must lie between the gridpoints (point - step) and point
              u, v = point - step, point

              return f(u) + (x - u) * (f(v) - f(u)) / (v - u)
          end
```

```
Out[119]: linapprox (generic function with 1 method)
```

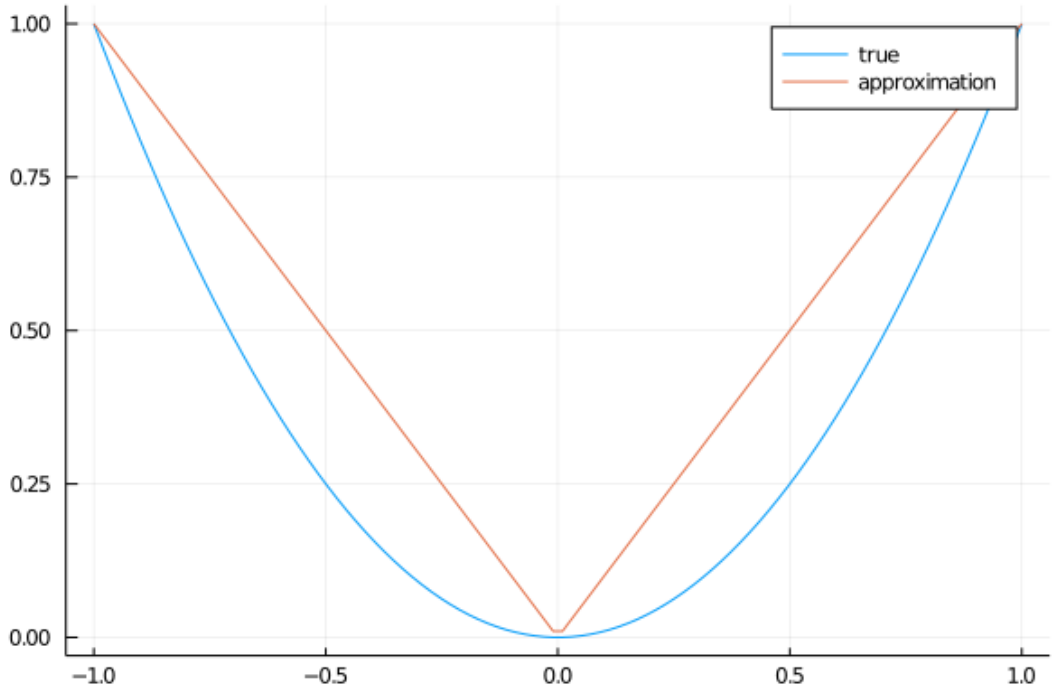
Let's test it

```
In [120]: f_ex5(x) = x^2
          g_ex5(x) = linapprox(f_ex5, -1, 1, 3, x)
```

```
Out[120]: g_ex5 (generic function with 1 method)
```

```
In [121]: x_grid = range(-1.0, 1.0, length = 100)
          y_vals = f_ex5.(x_grid)
          y = g_ex5.(x_grid)
          plot(x_grid, y_vals, label = "true")
          plot!(x_grid, y, label = "approximation")
```

Out[121]:



4.10.6 Exercise 6

```
In [122]: f_ex6 = open("us_cities.txt", "r")
          total_pop = 0
          for line in eachline(f_ex6)
              city, population = split(line, ':')  # tuple unpacking
              total_pop += parse(Int, population)
          end
          close(f_ex6)
          println("Total population = $total_pop")
```

```
Total population = 23831986
```

Chapter 5

Arrays, Tuples, Ranges, and Other Fundamental Types

5.1 Contents

> "Let's be clear: the work of science has nothing whatever to do with consensus. Consensus is the business of politics. Science, on the contrary, requires only one investigator who happens to be right, which means that he or she has results that are verifiable by reference to the real world. In science consensus is irrelevant. What is relevant is reproducible results." – Michael Crichton

5.2 Overview

In Julia, arrays and tuples are the most important data type for working with numerical data.

In this lecture we give more details on

- creating and manipulating Julia arrays
- fundamental array processing operations
- basic matrix algebra
- tuples and named tuples
- ranges
- nothing, missing, and unions

5.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

5.3 Array Basics

(See multi-dimensional arrays documentation)

Since it is one of the most important types, we will start with arrays.

Later, we will see how arrays (and all other types in Julia) are handled in a generic and extensible way.

5.3.1 Shape and Dimension

We've already seen some Julia arrays in action

```
In [3]: a = [10, 20, 30]
```

```
Out[3]: 3-element Array{Int64,1}:
         10
         20
         30
```

```
In [4]: a = [1.0, 2.0, 3.0]
```

```
Out[4]: 3-element Array{Float64,1}:
         1.0
         2.0
         3.0
```

The output tells us that the arrays are of types `Array{Int64,1}` and `Array{Float64,1}` respectively.

Here `Int64` and `Float64` are types for the elements inferred by the compiler.

We'll talk more about types later.

The `1` in `Array{Int64,1}` and `Array{Any,1}` indicates that the array is one dimensional (i.e., a `Vector`).

This is the default for many Julia functions that create arrays

```
In [5]: typeof(randn(100))
```

```
Out[5]: Array{Float64,1}
```

In Julia, one dimensional vectors are best interpreted as column vectors, which we will see when we take transposes.

We can check the dimensions of `a` using `size()` and `ndims()` functions

```
In [6]: ndims(a)
```

```
Out[6]: 1
```

```
In [7]: size(a)
```

```
Out[7]: (3,)
```

The syntax `(3,)` displays a tuple containing one element – the size along the one dimension that exists.

Array vs Vector vs Matrix

In Julia, `Vector` and `Matrix` are just aliases for one- and two-dimensional arrays respectively

```
In [8]: Array{Int64, 1} == Vector{Int64}
        Array{Int64, 2} == Matrix{Int64}
```

```
Out[8]: true
```

Vector construction with `,` is then interpreted as a column vector.

To see this, we can create a column vector and row vector more directly

```
In [9]: [1, 2, 3] == [1; 2; 3]  # both column vectors
```

```
Out[9]: true
```

```
In [10]: [1 2 3]  # a row vector is 2-dimensional
```

```
Out[10]: 1×3 Array{Int64,2}:
          1  2  3
```

As we've seen, in Julia we have both

- one-dimensional arrays (i.e., flat arrays)
- arrays of size `(1, n)` or `(n, 1)` that represent row and column vectors respectively

Why do we need both?

On one hand, dimension matters for matrix algebra.

- Multiplying by a row vector is different to multiplying by a column vector.

On the other, we use arrays in many settings that don't involve matrix algebra.

In such cases, we don't care about the distinction between row and column vectors.

This is why many Julia functions return flat arrays by default.

5.3.2 Creating Arrays

Functions that Create Arrays

We've already seen some functions for creating a vector filled with `0.0`

```
In [11]: zeros(3)

Out[11]: 3-element Array{Float64,1}:
          0.0
          0.0
          0.0
```

This generalizes to matrices and higher dimensional arrays

```
In [12]: zeros(2, 2)

Out[12]: 2×2 Array{Float64,2}:
          0.0  0.0
          0.0  0.0
```

To return an array filled with a single value, use `fill`

```
In [13]: fill(5.0, 2, 2)

Out[13]: 2×2 Array{Float64,2}:
          5.0  5.0
          5.0  5.0
```

Finally, you can create an empty array using the `Array()` constructor

```
In [14]: x = Array{Float64}(undef, 2, 2)

Out[14]: 2×2 Array{Float64,2}:
          6.91839e-310  6.91838e-310
          6.91839e-310  0.0
```

The printed values you see here are just garbage values.

(the existing contents of the allocated memory slots being interpreted as 64 bit floats)

If you need more control over the types, fill with a non-floating point

```
In [15]: fill(0, 2, 2)  # fills with 0, not 0.0

Out[15]: 2×2 Array{Int64,2}:
          0  0
          0  0
```

Or fill with a boolean type

```
In [16]: fill(false, 2, 2)  # produces a boolean matrix

Out[16]: 2×2 Array{Bool,2}:
          0  0
          0  0
```

Creating Arrays from Existing Arrays

For the most part, we will avoid directly specifying the types of arrays, and let the compiler deduce the optimal types on its own.

The reasons for this, discussed in more detail in this lecture, are to ensure both clarity and generality.

One place this can be inconvenient is when we need to create an array based on an existing array.

First, note that assignment in Julia binds a name to a value, but does not make a copy of that type

```
In [17]: x = [1, 2, 3]
         y = x
         y[1] = 2
         x
```

```
Out[17]: 3-element Array{Int64,1}:
          2
          2
          3
```

In the above, `y = x` simply creates a new named binding called `y` which refers to whatever `x` currently binds to.

To copy the data, you need to be more explicit

```
In [18]: x = [1, 2, 3]
         y = copy(x)
         y[1] = 2
         x
```

```
Out[18]: 3-element Array{Int64,1}:
          1
          2
          3
```

However, rather than making a copy of `x`, you may want to just have a similarly sized array

```
In [19]: x = [1, 2, 3]
         y = similar(x)
         y
```

```
Out[19]: 3-element Array{Int64,1}:
          1
          1
          0
```

We can also use `similar` to pre-allocate a vector with a different size, but the same shape

```
In [20]: x = [1, 2, 3]
         y = similar(x, 4)  # make a vector of length 4
```

```
Out[20]: 4-element Array{Int64,1}:
          140029121887504
          140029758928704
          140029448573616
          140029694705664
```

Which generalizes to higher dimensions

```
In [21]: x = [1, 2, 3]
         y = similar(x, 2, 2)  # make a 2x2 matrix
```

```
Out[21]: 2×2 Array{Int64,2}:
          140029122207120  140029122207184
          140029122207152  140029493746368
```

Manual Array Definitions

As we've seen, you can create one dimensional arrays from manually specified data like so

```
In [22]: a = [10, 20, 30, 40]
```

```
Out[22]: 4-element Array{Int64,1}:
          10
          20
          30
          40
```

In two dimensions we can proceed as follows

```
In [23]: a = [10 20 30 40]  # two dimensional, shape is 1 x n
```

```
Out[23]: 1×4 Array{Int64,2}:
          10  20  30  40
```

```
In [24]: ndims(a)
```

```
Out[24]: 2
```

```
In [25]: a = [10 20; 30 40]  # 2 x 2
```

```
Out[25]: 2×2 Array{Int64,2}:
          10  20
          30  40
```

You might then assume that `a = [10; 20; 30; 40]` creates a two dimensional column vector but this isn't the case.

```
In [26]: a = [10; 20; 30; 40]
```

```
Out[26]: 4-element Array{Int64,1}:
          10
          20
          30
          40
```

```
In [27]: ndims(a)
```

```
Out[27]: 1
```

Instead transpose the matrix (or adjoint if complex)

```
In [28]: a = [10 20 30 40]'
```

```
Out[28]: 4×1 Adjoint{Int64,Array{Int64,2}}:
          10
          20
          30
          40
```

```
In [29]: ndims(a)
```

```
Out[29]: 2
```

5.3.3 Array Indexing

We've already seen the basics of array indexing

```
In [30]: a = [10 20 30 40]
         a[end-1]
```

```
Out[30]: 30
```

```
In [31]: a[1:3]
```

```
Out[31]: 3-element Array{Int64,1}:
          10
          20
          30
```

For 2D arrays the index syntax is straightforward

```
In [32]: a = randn(2, 2)
         a[1, 1]
```

```
Out[32]: 0.15765041580654648
```

```
In [33]: a[1, :]  # first row
```

```
Out[33]: 2-element Array{Float64,1}:
          0.15765041580654648
          0.2652121417935994

In [34]: a[:, 1]  # first column

Out[34]: 2-element Array{Float64,1}:
          0.15765041580654648
          0.134644163495092
```

Booleans can be used to extract elements

```
In [35]: a = randn(2, 2)

Out[35]: 2×2 Array{Float64,2}:
          0.616704   0.374922
          1.33094   -0.670024

In [36]: b = [true false; false true]

Out[36]: 2×2 Array{Bool,2}:
          1  0
          0  1

In [37]: a[b]

Out[37]: 2-element Array{Float64,1}:
           0.6167040565642389
          -0.6700242069255393
```

This is useful for conditional extraction, as we'll see below.

An aside: some or all elements of an array can be set equal to one number using slice notation.

```
In [38]: a = zeros(4)

Out[38]: 4-element Array{Float64,1}:
          0.0
          0.0
          0.0
          0.0

In [39]: a[2:end] .= 42

Out[39]: 3-element view(::Array{Float64,1}, 2:4) with eltype Float64:
          42.0
          42.0
          42.0

In [40]: a

Out[40]: 4-element Array{Float64,1}:
           0.0
          42.0
          42.0
          42.0
```

5.3.4 Views and Slices

Using the `:` notation provides a slice of an array, copying the sub-array to a new array with a similar type.

```
In [41]: a = [1 2; 3 4]
         b = a[:, 2]
         @show b
         a[:, 2] = [4, 5] # modify a
         @show a
         @show b;
```

```
b = [2, 4]
a = [1 4; 3 5]
b = [2, 4]
```

A **view** on the other hand does not copy the value

```
In [42]: a = [1 2; 3 4]
         @views b = a[:, 2]
         @show b
         a[:, 2] = [4, 5]
         @show a
         @show b;
```

```
b = [2, 4]
a = [1 4; 3 5]
b = [4, 5]
```

Note that the only difference is the `@views` macro, which will replace any slices with views in the expression.

An alternative is to call the `view` function directly – though it is generally discouraged since it is a step away from the math.

```
In [43]: @views b = a[:, 2]
         view(a, :, 2) == b
```

```
Out[43]: true
```

As with most programming in Julia, it is best to avoid prematurely assuming that `@views` will have a significant impact on performance, and stress code clarity above all else.

Another important lesson about `@views` is that they **are not** normal, dense arrays.

```
In [44]: a = [1 2; 3 4]
         b_slice = a[:, 2]
         @show typeof(b_slice)
         @show typeof(a)
         @views b = a[:, 2]
         @show typeof(b);
```

```
    typeof(b_slice) = Array{Int64,1}
typeof(a) = Array{Int64,2}
typeof(b) =
SubArray{Int64,1,Array{Int64,2},Tuple{Base.Slice{Base.OneTo{Int64}},Int64},true}
```

The type of `b` is a good example of how types are not as they may seem.

Similarly

```
In [45]: a = [1 2; 3 4]
         b = a'   # transpose
         typeof(b)
```

```
Out[45]: Adjoint{Int64,Array{Int64,2}}
```

To copy into a dense array

```
In [46]: a = [1 2; 3 4]
         b = a' # transpose
         c = Matrix(b)  # convert to matrix
         d = collect(b) # also `collect` works on any iterable
         c == d
```

```
Out[46]: true
```

5.3.5 Special Matrices

As we saw with `transpose`, sometimes types that look like matrices are not stored as a dense array.

As an example, consider creating a diagonal matrix

```
In [47]: d = [1.0, 2.0]
         a = Diagonal(d)
```

```
Out[47]: 2×2 Diagonal{Float64,Array{Float64,1}}:
          1.0   ⋅
           ⋅   2.0
```

As you can see, the type is `2×2 Diagonal{Float64,Array{Float64,1}}`, which is not a 2-dimensional array.

The reasons for this are both efficiency in storage, as well as efficiency in arithmetic and matrix operations.

In every important sense, matrix types such as `Diagonal` are just as much a "matrix" as the dense matrices we have using (see the introduction to types lecture for more)

```
In [48]: @show 2a
         b = rand(2,2)
         @show b * a;
```

```
    2a = [2.0 0.0; 0.0 4.0]
b * a = [0.07902796541012158 0.36525218581573515; 0.5277291038116809
1.824094575599461]
```

Another example is in the construction of an identity matrix, where a naive implementation is

```
In [49]: b = [1.0 2.0; 3.0 4.0]
         b - Diagonal([1.0, 1.0])  # poor style, inefficient code
```

```
Out[49]: 2×2 Array{Float64,2}:
          0.0  2.0
          3.0  3.0
```

Whereas you should instead use

```
In [50]: b = [1.0 2.0; 3.0 4.0]
         b - I  # good style, and note the lack of dimensions of I
```

```
Out[50]: 2×2 Array{Float64,2}:
          0.0  2.0
          3.0  3.0
```

While the implementation of `I` is a little abstract to go into at this point, a hint is:

```
In [51]: typeof(I)
```

```
Out[51]: UniformScaling{Bool}
```

This is a `UniformScaling` type rather than an identity matrix, making it much more powerful and general.

5.3.6 Assignment and Passing Arrays

As discussed above, in Julia, the left hand side of an assignment is a "binding" or a label to a value.

```
In [52]: x = [1 2 3]
         y = x  # name `y` binds to whatever value `x` bound to
```

```
Out[52]: 1×3 Array{Int64,2}:
          1  2  3
```

The consequence of this, is that you can re-bind that name.

```
In [53]: x = [1 2 3]
         y = x        # name `y` binds to whatever `x` bound to
         z = [2 3 4]
         y = z        # only changes name binding, not value!
         @show (x, y, z);
```

```
(x, y, z) = ([1 2 3], [2 3 4], [2 3 4])
```

What this means is that if `a` is an array and we set `b = a` then `a` and `b` point to exactly the same data.

In the above, suppose you had meant to change the value of `x` to the values of `y`, you need to assign the values rather than the name.

```
In [54]: x = [1 2 3]
         y = x       # name `y` binds to whatever `x` bound to
         z = [2 3 4]
         y .= z      # now dispatches the assignment of each element
         @show (x, y, z);
```

```
(x, y, z) = ([2 3 4], [2 3 4], [2 3 4])
```

Alternatively, you could have used `y[:] = z`.

This applies to in-place functions as well.

First, define a simple function for a linear map

```
In [55]: function f(x)
             return [1 2; 3 4] * x  # matrix * column vector
         end

         val = [1, 2]
         f(val)
```

```
Out[55]: 2-element Array{Int64,1}:
           5
          11
```

In general, these "out-of-place" functions are preferred to "in-place" functions, which modify the arguments.

```
In [56]: function f(x)
             return [1 2; 3 4] * x # matrix * column vector
         end

         val = [1, 2]
         y = similar(val)

         function f!(out, x)
             out .= [1 2; 3 4] * x
         end

         f!(y, val)
         y
```

```
Out[56]: 2-element Array{Int64,1}:
           5
          11
```

This demonstrates a key convention in Julia: functions which modify any of the arguments have the name ending with `!` (e.g. `push!`).

We can also see a common mistake, where instead of modifying the arguments, the name binding is swapped

```
In [57]: function f(x)
             return [1 2; 3 4] * x  # matrix * column vector
         end

         val = [1, 2]
         y = similar(val)

         function f!(out, x)
             out = [1 2; 3 4] * x   # MISTAKE! Should be .= or [:]
         end
         f!(y, val)
         y
```

```
Out[57]: 2-element Array{Int64,1}:
                    5674
          140029483809008
```

The frequency of making this mistake is one of the reasons to avoid in-place functions, unless proven to be necessary by benchmarking.

5.3.7 In-place and Immutable Types

Note that scalars are always immutable, such that

```
In [58]: y = [1 2]
         y .-= 2    # y .= y .- 2, no problem

         x = 5
         # x .-= 2  # Fails!
         x = x - 2  # subtle difference - creates a new value and rebinds the
 ↪variable
```

```
Out[58]: 3
```

In particular, there is no way to pass any immutable into a function and have it modified

```
In [59]: x = 2

         function f(x)
             x = 3     # MISTAKE! does not modify x, creates a new value!
         end

         f(x)          # cannot modify immutables in place
         @show x;
```

```
  x = 2
```

This is also true for other immutable types such as tuples, as well as some vector types

In [60]:
```
using StaticArrays
xdynamic = [1, 2]
xstatic = @SVector [1, 2]  # turns it into a highly optimized static vector

f(x) = 2x
@show f(xdynamic)
@show f(xstatic)

# inplace version
function g(x)
    x .= 2x
    return "Success!"
end
@show xdynamic
@show g(xdynamic)
@show xdynamic;

# g(xstatic) # fails, static vectors are immutable
```

```
   f(xdynamic) = [2, 4]
f(xstatic) = [2, 4]
xdynamic = [1, 2]
g(xdynamic) = "Success!"
xdynamic = [2, 4]
```

5.4 Operations on Arrays

5.4.1 Array Methods

Julia provides standard functions for acting on arrays, some of which we've already seen

In [61]:
```
a = [-1, 0, 1]

@show length(a)
@show sum(a)
@show mean(a)
@show std(a)      # standard deviation
@show var(a)      # variance
@show maximum(a)
@show minimum(a)
@show extrema(a)  # (mimimum(a), maximum(a))
```

```
   length(a) = 3
sum(a) = 0
mean(a) = 0.0
std(a) = 1.0
var(a) = 1.0
maximum(a) = 1
minimum(a) = -1
extrema(a) = (-1, 1)
```

```
Out[61]: (-1, 1)
```

To sort an array

```
In [62]: b = sort(a, rev = true)  # returns new array, original not modified
```

```
Out[62]: 3-element Array{Int64,1}:
           1
           0
          -1
```

```
In [63]: b = sort!(a, rev = true)  # returns *modified original* array
```

```
Out[63]: 3-element Array{Int64,1}:
           1
           0
          -1
```

```
In [64]: b == a  # tests if have the same values
```

```
Out[64]: true
```

```
In [65]: b === a  # tests if arrays are identical (i.e share same memory)
```

```
Out[65]: true
```

5.4.2 Matrix Algebra

For two dimensional arrays, * means matrix multiplication

```
In [66]: a = ones(1, 2)
```

```
Out[66]: 1×2 Array{Float64,2}:
          1.0  1.0
```

```
In [67]: b = ones(2, 2)
```

```
Out[67]: 2×2 Array{Float64,2}:
          1.0  1.0
          1.0  1.0
```

```
In [68]: a * b
```

```
Out[68]: 1×2 Array{Float64,2}:
          2.0  2.0
```

```
In [69]: b * a'
```

```
Out[69]: 2×1 Array{Float64,2}:
          2.0
          2.0
```

To solve the linear system $AX = B$ for X use `A \ B`

```
In [70]: A = [1 2; 2 3]
```

```
Out[70]: 2×2 Array{Int64,2}:
          1  2
          2  3
```

```
In [71]: B = ones(2, 2)
```

```
Out[71]: 2×2 Array{Float64,2}:
          1.0  1.0
          1.0  1.0
```

```
In [72]: A \ B
```

```
Out[72]: 2×2 Array{Float64,2}:
          -1.0  -1.0
           1.0   1.0
```

```
In [73]: inv(A) * B
```

```
Out[73]: 2×2 Array{Float64,2}:
          -1.0  -1.0
           1.0   1.0
```

Although the last two operations give the same result, the first one is numerically more stable and should be preferred in most cases.

Multiplying two **one** dimensional vectors gives an error – which is reasonable since the meaning is ambiguous.

More precisely, the error is that there isn't an implementation of `*` for two one dimensional vectors.

The output explains this, and lists some other methods of `*` which Julia thinks are close to what we want.

```
In [74]: ones(2) * ones(2)  # does not conform, expect error
```

```
MethodError: no method matching *(::Array{Float64,1}, ::
↪Array{Float64,1})
  Closest candidates are:
    *(::Any, ::Any, !Matched::Any, !Matched::Any…) at operators.jl:
↪529
```

```
    *(!Matched::Adjoint{#s662,#s661} where #s661<:
↪Union{DenseArray{T,2}, Base.ReinterpretArray{T,2,S,A} where S
↪where A<:Union{SubArray{T,N,A,I,true} where I<:
↪Union{Tuple{Vararg{Real,N} where N},
↪Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray}, Base.
↪ReshapedArray{T,2,A,MI} where MI<:Tuple{Vararg{Base.
↪MultiplicativeInverses.SignedMultiplicativeInverse{Int64},N}
↪where N} where A<:Union{Base.ReinterpretArray{T,N,S,A} where S
↪where A<:Union{SubArray{T,N,A,I,true} where I<:
↪Union{Tuple{Vararg{Real,N} where N},
↪Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray} where N where T,
↪SubArray{T,N,A,I,true} where I<:Union{Tuple{Vararg{Real,N} where
↪N}, Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray}, SubArray{T,2,A,I,L}
↪where L where I<:Tuple{Vararg{Union{Int64, AbstractRange{Int64},
↪Base.AbstractCartesianIndex},N} where N} where A<:Union{Base.
↪ReinterpretArray{T,N,S,A} where S where A<:
↪Union{SubArray{T,N,A,I,true} where I<:Union{Tuple{Vararg{Real,N}
↪where N}, Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where
↪A<:DenseArray where N where T, DenseArray} where N where T, Base.
↪ReshapedArray{T,N,A,MI} where MI<:Tuple{Vararg{Base.
↪MultiplicativeInverses.SignedMultiplicativeInverse{Int64},N}
↪where N} where A<:Union{Base.ReinterpretArray{T,N,S,A} where S
↪where A<:Union{SubArray{T,N,A,I,true} where I<:
↪Union{Tuple{Vararg{Real,N} where N},
↪Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray} where N where T,
↪SubArray{T,N,A,I,true} where I<:Union{Tuple{Vararg{Real,N} where
↪N}, Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray} where N where T,
↪DenseArray}} where #s662, ::Union{DenseArray{S,1}, Base.
↪ReinterpretArray{S,1,S1,A} where S1 where A<:
↪Union{SubArray{T,N,A,I,true} where I<:Union{Tuple{Vararg{Real,N}
↪where N}, Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where
↪A<:DenseArray where N where T, DenseArray}, Base.
↪ReshapedArray{S,1,A,MI} where MI<:Tuple{Vararg{Base.
↪MultiplicativeInverses.SignedMultiplicativeInverse{Int64},N}
↪where N} where A<:Union{Base.ReinterpretArray{T,N,S,A} where S
↪where A<:Union{SubArray{T,N,A,I,true} where I<:
↪Union{Tuple{Vararg{Real,N} where N},
↪Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray} where N where T,
↪SubArray{T,N,A,I,true} where I<:Union{Tuple{Vararg{Real,N} where
↪N}, Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where A<:
↪DenseArray where N where T, DenseArray}, SubArray{S,1,A,I,L}
↪where L where I<:Tuple{Vararg{Union{Int64, AbstractRange{Int64},
↪Base.AbstractCartesianIndex},N} where N} where A<:Union{Base.
↪ReinterpretArray{T,N,S,A} where S where A<:
↪Union{SubArray{T,N,A,I,true} where I<:Union{Tuple{Vararg{Real,N}
↪where N}, Tuple{AbstractUnitRange,Vararg{Any,N} where N}} where
↪A<:DenseArray where N where T, DenseArray} where N where T, Base.
↪ReshapedArray{T,N,A,MI} where MI<:Tuple{Vararg{Base.
↪MultiplicativeInverses.SignedMultiplicativeInverse{Int64},N}
↪where N} where A<:Union{Base.ReinterpretArray{T,N,S,A} where S
↪where A<:Union{SubArray{T,N,A,I,true} where I<:
```

```
    *(!Matched::Adjoint{#s662,#s661} where #s661<:LinearAlgebra.
↪AbstractTriangular where #s662, ::AbstractArray{T,1} where T) at /
↪buildworker/worker/package_linux64/build/usr/share/julia/stdlib/
↪v1.4/LinearAlgebra/src/triangular.jl:1971
    …


      Stacktrace:

       [1] top-level scope at In[74]:1
```

Instead, you could take the transpose to form a row vector

```
In [75]: ones(2)' * ones(2)
```

```
Out[75]: 2.0
```

Alternatively, for inner product in this setting use `dot()` or the unicode `\cdot<TAB>`

```
In [76]: @show dot(ones(2), ones(2))
         @show ones(2) ⋅ ones(2);
```

```
    dot(ones(2), ones(2)) = 2.0
ones(2) ⋅ ones(2) = 2.0
```

Matrix multiplication using one dimensional vectors similarly follows from treating them as column vectors. Post-multiplication requires a transpose

```
In [77]: b = ones(2, 2)
         b * ones(2)
```

```
Out[77]: 2-element Array{Float64,1}:
          2.0
          2.0
```

```
In [78]: ones(2)' * b
```

```
Out[78]: 1×2 Adjoint{Float64,Array{Float64,1}}:
          2.0  2.0
```

Note that the type of the returned value in this case is not `Array{Float64,1}` but rather `Adjoint{Float64,Array{Float64,1}}`.

This is since the left multiplication by a row vector should also be a row-vector. It also hints that the types in Julia more complicated than first appears in the surface notation, as we will explore further in the introduction to types lecture.

5.4.3 Elementwise Operations

Algebraic Operations

Suppose that we wish to multiply every element of matrix `A` with the corresponding element of matrix `B`.

In that case we need to replace `*` (matrix multiplication) with `.*` (elementwise multiplication).

For example, compare

```
In [79]: ones(2, 2) * ones(2, 2)   # matrix multiplication

Out[79]: 2×2 Array{Float64,2}:
          2.0  2.0
          2.0  2.0

In [80]: ones(2, 2) .* ones(2, 2)   # element by element multiplication

Out[80]: 2×2 Array{Float64,2}:
          1.0  1.0
          1.0  1.0
```

This is a general principle: `.x` means apply operator `x` elementwise

```
In [81]: A = -ones(2, 2)

Out[81]: 2×2 Array{Float64,2}:
          -1.0  -1.0
          -1.0  -1.0

In [82]: A.^2  # square every element

Out[82]: 2×2 Array{Float64,2}:
          1.0  1.0
          1.0  1.0
```

However in practice some operations are mathematically valid without broadcasting, and hence the `.` can be omitted.

```
In [83]: ones(2, 2) + ones(2, 2)  # same as ones(2, 2) .+ ones(2, 2)

Out[83]: 2×2 Array{Float64,2}:
          2.0  2.0
          2.0  2.0
```

Scalar multiplication is similar

```
In [84]: A = ones(2, 2)
```

```
Out[84]: 2×2 Array{Float64,2}:
          1.0  1.0
          1.0  1.0
```

```
In [85]: 2 * A  # same as 2 .* A
```

```
Out[85]: 2×2 Array{Float64,2}:
          2.0  2.0
          2.0  2.0
```

In fact you can omit the `*` altogether and just write `2A`.

Unlike MATLAB and other languages, scalar addition requires the `.+` in order to correctly broadcast

```
In [86]: x = [1, 2]
         x .+ 1     # not x + 1
         x .- 1     # not x - 1
```

```
Out[86]: 2-element Array{Int64,1}:
          0
          1
```

Elementwise Comparisons

Elementwise comparisons also use the `.x` style notation

```
In [87]: a = [10, 20, 30]
```

```
Out[87]: 3-element Array{Int64,1}:
          10
          20
          30
```

```
In [88]: b = [-100, 0, 100]
```

```
Out[88]: 3-element Array{Int64,1}:
          -100
             0
           100
```

```
In [89]: b .> a
```

```
Out[89]: 3-element BitArray{1}:
          0
          0
          1
```

```
In [90]: a .== b
```

```
Out[90]: 3-element BitArray{1}:
          0
          0
          0
```

We can also do comparisons against scalars with parallel syntax

```
In [91]: b
```

```
Out[91]: 3-element Array{Int64,1}:
          -100
             0
           100
```

```
In [92]: b .> 1
```

```
Out[92]: 3-element BitArray{1}:
          0
          0
          1
```

This is particularly useful for *conditional extraction* – extracting the elements of an array that satisfy a condition

```
In [93]: a = randn(4)
```

```
Out[93]: 4-element Array{Float64,1}:
          -0.6434467928769482
          -0.35303489730240734
           0.9772679080446901
          -1.4015326160821104
```

```
In [94]: a .< 0
```

```
Out[94]: 4-element BitArray{1}:
          1
          1
          0
          1
```

```
In [95]: a[a .< 0]
```

```
Out[95]: 3-element Array{Float64,1}:
          -0.6434467928769482
          -0.35303489730240734
          -1.4015326160821104
```

Changing Dimensions

The primary function for changing the dimensions of an array is `reshape()`

```
In [96]: a = [10, 20, 30, 40]

Out[96]: 4-element Array{Int64,1}:
          10
          20
          30
          40

In [97]: b = reshape(a, 2, 2)

Out[97]: 2×2 Array{Int64,2}:
          10  30
          20  40

In [98]: b

Out[98]: 2×2 Array{Int64,2}:
          10  30
          20  40
```

Notice that this function returns a view on the existing array.

This means that changing the data in the new array will modify the data in the old one.

```
In [99]: b[1, 1] = 100  # continuing the previous example

Out[99]: 100

In [100]: b

Out[100]: 2×2 Array{Int64,2}:
           100  30
            20  40

In [101]: a

Out[101]: 4-element Array{Int64,1}:
           100
            20
            30
            40
```

To collapse an array along one dimension you can use `dropdims()`

```
In [102]: a = [1 2 3 4]  # two dimensional

Out[102]: 1×4 Array{Int64,2}:
           1  2  3  4

In [103]: dropdims(a, dims = 1)
```

```
Out[103]: 4-element Array{Int64,1}:
           1
           2
           3
           4
```

The return value is an array with the specified dimension "flattened".

5.4.4 Broadcasting Functions

Julia provides standard mathematical functions such as `log`, `exp`, `sin`, etc.

```
In [104]: log(1.0)
```

```
Out[104]: 0.0
```

By default, these functions act *elementwise* on arrays

```
In [105]: log.(1:4)
```

```
Out[105]: 4-element Array{Float64,1}:
           0.0
           0.6931471805599453
           1.0986122886681098
           1.3862943611198906
```

Note that we can get the same result as with a comprehension or more explicit loop

```
In [106]: [ log(x) for x in 1:4 ]
```

```
Out[106]: 4-element Array{Float64,1}:
           0.0
           0.6931471805599453
           1.0986122886681098
           1.3862943611198906
```

Nonetheless the syntax is convenient.

5.4.5 Linear Algebra

(See linear algebra documentation)

Julia provides some a great deal of additional functionality related to linear operations

```
In [107]: A = [1 2; 3 4]
```

```
Out[107]: 2×2 Array{Int64,2}:
           1  2
           3  4
```

```
In [108]: det(A)
```

```
Out[108]: -2.0
```

```
In [109]: tr(A)
```

```
Out[109]: 5
```

```
In [110]: eigvals(A)
```

```
Out[110]: 2-element Array{Float64,1}:
           -0.3722813232690143
            5.372281323269014
```

```
In [111]: rank(A)
```

```
Out[111]: 2
```

5.5 Ranges

As with many other types, a `Range` can act as a vector.

```
In [112]: a = 10:12        # a range, equivalent to 10:1:12
          @show Vector(a)  # can convert, but shouldn't

          b = Diagonal([1.0, 2.0, 3.0])
          b * a .- [1.0; 2.0; 3.0]
```

```
Vector(a) = [10, 11, 12]
```

```
Out[112]: 3-element Array{Float64,1}:
            9.0
           20.0
           33.0
```

Ranges can also be created with floating point numbers using the same notation.

```
In [113]: a = 0.0:0.1:1.0  # 0.0, 0.1, 0.2, ... 1.0
```

```
Out[113]: 0.0:0.1:1.0
```

But care should be taken if the terminal node is not a multiple of the set sizes.

```
In [114]: maxval = 1.0
          minval = 0.0
          stepsize = 0.15
          a = minval:stepsize:maxval # 0.0, 0.15, 0.3, ...
          maximum(a) == maxval
```

```
Out[114]: false
```

To evenly space points where the maximum value is important, i.e., `linspace` in other languages

```
In [115]: maxval = 1.0
          minval = 0.0
          numpoints = 10
          a = range(minval, maxval, length=numpoints)
          # or range(minval, stop=maxval, length=numpoints)

          maximum(a) == maxval
```

```
Out[115]: true
```

5.6 Tuples and Named Tuples

(See tuples and named tuples documentation)

We were introduced to tuples earlier, which provide high-performance immutable sets of distinct types.

```
In [116]: t = (1.0, "test")
          t[1]            # access by index
          a, b = t        # unpack
          # t[1] = 3.0    # would fail as tuples are immutable
          println("a = $a and b = $b")
```

```
a = 1.0 and b = test
```

As well as **named tuples**, which extend tuples with names for each argument.

```
In [117]: t = (val1 = 1.0, val2 = "test")
          t.val1      # access by index
          # a, b = t  # bad style, better to unpack by name with @unpack
          println("val1 = $(t.val1) and val1 = $(t.val1)") # access by name
```

```
val1 = 1.0 and val1 = 1.0
```

While immutable, it is possible to manipulate tuples and generate new ones

```
In [118]: t2 = (val3 = 4, val4 = "test!!")
          t3 = merge(t, t2)  # new tuple
```

```
Out[118]: (val1 = 1.0, val2 = "test", val3 = 4, val4 = "test!!")
```

Named tuples are a convenient and high-performance way to manage and unpack sets of parameters

```
In [119]: function f(parameters)
              α, β = parameters.α, parameters.β  # poor style, error prone if
          ↪adding parameters
              return α + β
          end

          parameters = (α = 0.1, β = 0.2)
          f(parameters)
```

```
Out[119]: 0.30000000000000004
```

This functionality is aided by the `Parameters.jl` package and the `@unpack` macro

```
In [120]: using Parameters

          function f(parameters)
              @unpack α, β = parameters  # good style, less sensitive to errors
              return α + β
          end

          parameters = (α = 0.1, β = 0.2)
          f(parameters)
```

```
Out[120]: 0.30000000000000004
```

In order to manage default values, use the `@with_kw` macro

```
In [121]: using Parameters
          paramgen = @with_kw (α = 0.1, β = 0.2)  # create named tuples with defaults

          # creates named tuples, replacing defaults
          @show paramgen()  # calling without arguments gives all defaults
          @show paramgen(α = 0.2)
          @show paramgen(α = 0.2, β = 0.5);
```

```
paramgen() = (α = 0.1, β = 0.2)
paramgen(α = 0.2) = (α = 0.2, β = 0.2)
paramgen(α = 0.2, β = 0.5) = (α = 0.2, β = 0.5)
```

An alternative approach, defining a new type using `struct` tends to be more prone to accidental misuse, and leads to a great deal of boilerplate code.

For that, and other reasons of generality, we will use named tuples for collections of parameters where possible.

5.7 Nothing, Missing, and Unions

Sometimes a variable, return type from a function, or value in an array needs to represent the absence of a value rather than a particular value.

There are two distinct use cases for this

1. `nothing` ("software engineers null"): used where no value makes sense in a particular context due to a failure in the code, a function parameter not passed in, etc.
2. `missing` ("data scientists null"): used when a value would make conceptual sense, but it isn't available.

5.7.1 Nothing and Basic Error Handling

The value `nothing` is a single value of type `Nothing`

```
In [122]: typeof(nothing)
```

```
Out[122]: Nothing
```

An example of a reasonable use of `nothing` is if you need to have a variable defined in an outer scope, which may or may not be set in an inner one

```
In [123]: function f(y)
              x = nothing
              if y > 0.0
                  # calculations to set `x`
                  x = y
              end

              # later, can check `x`
              if isnothing(x)
                  println("x was not set")
              else
                  println("x = $x")
              end
              x
          end

          @show f(1.0)
          @show f(-1.0);
```

```
    x = 1.0
f(1.0) = 1.0
x was not set
f(-1.0) = nothing
```

While in general you want to keep a variable name bound to a single type in Julia, this is a notable exception.

Similarly, if needed, you can return a `nothing` from a function to indicate that it did not calculate as expected.

```
In [124]: function f(x)
              if x > 0.0
                  return sqrt(x)
              else
                  return nothing
```

```
        end
    end
    x1 = 1.0
    x2 = -1.0
    y1 = f(x1)
    y2 = f(x2)

    # check results with isnothing
    if isnothing(y1)
        println("f($x2) successful")
    else
        println("f($x2) failed");
    end
```

```
f(-1.0) failed
```

As an aside, an equivalent way to write the above function is to use the ternary operator, which gives a compact if/then/else structure

```
In [125]: function f(x)
              x > 0.0 ? sqrt(x) : nothing  # the "a ? b : c" pattern is the ternary
          end

          f(1.0)
```

```
Out[125]: 1.0
```

We will sometimes use this form when it makes the code more clear (and it will occasionally make the code higher performance).

Regardless of how `f(x)` is written, the return type is an example of a union, where the result could be one of an explicit set of types.

In this particular case, the compiler would deduce that the type would be a `Union{Nothing,Float64}` – that is, it returns either a floating point or a `nothing`.

You will see this type directly if you use an array containing both types

```
In [126]: x = [1.0, nothing]
```

```
Out[126]: 2-element Array{Union{Nothing, Float64},1}:
           1.0
           nothing
```

When considering error handling, whether you want a function to return `nothing` or simply fail depends on whether the code calling `f(x)` is carefully checking the results.

For example, if you were calling on an array of parameters where a priori you were not sure which ones will succeed, then

```
In [127]: x = [0.1, -1.0, 2.0, -2.0]
          y = f.(x)

          # presumably check `y`
```

```
Out[127]: 4-element Array{Union{Nothing, Float64},1}:
           0.31622776601683794
            nothing
           1.4142135623730951
            nothing
```

On the other hand, if the parameter passed is invalid and you would prefer not to handle a graceful failure, then using an assertion is more appropriate.

```
In [128]: function f(x)
              @assert x > 0.0
              sqrt(x)
          end

          f(1.0)
```

```
Out[128]: 1.0
```

Finally, `nothing` is a good way to indicate an optional parameter in a function

```
In [129]: function f(x; z = nothing)

              if isnothing(z)
                  println("No z given with $x")
              else
                  println("z = $z given with $x")
              end
          end

          f(1.0)
          f(1.0, z=3.0)
```

```
          No z given with 1.0
      z = 3.0 given with 1.0
```

An alternative to `nothing`, which can be useful and sometimes higher performance, is to use `NaN` to signal that a value is invalid returning from a function.

```
In [130]: function f(x)
              if x > 0.0
                  return x
              else
                  return NaN
              end
          end

          f(0.1)
          f(-1.0)

          @show typeof(f(-1.0))
          @show f(-1.0) == NaN  # note, this fails!
          @show isnan(f(-1.0))  # check with this
```

```
    typeof(f(-1.0)) = Float64
f(-1.0) == NaN = false
isnan(f(-1.0)) = true
```

```
Out[130]: true
```

Note that in this case, the return type is `Float64` regardless of the input for `Float64` input.

Keep in mind, though, that this only works if the return type of a function is `Float64`.

5.7.2 Exceptions

(See exceptions documentation)

While returning a `nothing` can be a good way to deal with functions which may or may not return values, a more robust error handling method is to use exceptions.

Unless you are writing a package, you will rarely want to define and throw your own exceptions, but will need to deal with them from other libraries.

The key distinction for when to use an exceptions vs. return a `nothing` is whether an error is unexpected rather than a normal path of execution.

An example of an exception is a `DomainError`, which signifies that a value passed to a function is invalid.

```
In [131]: # throws exception, turned off to prevent breaking notebook
          # sqrt(-1.0)

          # to see the error
          try sqrt(-1.0); catch err; err end  # catches the exception and prints it
```

```
Out[131]: DomainError(-1.0, "sqrt will only return a complex result if called with
  ↪a complex
          argument. Try sqrt(Complex(x)).")
```

Another example you will see is when the compiler cannot convert between types.

```
In [132]: # throws exception, turned off to prevent breaking notebook
          # convert(Int64, 3.12)

          # to see the error
          try convert(Int64, 3.12); catch err; err end  # catches the exception
  ↪and prints it.
```

```
Out[132]: InexactError(:Int64, Int64, 3.12)
```

If these exceptions are generated from unexpected cases in your code, it may be appropriate simply let them occur and ensure you can read the error.

Occasionally you will want to catch these errors and try to recover, as we did above in the `try` block.

```
In [133]: function f(x)
              try
                  sqrt(x)
              catch err                # enters if exception thrown
                  sqrt(complex(x, 0))  # convert to complex number
              end
          end

          f(0.0)
          f(-1.0)
```

```
Out[133]: 0.0 + 1.0im
```

5.7.3 Missing

(see "missing" documentation)

The value `missing` of type `Missing` is used to represent missing value in a statistical sense.

For example, if you loaded data from a panel, and gaps existed

```
In [134]: x = [3.0, missing, 5.0, missing, missing]
```

```
Out[134]: 5-element Array{Union{Missing, Float64},1}:
           3.0
           missing
           5.0
           missing
           missing
```

A key feature of `missing` is that it propagates through other function calls - unlike `nothing`

```
In [135]: f(x) = x^2

          @show missing + 1.0
          @show missing * 2
          @show missing * "test"
          @show f(missing);      # even user-defined functions
          @show mean(x);
```

```
missing + 1.0 = missing
missing * 2 = missing
missing * "test" = missing
f(missing) = missing
mean(x) = missing
```

The purpose of this is to ensure that failures do not silently fail and provide meaningless numerical results.

This even applies for the comparison of values, which

```
In [136]: x = missing
```

```
@show x == missing
@show x === missing  # an exception
@show ismissing(x);
```

```
    x == missing = missing
x === missing = true
ismissing(x) = true
```

Where `ismissing` is the canonical way to test the value.

In the case where you would like to calculate a value without the missing values, you can use `skipmissing`.

```
In [137]: x = [1.0, missing, 2.0, missing, missing, 5.0]
```

```
@show mean(x)
@show mean(skipmissing(x))
@show coalesce.(x, 0.0);  # replace missing with 0.0;
```

```
    mean(x) = missing
mean(skipmissing(x)) = 2.6666666666666665
coalesce.(x, 0.0) = [1.0, 0.0, 2.0, 0.0, 0.0, 5.0]
```

As `missing` is similar to R's `NA` type, we will see more of `missing` when we cover `DataFrames`.

5.8 Exercises

5.8.1 Exercise 1

This exercise uses matrix operations that arise in certain problems, including when dealing with linear stochastic difference equations.

If you aren't familiar with all the terminology don't be concerned – you can skim read the background discussion and focus purely on the matrix exercise.

With that said, consider the stochastic difference equation

$$X_{t+1} = AX_t + b + \Sigma W_{t+1} \tag{1}$$

Here

- X_t, b and X_{t+1} are $n \times 1$
- A is $n \times n$
- Σ is $n \times k$
- W_t is $k \times 1$ and $\{W_t\}$ is iid with zero mean and variance-covariance matrix equal to the identity matrix

Let S_t denote the $n \times n$ variance-covariance matrix of X_t.

Using the rules for computing variances in matrix expressions, it can be shown from (1) that $\{S_t\}$ obeys

$$S_{t+1} = AS_tA' + \Sigma\Sigma' \tag{2}$$

It can be shown that, provided all eigenvalues of A lie within the unit circle, the sequence $\{S_t\}$ converges to a unique limit S.

This is the **unconditional variance** or **asymptotic variance** of the stochastic difference equation.

As an exercise, try writing a simple function that solves for the limit S by iterating on (2) given A and Σ.

To test your solution, observe that the limit S is a solution to the matrix equation

$$S = ASA' + Q \quad \text{where} \quad Q := \Sigma\Sigma' \tag{3}$$

This kind of equation is known as a **discrete time Lyapunov equation**.

The QuantEcon package provides a function called `solve_discrete_lyapunov` that implements a fast "doubling" algorithm to solve this equation.

Test your iterative method against `solve_discrete_lyapunov` using matrices

$$A = \begin{bmatrix} 0.8 & -0.2 \\ -0.1 & 0.7 \end{bmatrix} \qquad \Sigma = \begin{bmatrix} 0.5 & 0.4 \\ 0.4 & 0.6 \end{bmatrix}$$

5.8.2 Exercise 2

Take a stochastic process for $\{y_t\}_{t=0}^T$

$$y_{t+1} = \gamma + \theta y_t + \sigma w_{t+1}$$

where

- w_{t+1} is distributed `Normal(0,1)`
- $\gamma = 1, \sigma = 1, y_0 = 0$
- $\theta \in \Theta \equiv \{0.8, 0.9, 0.98\}$

Given these parameters

- Simulate a single y_t series for each $\theta \in \Theta$ for $T = 150$. Feel free to experiment with different T.
- Overlay plots of the rolling mean of the process for each $\theta \in \Theta$, i.e. for each $1 \leq \tau \leq T$ plot

$$\frac{1}{\tau}\sum_{t=1}^{\tau} y_T$$

- Simulate $N = 200$ paths of the stochastic process above to the T, for each $\theta \in \Theta$, where we refer to an element of a particular simulation as y_t^n.

- Overlay plots a histogram of the stationary distribution of the final y_T^n for each $\theta \in \Theta$. Hint: pass `alpha` to a plot to make it transparent (e.g. `histogram(vals, alpha = 0.5)`) or use `stephist(vals)` to show just the step function for the histogram.
- Numerically find the mean and variance of this as an ensemble average, i.e. $\sum_{n=1}^N \frac{y_T^n}{N}$ and $\sum_{n=1}^N \frac{(y_T^n)^2}{N} - \left(\sum_{n=1}^N \frac{y_T^n}{N}\right)^2$.

Later, we will interpret some of these in this lecture.

5.8.3 Exercise 3

Let the data generating process for a variable be

$$y = ax_1 + bx_1^2 + cx_2 + d + \sigma w$$

where y, x_1, x_2 are scalar observables, a, b, c, d are parameters to estimate, and w are iid normal with mean 0 and variance 1.

First, let's simulate data we can use to estimate the parameters

- Draw $N = 50$ values for x_1, x_2 from iid normal distributions.

Then, simulate with different w * Draw a w vector for the `N` values and then `y` from this simulated data if the parameters were $a = 0.1, b = 0.2 c = 0.5, d = 1.0, \sigma = 0.1$. * Repeat that so you have `M = 20` different simulations of the `y` for the `N` values.

Finally, calculate order least squares manually (i.e., put the observables into matrices and vectors, and directly use the equations for OLS rather than a package).

- For each of the `M=20` simulations, calculate the OLS estimates for a, b, c, d, σ.
- Plot a histogram of these estimates for each variable.

5.8.4 Exercise 4

Redo Exercise 1 using the `fixedpoint` function from `NLsolve` this lecture.

Compare the number of iterations of the NLsolve's Anderson Acceleration to the handcoded iteration used in Exercise 1.

Hint: Convert the matrix to a vector to use `fixedpoint`. e.g. `A = [1 2; 3 4]` then `x = reshape(A, 4)` turns it into a vector. To reverse, `reshape(x, 2, 2)`.

5.9 Solutions

5.9.1 Exercise 1

Here's the iterative approach

```
In [138]: function compute_asymptotic_var(A, Σ;
                                           S0 = Σ * Σ',
                                           tolerance = 1e-6,
                                           maxiter = 500)
              V = Σ * Σ'
```

```
        S = S0
        err = tolerance + 1
        i = 1
        while err > tolerance && i ≤ maxiter
            next_S = A * S * A' + V
            err = norm(S - next_S)
            S = next_S
            i += 1
        end
        return S
    end
```

```
Out[138]: compute_asymptotic_var (generic function with 1 method)
```

```
In [139]: A = [0.8  -0.2;
               -0.1  0.7]

          Σ = [0.5 0.4;
               0.4 0.6]
```

```
Out[139]: 2×2 Array{Float64,2}:
           0.5  0.4
           0.4  0.6
```

Note that all eigenvalues of A lie inside the unit disc.

```
In [140]: maximum(abs, eigvals(A))
```

```
Out[140]: 0.9
```

Let's compute the asymptotic variance

```
In [141]: our_solution = compute_asymptotic_var(A, Σ)
```

```
Out[141]: 2×2 Array{Float64,2}:
           0.671228  0.633476
           0.633476  0.858874
```

Now let's do the same thing using QuantEcon's `solve_discrete_lyapunov()` function and check we get the same result.

```
In [142]: using QuantEcon
```

```
In [143]: norm(our_solution - solve_discrete_lyapunov(A, Σ * Σ'))
```

```
Out[143]: 3.883245447999784e-6
```

Chapter 6

Introduction to Types and Generic Programming

6.1 Contents

6.2 Overview

In Julia, arrays and tuples are the most important data type for working with numerical data.

In this lecture we give more details on

- declaring types
- abstract types
- motivation for generic programming
- multiple dispatch
- building user-defined types

6.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

6.3 Finding and Interpreting Types

6.3.1 Finding The Type

As we have seen in the previous lectures, in Julia all values have a type, which can be queried using the `typeof` function

```
In [3]: @show typeof(1)
        @show typeof(1.0);
```

```
    typeof(1) = Int64
typeof(1.0) = Float64
```

The hard-coded values `1` and `1.0` are called literals in a programming language, and the compiler deduces their types (`Int64` and `Float64` respectively in the example above).

You can also query the type of a value

```
In [4]: x = 1
        typeof(x)
```

```
Out[4]: Int64
```

The name `x` binds to the value `1`, created as a literal.

6.3.2 Parametric Types

(See parametric types documentation).

The next two types use curly bracket notation to express the fact that they are *parametric*

```
In [5]: @show typeof(1.0 + 1im)
        @show typeof(ones(2, 2));
```

```
    typeof(1.0 + 1im) = Complex{Float64}
typeof(ones(2, 2)) = Array{Float64,2}
```

We will learn more details about generic programming later, but the key is to interpret the curly brackets as swappable parameters for a given type.

For example, `Array{Float64, 2}` can be read as

1. `Array` is a parametric type representing a dense array, where the first parameter is the type stored, and the second is the number of dimensions.
2. `Float64` is a concrete type declaring that the data stored will be a particular size of floating point.
3. `2` is the number of dimensions of that array.

A concrete type is one where values can be created by the compiler (equivalently, one which can be the result of `typeof(x)` for some object `x`).

Values of a **parametric type** cannot be concretely constructed unless all of the parameters are given (themselves with concrete types).

In the case of `Complex{Float64}`

1. `Complex` is an abstract complex number type.
2. `Float64` is a concrete type declaring what the type of the real and imaginary parts of the value should store.

Another type to consider is the `Tuple` and `NamedTuple`

```
In [6]: x = (1, 2.0, "test")
        @show typeof(x)
```

```
typeof(x) = Tuple{Int64,Float64,String}
```

```
Out[6]: Tuple{Int64,Float64,String}
```

In this case, `Tuple` is the parametric type, and the three parameters are a list of the types of each value.

For a named tuple

```
In [7]: x = (a = 1, b = 2.0, c = "test")
        @show typeof(x)
```

```
typeof(x) = NamedTuple{(:a, :b, :c),Tuple{Int64,Float64,String}}
```

```
Out[7]: NamedTuple{(:a, :b, :c),Tuple{Int64,Float64,String}}
```

The parametric `NamedTuple` type contains two parameters: first a list of names for each field of the tuple, and second the underlying `Tuple` type to store the values.

Anytime a value is prefixed by a colon, as in the `:a` above, the type is `Symbol` – a special kind of string used by the compiler.

```
In [8]: typeof(:a)
```

```
Out[8]: Symbol
```

Remark: Note that, by convention, type names use CamelCase – `Array`, `AbstractArray`, etc.

6.3.3 Variables, Types, and Values

Since variables and functions are lower case by convention, this can be used to easily identify types when reading code and output.

After assigning a variable name to a value, we can query the type of the value via the name.

```
In [9]: x = 42
        @show typeof(x);
```

```
typeof(x) = Int64
```

Thus, `x` is just a symbol bound to a value of type `Int64`.

We can *rebind* the symbol `x` to any other value, of the same type or otherwise.

```
In [10]: x = 42.0
```

```
Out[10]: 42.0
```

Now `x` "points to" another value, of type `Float64`

```
In [11]: typeof(x)
```

```
Out[11]: Float64
```

However, beyond a few notable exceptions (e.g. `nothing` used for error handling), changing types is usually a symptom of poorly organized code, and makes type inference more difficult for the compiler.

6.4 The Type Hierarchy

Let's discuss how types are organized.

6.4.1 Abstract vs Concrete Types

(See abstract types documentation)

Up to this point, most of the types we have worked with (e.g., `Float64, Int64`) are examples of **concrete types**.

Concrete types are types that we can *instantiate* – i.e., pair with data in memory.

We will now examine **abstract types** that cannot be instantiated (e.g., `Real`, `AbstractFloat`).

For example, while you will never have a `Real` number directly in memory, the abstract types help us organize and work with related concrete types.

6.4.2 Subtypes and Supertypes

How exactly do abstract types organize or relate different concrete types?

In the Julia language specification, the types form a hierarchy.

You can check if a type is a subtype of another with the `<:` operator.

```
In [12]: @show Float64 <: Real
         @show Int64 <: Real
         @show Complex{Float64} <: Real
         @show Array <: Real;
```

```
    Float64 <: Real = true
Int64 <: Real = true
Complex{Float64} <: Real = false
Array <: Real = false
```

In the above, both `Float64` and `Int64` are **subtypes** of `Real`, whereas the `Complex` numbers are not.

They are, however, all subtypes of `Number`

```
In [13]: @show Real <: Number
         @show Float64 <: Number
         @show Int64 <: Number
         @show Complex{Float64} <: Number;
```

```
    Real <: Number = true
Float64 <: Number = true
Int64 <: Number = true
Complex{Float64} <: Number = true
```

`Number` in turn is a subtype of `Any`, which is a parent of all types.

```
In [14]: Number <: Any
```

```
Out[14]: true
```

In particular, the type tree is organized with `Any` at the top and the concrete types at the bottom.

We never actually see *instances* of abstract types (i.e., `typeof(x)` never returns an abstract type).

The point of abstract types is to categorize the concrete types, as well as other abstract types that sit below them in the hierarchy.

There are some further functions to help you explore the type hierarchy, such as `show_supertypes` which walks up the tree of types to `Any` for a given type.

```
In [15]: using Base: show_supertypes  # import the function from the `Base` package

         show_supertypes(Int64)
```

```
Int64 <: Signed <: Integer <: Real <: Number <: Any
```

And the `subtypes` which gives a list of the available subtypes for any packages or code currently loaded

```
In [16]: @show subtypes(Real)
         @show subtypes(AbstractFloat);
```

```
   subtypes(Real) = Any[AbstractFloat, AbstractIrrational, Integer, Rational]
subtypes(AbstractFloat) = Any[BigFloat, Float16, Float32, Float64]
```

6.5 Deducing and Declaring Types

We will discuss this in detail in generic programming, but much of Julia's performance gains and generality of notation comes from its type system.

For example

```
In [17]: x1 = [1, 2, 3]
         x2 = [1.0, 2.0, 3.0]

         @show typeof(x1)
         @show typeof(x2)
```

```
   typeof(x1) = Array{Int64,1}
typeof(x2) = Array{Float64,1}
```

```
Out[17]: Array{Float64,1}
```

These return `Array{Int64,1}` and `Array{Float64,1}` respectively, which the compiler is able to infer from the right hand side of the expressions.

Given the information on the type, the compiler can work through the sequence of expressions to infer other types.

```
In [18]: f(y) = 2y # define some function
```

```
         x = [1, 2, 3]
         z = f(x) # call with an integer array - compiler deduces type
```

```
Out[18]: 3-element Array{Int64,1}:
          2
          4
          6
```

6.5.1 Good Practices for Functions and Variable Types

In order to keep many of the benefits of Julia, you will sometimes want to ensure the compiler can always deduce a single type from any function or expression.

An example of bad practice is to use an array to hold unrelated types

```
In [19]: x = [1.0, "test", 1]  # typically poor style
```

```
Out[19]: 3-element Array{Any,1}:
          1.0
           "test"
          1
```

The type of this array is `Array{Any,1}`, where `Any` means the compiler has determined that any valid Julia type can be added to the array.

While occasionally useful, this is to be avoided whenever possible in performance sensitive code.

The other place this can come up is in the declaration of functions.

As an example, consider a function which returns different types depending on the arguments.

```
In [20]: function f(x)
             if x > 0
                 return 1.0
             else
                 return 0  # probably meant `0.0`
             end
         end

         @show f(1)
         @show f(-1);
```

```
    f(1) = 1.0
f(-1) = 0
```

The issue here is relatively subtle: `1.0` is a floating point, while `0` is an integer.

Consequently, given the type of `x`, the compiler cannot in general determine what type the function will return.

This issue, called **type stability**, is at the heart of most Julia performance considerations.

Luckily, trying to ensure that functions return the same types is also generally consistent with simple, clear code.

6.5.2 Manually Declaring Function and Variable Types

(See type declarations documentation)

You will notice that in the lecture notes we have never directly declared any types.

This is intentional both for exposition and as a best practice for using packages (as opposed to writing new packages, where declaring these types is very important).

It is also in contrast to some of the sample code you will see in other Julia sources, which you will need to be able to read.

To give an example of the declaration of types, the following are equivalent

```
In [21]: function f(x, A)
             b = [5.0, 6.0]
             return A * x .+ b
         end

         val = f([0.1, 2.0], [1.0 2.0; 3.0 4.0])
```

```
Out[21]: 2-element Array{Float64,1}:
           9.1
          14.3
```

```
In [22]: function f2(x::Vector{Float64}, A::Matrix{Float64})::Vector{Float64}
             # argument and return types
             b::Vector{Float64} = [5.0, 6.0]
             return A * x .+ b
         end

         val = f2([0.1; 2.0], [1.0 2.0; 3.0 4.0])
```

```
Out[22]: 2-element Array{Float64,1}:
           9.1
          14.3
```

While declaring the types may be verbose, would it ever generate faster code?

The answer is almost never.

Furthermore, it can lead to confusion and inefficiencies since many things that behave like vectors and matrices are not `Matrix{Float64}` and `Vector{Float64}`.

Here, the first line works and the second line fails

```
In [23]: @show f([0.1; 2.0], [1 2; 3 4])
         @show f([0.1; 2.0], Diagonal([1.0, 2.0]))

         # f2([0.1; 2.0], [1 2; 3 4]) # not a `Float64`
         # f2([0.1; 2.0], Diagonal([1.0, 2.0])) # not a `Matrix{Float64}`
```

```
f([0.1; 2.0], [1 2; 3 4]) = [9.1, 14.3]
f([0.1; 2.0], Diagonal([1.0, 2.0])) = [5.1, 10.0]
```

```
Out[23]: 2-element Array{Float64,1}:
           5.1
          10.0
```

6.6 Creating New Types

(See type declarations documentation)

Up until now, we have used `NamedTuple` to collect sets of parameters for our models and examples.

These are useful for maintaining values for model parameters, but you will eventually need to be able to use code that creates its own types.

6.6.1 Syntax for Creating Concrete Types

(See composite types documentation)

While other sorts of types exist, we almost always use the `struct` keyword, which is for creation of composite data types

- "Composite" refers to the fact that the data types in question can be used as collection of named fields.
- The `struct` terminology is used in a number of programming languages to refer to composite data types.

Let's start with a trivial example where the `struct` we build has fields named `a, b, c`, are not typed

```
In [24]: struct FooNotTyped  # immutable by default, use `mutable struct` otherwise
             a # BAD! not typed
             b
             c
         end
```

And another where the types of the fields are chosen

```
In [25]: struct Foo
             a::Float64
             b::Int64
             c::Vector{Float64}
         end
```

In either case, the compiler generates a function to create new values of the data type, called a "constructor".

It has the same name as the data type but uses function call notion

```
In [26]: foo_nt = FooNotTyped(2.0, 3, [1.0, 2.0, 3.0])  # new `FooNotTyped`
         foo = Foo(2.0, 3, [1.0, 2.0, 3.0]) # creates a new `Foo`

         @show typeof(foo)
         @show foo.a       # get the value for a field
         @show foo.b
         @show foo.c;

         # foo.a = 2.0     # fails since it is immutable
```

```
    typeof(foo) = Foo
foo.a = 2.0
foo.b = 3
foo.c = [1.0, 2.0, 3.0]
```

You will notice two differences above for the creation of a `struct` compared to our use of `NamedTuple`.

- Types are declared for the fields, rather than inferred by the compiler.
- The construction of a new instance has no named parameters to prevent accidental misuse if the wrong order is chosen.

6.6.2 Issues with Type Declarations

Was it necessary to manually declare the types `a::Float64` in the above struct?

The answer, in practice, is usually yes.

Without a declaration of the type, the compiler is unable to generate efficient code, and the use of a `struct` declared without types could drop performance by orders of magnitude.

Moreover, it is very easy to use the wrong type, or unnecessarily constrain the types.

The first example, which is usually just as low-performance as no declaration of types at all, is to accidentally declare it with an abstract type

```
In [27]: struct Foo2
             a::Float64
             b::Integer  # BAD! Not a concrete type
             c::Vector{Real}  # BAD! Not a concrete type
         end
```

The second issue is that by choosing a type (as in the `Foo` above), you may be unnecessarily constraining what is allowed

```
In [28]: f(x) = x.a + x.b + sum(x.c) # use the type
         a = 2.0
         b = 3
         c = [1.0, 2.0, 3.0]
         foo = Foo(a, b, c)
         @show f(foo)   # call with the foo, no problem

         # some other typed for the values
         a = 2   # not a floating point but `f()` would work
         b = 3
         c = [1.0, 2.0, 3.0]'   # transpose is not a `Vector` but `f()` would work
         # foo = Foo(a, b, c)   # fails to compile

         # works with `NotTyped` version, but low performance
         foo_nt = FooNotTyped(a, b, c)
         @show f(foo_nt);
```

```
    f(foo) = 11.0
f(foo_nt) = 11.0
```

6.6.3 Declaring Parametric Types (Advanced)

(See type parametric types documentation)

Motivated by the above, we can create a type which can adapt to holding fields of different types.

```
In [29]: struct Foo3{T1, T2, T3}
             a::T1   # could be any type
             b::T2
             c::T3
         end

         # works fine
         a = 2
         b = 3
         c = [1.0, 2.0, 3.0]'    # transpose is not a `Vector` but `f()` would work
         foo = Foo3(a, b, c)
         @show typeof(foo)
         f(foo)
```

```
typeof(foo) = Foo3{Int64,Int64,Adjoint{Float64,Array{Float64,1}}}
```

```
Out[29]: 11.0
```

Of course, this is probably too flexible, and the `f` function might not work on an arbitrary set of `a, b, c`.

You could constrain the types based on the abstract parent type using the `<:` operator

```
In [30]: struct Foo4{T1 <: Real, T2 <: Real, T3 <: AbstractVecOrMat{<:Real}}
             a::T1
             b::T2
             c::T3  # should check dimensions as well
         end
         foo = Foo4(a, b, c)  # no problem, and high performance
         @show typeof(foo)
         f(foo)
```

```
typeof(foo) = Foo4{Int64,Int64,Adjoint{Float64,Array{Float64,1}}}
```

```
Out[30]: 11.0
```

This ensures that

- `a` and `b` are a subtype of `Real`, and `+` in the definition of `f` works
- `c` is a one dimensional abstract array of `Real` values

The code works, and is equivalent in performance to a `NamedTuple`, but is more verbose and error prone.

6.6.4 Keyword Argument Constructors (Advanced)

There is no way to avoid learning parametric types to achieve high performance code.

However, the other issue where constructor arguments are error-prone, can be remedied with the `Parameters.jl` library.

In [31]:
```
using Parameters

@with_kw  struct Foo5
    a::Float64 = 2.0     # adds default value
    b::Int64
    c::Vector{Float64}
end

foo = Foo5(a = 0.1, b = 2, c = [1.0, 2.0, 3.0])
foo2 = Foo5(c = [1.0, 2.0, 3.0], b = 2)  # rearrange order, uses default
↪values

@show foo
@show foo2

function f(x)
    @unpack a, b, c = x     # can use `@unpack` on any struct
    return a + b + sum(c)
end

f(foo)
```

```
  foo = Foo5
a: Float64 0.1
b: Int64 2
c: Array{Float64}((3,)) [1.0, 2.0, 3.0]

foo2 = Foo5
  a: Float64 2.0
  b: Int64 2
  c: Array{Float64}((3,)) [1.0, 2.0, 3.0]
```

Out[31]: 8.1

6.6.5 Tips and Tricks for Writing Generic Functions

As discussed in the previous sections, there is major advantage to never declaring a type unless it is absolutely necessary.

The main place where it is necessary is designing code around multiple dispatch.

If you are careful to write code that doesn't unnecessarily assume types, you will both achieve higher performance and allow seamless use of a number of powerful libraries such as auto-differentiation, static arrays, GPUs, interval arithmetic and root finding, arbitrary precision numbers, and many more packages – including ones that have not even been written yet.

A few simple programming patterns ensure that this is possible

- Do not declare types when declaring variables or functions unless necessary.

In [32]:
```
# BAD
x = [5.0, 6.0, 2.1]

function g(x::Array{Float64, 1})   # not generic!
    y = zeros(length(x))   # not generic, hidden float!
```

```
    z = Diagonal(ones(length(x)))  # not generic, hidden float!
    q = ones(length(x))
    y .= z * x + q
    return y
end

g(x)

# GOOD
function g2(x)  # or `x::AbstractVector`
    y = similar(x)
    z = I
    q = ones(eltype(x), length(x))  # or `fill(one(x), length(x))`
    y .= z * x + q
    return y
end

g2(x)
```

```
Out[32]: 3-element Array{Float64,1}:
          6.0
          7.0
          3.1
```

- Preallocate related vectors with `similar` where possible, and use `eltype` or `typeof`. This is important when using Multiple Dispatch given the different input types the function can call

```
In [33]: function g(x)
             y = similar(x)
             for i in eachindex(x)
                 y[i] = x[i]^2      # could broadcast
             end
             return y
         end

         g([BigInt(1), BigInt(2)])
```

```
Out[33]: 2-element Array{BigInt,1}:
          1
          4
```

- Use `typeof` or `eltype` to declare a type

```
In [34]: @show typeof([1.0, 2.0, 3.0])
         @show eltype([1.0, 2.0, 3.0]);
```

```
   typeof([1.0, 2.0, 3.0]) = Array{Float64,1}
eltype([1.0, 2.0, 3.0]) = Float64
```

- Beware of hidden floating points

```
In [35]: @show typeof(ones(3))
         @show typeof(ones(Int64, 3))
         @show typeof(zeros(3))
         @show typeof(zeros(Int64, 3));
```

```
    typeof(ones(3)) = Array{Float64,1}
typeof(ones(Int64, 3)) = Array{Int64,1}
typeof(zeros(3)) = Array{Float64,1}
typeof(zeros(Int64, 3)) = Array{Int64,1}
```

- Use `one` and `zero` to write generic code

```
In [36]: @show typeof(1)
         @show typeof(1.0)
         @show typeof(BigFloat(1.0))
         @show typeof(one(BigFloat))  # gets multiplicative identity, passing in
 ↪type
         @show typeof(zero(BigFloat))

         x = BigFloat(2)

         @show typeof(one(x))  # can call with a variable for convenience
         @show typeof(zero(x));
```

```
    typeof(1) = Int64
typeof(1.0) = Float64
typeof(BigFloat(1.0)) = BigFloat
typeof(one(BigFloat)) = BigFloat
typeof(zero(BigFloat)) = BigFloat
typeof(one(x)) = BigFloat
typeof(zero(x)) = BigFloat
```

This last example is a subtle, because of something called type promotion

- Assume reasonable type promotion exists for numeric types

```
In [37]: # ACCEPTABLE
         function g(x::AbstractFloat)
             return x + 1.0   # assumes `1.0` can be converted to something
 ↪compatible with
         `typeof(x)`
         end

         x = BigFloat(1.0)

         @show typeof(g(x));  # this has "promoted" the `1.0` to a `BigFloat`
```

```
  typeof(g(x)) = BigFloat
```

But sometimes assuming promotion is not enough

```
In [38]: # BAD
         function g2(x::AbstractFloat)
             if x > 0.0   # can't efficiently call with `x::Integer`
                 return x + 1.0   # OK - assumes you can promote `Float64` to
 ↪`AbstractFloat`
             otherwise
```

```
            return 0   # BAD! Returns a `Int64`
        end
    end

    x = BigFloat(1.0)
    x2 = BigFloat(-1.0)

    @show typeof(g2(x))
    @show typeof(g2(x2))  # type unstable

    # GOOD
    function g3(x) #
        if x > zero(x)   # any type with an additive identity
            return x + one(x)  # more general but less important of a change
        otherwise
            return zero(x)
        end
    end

    @show typeof(g3(x))
    @show typeof(g3(x2));  # type stable
```

```
   typeof(g2(x)) = BigFloat
typeof(g2(x2)) = Nothing
typeof(g3(x)) = BigFloat
typeof(g3(x2)) = Nothing
```

These patterns are relatively straightforward, but generic programming can be thought of as a Leontief production function: if *any* of the functions you write or call are not precise enough, then it may break the chain.

This is all the more reason to exploit carefully designed packages rather than "do-it-yourself".

6.6.6 A Digression on Style and Naming

The previous section helps to establish some of the reasoning behind the style choices in these lectures: "be aware of types, but avoid declaring them".

The purpose of this is threefold:

- Provide easy to read code with minimal "syntactic noise" and a clear correspondence to the math.
- Ensure that code is sufficiently generic to exploit other packages and types.
- Avoid common mistakes and unnecessary performance degradations.

This is just one of many decisions and patterns to ensure that your code is consistent and clear.

The best resource is to carefully read other peoples code, but a few sources to review are

- Julia Style Guide.
- Invenia Blue Style Guide.
- Julia Praxis Naming Guides.
- QuantEcon Style Guide used in these lectures.

Now why would we emphasize naming and style as a crucial part of the lectures?

Because it is an essential tool for creating research that is **reproducible** and **correct**.

Some helpful ways to think about this are

- **Clearly written code is easier to review for errors**: The first-order concern of any code is that it correctly implements the whiteboard math.
- **Code is read many more times than it is written**: Saving a few keystrokes in typing a variable name is never worth it, nor is a divergence from the mathematical notation where a single symbol for a variable name would map better to the model.
- **Write code to be read in the future, not today**: If you are not sure anyone else will read the code, then write it for an ignorant future version of yourself who may have forgotten everything, and is likely to misuse the code.
- **Maintain the correspondence between the whiteboard math and the code**: For example, if you change notation in your model, then immediately update all variables in the code to reflect it.

Commenting Code

One common mistake people make when trying to apply these goals is to add in a large number of comments.

Over the years, developers have found that excess comments in code (and *especially* big comment headers used before every function declaration) can make code *harder* to read.

The issue is one of syntactic noise: if most of the comments are redundant given clear variable and function names, then the comments make it more difficult to mentally parse and read the code.

If you examine Julia code in packages and the core language, you will see a great amount of care taken in function and variable names, and comments are only added where helpful.

For creating packages that you intend others to use, instead of a comment header, you should use docstrings.

6.7 Introduction to Multiple Dispatch

One of the defining features of Julia is **multiple dispatch**, whereby the same function name can do different things depending on the underlying types.

Without realizing it, in nearly every function call within packages or the standard library you have used this feature.

To see this in action, consider the absolute value function `abs`

```
In [39]: @show abs(-1)   # `Int64`
         @show abs(-1.0)  # `Float64`
         @show abs(0.0 - 1.0im);  # `Complex{Float64}`
```

```
    abs(-1) = 1
abs(-1.0) = 1.0
abs(0.0 - 1.0im) = 1.0
```

In all of these cases, the `abs` function has specialized code depending on the type passed in.

To do this, a function specifies different **methods** which operate on a particular set of types.

Unlike most cases we have seen before, this requires a type annotation.

To rewrite the `abs` function

```
In [40]: function ourabs(x::Real)
             if x > zero(x)   # note, not 0!
                 return x
             else
                 return -x
             end
         end

         function ourabs(x::Complex)
             sqrt(real(x)^2 + imag(x)^2)
         end

         @show ourabs(-1)   # `Int64`
         @show ourabs(-1.0) # `Float64`
         @show ourabs(1.0 - 2.0im);  # `Complex{Float64}`
```

```
    ourabs(-1) = 1
ourabs(-1.0) = 1.0
ourabs(1.0 - 2.0im) = 2.23606797749979
```

Note that in the above, `x` works for any type of `Real`, including `Int64`, `Float64`, and ones you may not have realized exist

```
In [41]: x = -2//3  # `Rational` number, -2/3
         @show typeof(x)
         @show ourabs(x);
```

```
    typeof(x) = Rational{Int64}
ourabs(x) = 2//3
```

You will also note that we used an abstract type, `Real`, and an incomplete parametric type, `Complex`, when defining the above functions.

Unlike the creation of `struct` fields, there is no penalty in using abstract types when you define function parameters, as they are used purely to determine which version of a function to use.

6.7.1 Multiple Dispatch in Algorithms (Advanced)

If you want an algorithm to have specialized versions when given different input types, you need to declare the types for the function inputs.

As an example where this could come up, assume that we have some grid `x` of values, the results of a function `f` applied at those values, and want to calculate an approximate derivative using forward differences.

In that case, given $x_n, x_{n+1}, f(x_n)$ and $f(x_{n+1})$, the forward-difference approximation of the derivative is

$$f'(x_n) \approx \frac{f(x_{n+1}) - f(x_n)}{x_{n+1} - x_n}$$

To implement this calculation for a vector of inputs, we notice that there is a specialized implementation if the grid is uniform.

The uniform grid can be implemented using an `AbstractRange`, which we can analyze with `typeof`, `supertype` and `show_supertypes`.

```
In [42]: x = range(0.0, 1.0, length = 20)
         x_2 = 1:1:20   # if integers

         @show typeof(x)
         @show typeof(x_2)
         @show supertype(typeof(x))
```

```
    typeof(x) =
StepRangeLen{Float64,Base.TwicePrecision{Float64},Base.TwicePrecision{Float64}}
typeof(x_2) = StepRange{Int64,Int64}
supertype(typeof(x)) = AbstractRange{Float64}
```

```
Out[42]: AbstractRange{Float64}
```

To see the entire tree about a particular type, use `show_supertypes`.

```
In [43]: show_supertypes(typeof(x))  # or typeof(x) |> show_supertypes
```

```
    StepRangeLen{Float64,Base.TwicePrecision{Float64},Base.
  ↪TwicePrecision{Float64}} <:
AbstractRange{Float64} <: AbstractArray{Float64,1} <: Any
```

```
In [44]: show_supertypes(typeof(x_2))
```

```
    StepRange{Int64,Int64} <: OrdinalRange{Int64,Int64} <: AbstractRange{Int64} <:
AbstractArray{Int64,1} <: Any
```

The types of the range objects can be very complicated, but are both subtypes of `AbstractRange`.

```
In [45]: @show typeof(x) <: AbstractRange
         @show typeof(x_2) <: AbstractRange;
```

```
    typeof(x) <: AbstractRange = true
typeof(x_2) <: AbstractRange = true
```

While you may not know the exact concrete type, any `AbstractRange` has an informal set of operations that are available.

In [46]:
```
@show minimum(x)
@show maximum(x)
@show length(x)
@show step(x);
```

```
   minimum(x) = 0.0
maximum(x) = 1.0
length(x) = 20
step(x) = 0.05263157894736842
```

Similarly, there are a number of operations available for any `AbstractVector`, such as `length`.

In [47]:
```
f(x) = x^2
f_x = f.(x)  # calculating at the range values

@show typeof(f_x)
@show supertype(typeof(f_x))
@show supertype(supertype(typeof(f_x)))  # walk up tree again!
@show length(f_x);   # and many more
```

```
   typeof(f_x) = Array{Float64,1}
supertype(typeof(f_x)) = DenseArray{Float64,1}
supertype(supertype(typeof(f_x))) = AbstractArray{Float64,1}
length(f_x) = 20
```

In [48]:
```
show_supertypes(typeof(f_x))
```

```
Array{Float64,1} <: DenseArray{Float64,1} <: AbstractArray{Float64,1} <: Any
```

There are also many functions that can use any `AbstractArray`, such as `diff`.

```
?diff
```

```
search: diff symdiff setdiff symdiff! setdiff! Cptrdiff_t

diff(A::AbstractVector) # finite difference operator of matrix or vector A

# if A is a matrix, specify the dimension over which to operate with the dims ke
diff(A::AbstractMatrix; dims::Integer)
```

Hence, we can call this function for anything of type `AbstractVector`.

Finally, we can make a high performance specialization for any `AbstractVector` and `AbstractRange`.

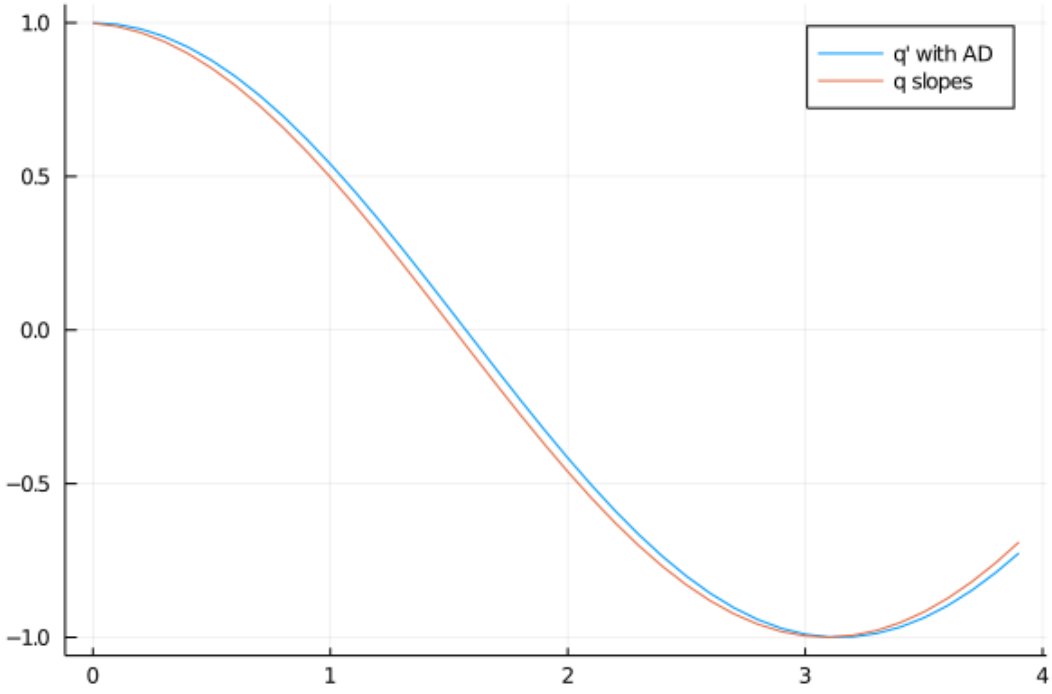
In [49]:
```
slopes(f_x::AbstractVector, x::AbstractRange) = diff(f_x) / step(x)
```

Out[49]:
```
slopes (generic function with 1 method)
```

We can use auto-differentiation to compare the results.

In [50]:
```
using Plots, ForwardDiff
gr(fmt = :png);

# operator to get the derivative of this function using AD
D(f) = x -> ForwardDiff.derivative(f, x)

# compare slopes with AD for sin(x)
q(x) = sin(x)
x = 0.0:0.1:4.0
q_x = q.(x)
q_slopes_x = slopes(q_x, x)

D_q_x = D(q).(x)  # broadcasts AD across vector

plot(x[1:end-1], D_q_x[1:end-1], label = "q' with AD")
plot!(x[1:end-1], q_slopes_x, label = "q slopes")
```

Out[50]:



Consider a variation where we pass a function instead of an `AbstractArray`

In [51]:
```
slopes(f::Function, x::AbstractRange) = diff(f.(x)) / step(x)  #
↪broadcast function

@show typeof(q) <: Function
@show typeof(x) <: AbstractRange
q_slopes_x = slopes(q, x)  # use slopes(f::Function, x)
@show q_slopes_x[1];
```

```
    typeof(q) <: Function = true
typeof(x) <: AbstractRange = true
q_slopes_x[1] = 0.9983341664682815
```

Finally, if `x` was an `AbstractArray` and not an `AbstractRange` we can no longer use a uniform step.

For this, we add in a version calculating slopes with forward first-differences

```
In [52]: # broadcasts over the diff
         slopes(f::Function, x::AbstractArray) = diff(f.(x)) ./ diff(x)

         x_array = Array(x)  # convert range to array
         @show typeof(x_array) <: AbstractArray
         q_slopes_x = slopes(q, x_array)
         @show q_slopes_x[1];
```

```
    typeof(x_array) <: AbstractArray = true
q_slopes_x[1] = 0.9983341664682815
```

In the final example, we see that it is able to use specialized implementations over both the `f` and the `x` arguments.

This is the "multiple" in multiple dispatch.

6.8 Exercises

6.8.1 Exercise 1

Explore the package StaticArrays.jl.

- Describe two abstract types and the hierarchy of three different concrete types.
- Benchmark the calculation of some simple linear algebra with a static array compared to the following for a dense array for `N = 3` and `N = 15`.

```
In [53]: using BenchmarkTools

         N = 3
         A = rand(N, N)
         x = rand(N)

         @btime $A * $x  # the $ in front of variable names is sometimes important
         @btime inv($A)
```

```
    84.900 ns (1 allocation: 112 bytes)
778.746 ns (5 allocations: 1.98 KiB)
```

```
Out[53]: 3×3 Array{Float64,2}:
           0.69559   2.62482  -5.72178
           1.46424  -4.30108   7.48458
          -1.66542   3.15164  -2.70676
```

6.8.2 Exercise 2

A key step in the calculation of the Kalman Filter is calculation of the Kalman gain, as can be seen with the following example using dense matrices from the Kalman lecture.

Using what you learned from Exercise 1, benchmark this using Static Arrays

In [54]:
```
Σ = [0.4  0.3;
     0.3  0.45]
G = I
R = 0.5 * Σ

gain(Σ, G, R) = Σ * G' * inv(G * Σ * G' + R)
@btime gain($Σ, $G, $R)
```

```
    950.875 ns (10 allocations: 1.94 KiB)
```

Out[54]:
```
2×2 Array{Float64,2}:
 0.666667     1.11022e-16
 1.11022e-16  0.666667
```

How many times faster are static arrays in this example?

6.8.3 Exercise 3

The Polynomial.jl provides a package for simple univariate Polynomials.

In [55]:
```
using Polynomials

p = Polynomial([2, -5, 2], :x)  # :x just gives a symbol for display

@show p
p' = derivative(p)   # gives the derivative of p, another polynomial
@show p(0.1), p'(0.1)  # call like a function
@show roots(p);   # find roots such that p(x) = 0
```

```
   p = Polynomial(2 - 5*x + 2*x^2)
(p(0.1), p'(0.1)) = (1.52, -4.6)
roots(p) = [0.5, 2.0]
```

Plot both `p(x)` and `p'(x)` for $x \in [-2, 2]$.

6.8.4 Exercise 4

Use your solution to Exercise 8(a/b) in Introductory Examples to create a specialized version of Newton's method for `Polynomials` using the `derivative` function.

The signature of the function should be `newtonsmethod(p::Polynomial, x_0; tolerance = 1E-7, maxiter = 100)`, where `p::Polynomial` ensures that this version of the function will be used anytime a polynomial is passed (i.e. dispatch).

Compare the results of this function to the built-in `roots(p)` function.

6.8.5 Exercise 5 (Advanced)

The trapezoidal rule approximates an integral with

$$\int_{\underline{x}}^{\bar{x}} f(x)\,dx \approx \sum_{n=1}^{N} \frac{f(x_{n-1}) + f(x_n)}{2} \Delta x_n$$

where $x_0 = \underline{x}$, $x_N = \bar{x}$, and $\Delta x_n \equiv x_{n-1} - x_n$.

Given an `x` and a function `f`, implement a few variations of the trapezoidal rule using multiple dispatch

- `trapezoidal(f, x)` for any `typeof(x) = AbstractArray` and `typeof(f) == AbstractArray` where `length(x) = length(f)`
- `trapezoidal(f, x)` for any `typeof(x) = AbstractRange` and `typeof(f) == AbstractArray` where `length(x) = length(f)`
  - Exploit the fact that `AbstractRange` has constant step sizes to specialize the algorithm
- `trapezoidal(f, x, x̄, N)` where `typeof(f) = Function`, and the other arguments are `Real`
  - For this, build a uniform grid with `N` points on `[x, x̄]` – call the `f` function at those grid points and use the existing `trapezoidal(f, x)` from the implementation

With these: 1. Test each variation of the function with $f(x) = x^2$ with $\underline{x} = 0$, $\bar{x} = 1$. 2. From the analytical solution of the function, plot the error of `trapezoidal(f, x, x̄, N)` relative to the analytical solution for a grid of different `N` values. 3. Consider trying different functions for $f(x)$ and compare the solutions for various `N`.

When trying different functions, instead of integrating by hand consider using a high-accuracy library for numerical integration such as QuadGK.jl

```
In [56]: using QuadGK

         f(x) = x^2
         value, accuracy = quadgk(f, 0.0, 1.0)
```

```
Out[56]: (0.3333333333333333, 5.551115123125783e-17)
```

6.8.6 Exercise 6 (Advanced)

Take a variation of your code in Exercise 5.

Use auto-differentiation to calculate the following derivative for the example functions

$$\frac{d}{d\bar{x}} \int_{\underline{x}}^{\bar{x}} f(x)\,dx$$

Hint: See the following code for the general pattern, and be careful to follow the rules for generic programming.

In [57]:
```
using ForwardDiff

function f(a, b; N = 50)
    r = range(a, b, length=N) # one
return mean(r)
end

Df(x) = ForwardDiff.derivative(y -> f(0.0, y), x)

@show f(0.0, 3.0)
@show f(0.0, 3.1)

Df(3.0)
```

```
  f(0.0, 3.0) = 1.5
f(0.0, 3.1) = 1.55
```

Out[57]: 0.5

Part II

Packages and Software Engineering in Julia

Chapter 7

Generic Programming

7.1 Contents

> I find OOP methodologically wrong. It starts with classes. It is as if mathematicians would start with axioms. You do not start with axioms - you start with proofs. Only when you have found a bunch of related proofs, can you come up with axioms. You end with axioms. The same thing is true in programming: you have to start with interesting algorithms. Only when you understand them well, can you come up with an interface that will let them work. – Alexander Stepanov

7.2 Overview

In this lecture we delve more deeply into the structure of Julia, and in particular into

- abstract and concrete types
- the type tree
- designing and using generic interfaces
- the role of generic interfaces in Julia performance

Understanding them will help you

- form a "mental model" of the Julia language
- design code that matches the "white-board" mathematics
- create code that can use (and be used by) a variety of other packages
- write "well organized" Julia code that's easy to read, modify, maintain and debug
- improve the speed at which your code runs

(Special thank you to Jeffrey Sarnoff)

7.2.1 Generic Programming is an Attitude

From *Mathematics to Generic Programming* [99]

> Generic programming is an approach to programming that focuses on designing algorithms and data structures so that they work in the most general setting without loss of efficiency… Generic programming is more of an *attitude* toward programming than a particular set of tools.

In that sense, it is important to think of generic programming as an interactive approach to uncover generality without compromising performance rather than as a set of rules.

As we will see, the core approach is to treat data structures and algorithms as loosely coupled, and is in direct contrast to the is-a approach of object-oriented programming.

This lecture has the dual role of giving an introduction into the design of generic algorithms and describing how Julia helps make that possible.

7.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Plots, QuadGK, Polynomials, Interpolations
        gr(fmt = :png);
```

7.3 Exploring Type Trees

The connection between data structures and the algorithms which operate on them is handled by the type system.

Concrete types (i.e., `Float64` or `Array{Float64, 2}`) are the data structures we apply an algorithm to, and the abstract types (e.g. the corresponding `Number` and `AbstractArray`) provide the mapping between a set of related data structures and algorithms.

```
In [3]: using Distributions
        x = 1
        y = Normal()
        z = "foo"
        @show x, y, z
        @show typeof(x), typeof(y), typeof(z)
        @show supertype(typeof(x))

        # pipe operator, |>, is is equivalent
        @show typeof(x) |> supertype
        @show supertype(typeof(y))
        @show typeof(z) |> supertype
        @show typeof(x) <: Any;
```

```
    (x, y, z) = (1, Normal{Float64}(μ=0.0, σ=1.0), "foo")
(typeof(x), typeof(y), typeof(z)) = (Int64, Normal{Float64}, String)
supertype(typeof(x)) = Signed
typeof(x) |> supertype = Signed
supertype(typeof(y)) = Distribution{Univariate,Continuous}
typeof(z) |> supertype = AbstractString
typeof(x) <: Any = true
```

Beyond the `typeof` and `supertype` functions, a few other useful tools for analyzing the tree of types are discussed in the introduction to types lecture

In [4]:
```
using Base: show_supertypes # import the function from the `Base` package

show_supertypes(Int64)
```

```
Int64 <: Signed <: Integer <: Real <: Number <: Any
```

In [5]:
```
subtypes(Integer)
```

Out[5]:
```
4-element Array{Any,1}:
 Bool
 GeometryTypes.OffsetInteger
 Signed
 Unsigned
```

Using the `subtypes` function, we can write an algorithm to traverse the type tree below any time `t` – with the confidence that all types support `subtypes`

In [6]:
```
#  from https://github.com/JuliaLang/julia/issues/24741
function subtypetree(t, level=1, indent=4)
        if level == 1
            println(t)
        end
        for s in subtypes(t)
          println(join(fill(" ", level * indent)) * string(s))  # print type
            subtypetree(s, level+1, indent)  # recursively print the next
↪type,
indenting
        end
    end
```

Out[6]:
```
subtypetree (generic function with 3 methods)
```

Applying this to `Number`, we see the tree of types currently loaded

In [7]:
```
subtypetree(Number) # warning: do not use this function on ``Any``!
```

```
Number
Complex
Real
    AbstractFloat
        BigFloat
```

```
            Float16
            Float32
            Float64
        AbstractIrrational
            Irrational
        FixedPointNumbers.FixedPoint
            FixedPointNumbers.Fixed
            FixedPointNumbers.Normed
        Integer
            Bool
            GeometryTypes.OffsetInteger
            Signed
                BigInt
                Int128
                Int16
                Int32
                Int64
                Int8
            Unsigned
                UInt128
                UInt16
                UInt32
                UInt64
                UInt8
        Rational
        Ratios.SimpleRatio
        StatsBase.TestStat
```

For the most part, all of the "leaves" will be concrete types.

7.3.1 Any

At the root of all types is `Any`

There are a few functions that work in the "most generalized" context: usable with anything that you can construct or access from other packages.

We have already called `typeof`, `show` and `supertype` – which will apply to a custom `struct` type since `MyType <: Any`

```
In [8]: # custom type
        struct MyType
            a::Float64
        end

        myval = MyType(2.0)
        @show myval
        @show typeof(myval)
        @show supertype(typeof(myval))
        @show typeof(myval) <: Any;
```

```
    myval = MyType(2.0)
typeof(myval) = MyType
supertype(typeof(myval)) = Any
typeof(myval) <: Any = true
```

Here we see another example of generic programming: every type `<: Any` supports the `@show` macro, which in turn, relies on the `show` function.

The `@show` macro (1) prints the expression as a string; (2) evaluates the expression; and (3) calls the `show` function on the returned values.

To see this with built-in types

```
In [9]: x = [1, 2]
        show(x)
```

```
    [1, 2]
```

The `Any` type is useful, because it provides a fall-back implementation for a variety of functions.

Hence, calling `show` on our custom type dispatches to the fallback function

```
In [10]: myval = MyType(2.0)
         show(myval)
```

```
    MyType(2.0)
```

The default fallback implementation used by Julia would be roughly equivalent to

```
function show(io::IO, x)
    str = string(x)
    print(io, str)
end
```

To implement a specialized implementation of the `show` function for our type, rather than using this fallback

```
In [11]: import Base.show  # to extend an existing function

         function show(io::IO, x::MyType)
             str = "(MyType.a = $(x.a))"  # custom display
             print(io, str)
         end
         show(myval)  # it creates an IO value first and then calls the above show
```

```
    (MyType.a = 2.0)
```

At that point, we can use the `@show` macro, which in turn calls `show`

```
In [12]: @show myval;
```

```
    myval = (MyType.a = 2.0)
```

Here we see another example of generic programming: any type with a `show` function works with `@show`.

Layering of functions (e.g. `@show` calling `show`) with a "fallback" implementation makes it possible for new types to be designed and only specialized where necessary.

7.3.2 Unlearning Object Oriented (OO) Programming (Advanced)

See Types for more on OO vs. generic types.

If you have never used programming languages such as C++, Java, and Python, then the type hierarchies above may seem unfamiliar and abstract.

In that case, keep an open mind that this discussion of abstract concepts will have practical consequences, but there is no need to read this section.

Otherwise, if you have used object-oriented programming (OOP) in those languages, then some of the concepts in these lecture notes will appear familiar.

Don't be fooled!

The superficial similarity can lead to misuse: types are *not* classes with poor encapsulation, and methods are *not* the equivalent to member functions with the order of arguments swapped.

In particular, previous OO knowledge often leads people to write Julia code such as

```
In [13]: # BAD! Replicating an OO design in Julia
         mutable struct MyModel
             a::Float64
             b::Float64
             algorithmcalculation::Float64

             MyModel(a, b) = new(a, b, 0.0) # an inner constructor
         end

         function myalgorithm!(m::MyModel, x)
             m.algorithmcalculation = m.a + m.b + x # some algorithm
         end

         function set_a!(m::MyModel, a)
             m.a = a
         end

         m = MyModel(2.0, 3.0)
         x = 0.1
         set_a!(m, 4.1)
         myalgorithm!(m, x)
         @show m.algorithmcalculation;
```

```
m.algorithmcalculation = 7.199999999999999
```

You may think to yourself that the above code is similar to OO, except that you * reverse the first argument, i.e., `myalgorithm!(m, x)` instead of the object-oriented `m.myalgorithm!(x)` * cannot control encapsulation of the fields `a`, `b`, but you can add getter/setters like `set_a` * do not have concrete inheritance

While this sort of programming is possible, it is (verbosely) missing the point of Julia and the power of generic programming.

When programming in Julia

- there is no encapsulation and most custom types you create will be immutable.

- Polymorphism is achieved without anything resembling OOP inheritance.
- Abstraction is implemented by keeping the data and algorithms that operate on them as orthogonal as possible – in direct contrast to OOP's association of algorithms and methods directly with a type in a tree.
- The supertypes in Julia are simply used for selecting which specialized algorithm to use (i.e., part of generic polymorphism) and have nothing to do with OO inheritance.
- The looseness that accompanies keeping algorithms and data structures as orthogonal as possible makes it easier to discover commonality in the design.

Iterative Design of Abstractions

As its essence, the design of generic software is that you will start with creating algorithms which are largely orthogonal to concrete types.

In the process, you will discover commonality which leads to abstract types with informally defined functions operating on them.

Given the abstract types and commonality, you then refine the algorithms as they are more limited or more general than you initially thought.

This approach is in direct contrast to object-oriented design and analysis (OOAD).

With that, where you specify a taxonomies of types, add operations to those types, and then move down to various levels of specialization (where algorithms are embedded at points within the taxonomy, and potentially specialized with inheritance).

In the examples that follow, we will show for exposition the hierarchy of types and the algorithms operating on them, but the reality is that the algorithms are often designed first, and the abstact types came later.

7.4 Distributions

First, consider working with "distributions".

Algorithms using distributions might (1) draw random numbers for Monte-Carlo methods; and (2) calculate the pdf or cdf – if it is defined.

The process of using concrete distributions in these sorts of applications led to the creation of the Distributions.jl package.

Let's examine the tree of types for a Normal distribution

```
In [14]: using Distributions
         d1 = Normal(1.0, 2.0) # an example type to explore
         @show d1
         show_supertypes(typeof(d1))
```

```
    d1 = Normal{Float64}(μ=1.0, σ=2.0)
Normal{Float64} <: Distribution{Univariate,Continuous} <:
Sampleable{Univariate,Continuous} <: Any
```

The `Sampleable{Univariate,Continuous}` type has a limited number of functions, chiefly the ability to draw a random number

```
In [15]: @show rand(d1);
```

```
rand(d1) = -3.8524551916467678
```

The purpose of that abstract type is to provide an interface for drawing from a variety of distributions, some of which may not have a well-defined predefined pdf.

If you were writing a function to simulate a stochastic process with arbitrary iid shocks, where you did not need to assume an existing pdf etc., this is a natural candidate.

For example, to simulate $x_{t+1} = ax_t + b\epsilon_{t+1}$ where $\epsilon \sim D$ for some D, which allows drawing random values.

```
In [16]: function simulateprocess(x₀; a = 1.0, b = 1.0, N = 5,
         d::Sampleable{Univariate,Continuous})
             x = zeros(typeof(x₀), N+1) # preallocate vector, careful on the type
             x[1] = x₀
             for t in 2:N+1
                 x[t] = a * x[t-1] + b * rand(d) # draw
             end
             return x
         end
         @show simulateprocess(0.0, d=Normal(0.2, 2.0));
```

```
simulateprocess(0.0, d = Normal(0.2, 2.0)) = [0.0, -2.2517753336924105,
-1.499729413286212, -3.5981086351011697, -2.892126808220728, -5.758551572845958]
```

The `Sampleable{Univariate,Continuous}` and, especially, the `Sampleable{Multivariate,Continuous}` abstract types are useful generic interfaces for Monte-Carlo and Bayesian methods.

Moving down the tree, the `Distributions{Univariate, Continuous}` abstract type has other functions we can use for generic algorithms operating on distributions.

These match the mathematics, such as `pdf`, `cdf`, `quantile`, `support`, `minimum`, `maximum`, etc.

```
In [17]: d1 = Normal(1.0, 2.0)
         d2 = Exponential(0.1)
         @show d1
         @show d2
         @show supertype(typeof(d1))
         @show supertype(typeof(d2))

         @show pdf(d1, 0.1)
         @show pdf(d2, 0.1)
         @show cdf(d1, 0.1)
         @show cdf(d2, 0.1)
         @show support(d1)
         @show support(d2)
         @show minimum(d1)
         @show minimum(d2)
         @show maximum(d1)
         @show maximum(d2);
```

```
    d1 = Normal{Float64}(μ=1.0, σ=2.0)
d2 = Exponential{Float64}(θ=0.1)
supertype(typeof(d1)) = Distribution{Univariate,Continuous}
supertype(typeof(d2)) = Distribution{Univariate,Continuous}
pdf(d1, 0.1) = 0.18026348123082397
pdf(d2, 0.1) = 3.6787944117144233
cdf(d1, 0.1) = 0.32635522028792
cdf(d2, 0.1) = 0.6321205588285577
support(d1) = RealInterval(-Inf, Inf)
support(d2) = RealInterval(0.0, Inf)
minimum(d1) = -Inf
minimum(d2) = 0.0
maximum(d1) = Inf
maximum(d2) = Inf
```

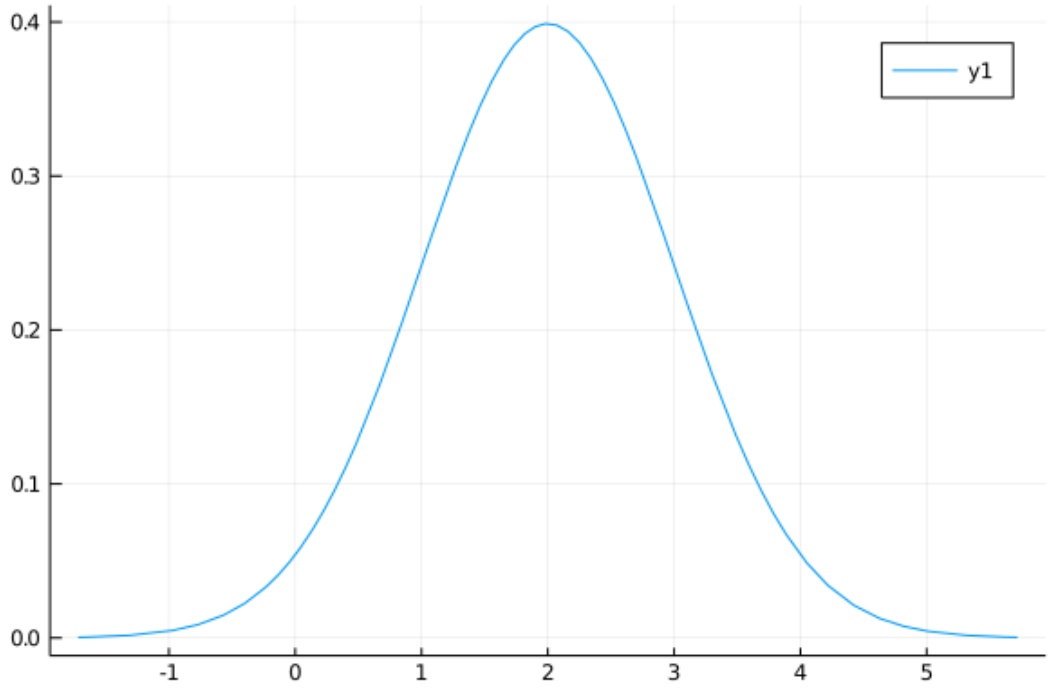
You could create your own `Distributions{Univariate, Continuous}` type by implementing those functions – as is described in the documentation.

If you fulfill all of the conditions of a particular interface, you can use algorithms from the present, past, and future that are written for the abstract `Distributions{Univariate, Continuous}` type.

As an example, consider the StatsPlots package

In [18]:
```
using StatsPlots
d = Normal(2.0, 1.0)
plot(d) # note no other arguments!
```

Out[18]:



Calling `plot` on any subtype of `Distributions{Univariate, Continuous}` displays the `pdf` and uses `minimum` and `maximum` to determine the range.

Let's create our own distribution type

```
In [19]: struct OurTruncatedExponential <: Distribution{Univariate,Continuous}
             α::Float64
             xmax::Float64
         end
         Distributions.pdf(d::OurTruncatedExponential, x) = d.α *exp(-d.α * x)/
 ↪exp(-d.α * d.xmax)
         Distributions.minimum(d::OurTruncatedExponential) = 0
         Distributions.maximum(d::OurTruncatedExponential) = d.xmax
         # ... more to have a complete type
```

To demonstrate this

```
In [20]: d = OurTruncatedExponential(1.0,2.0)
         @show minimum(d), maximum(d)
         @show support(d) # why does this work?
```

```
(minimum(d), maximum(d)) = (0, 2.0)
support(d) = RealInterval(0.0, 2.0)
```

```
Out[20]: RealInterval(0.0, 2.0)
```

Curiously, you will note that the `support` function works, even though we did not provide one.

This is another example of the power of multiple dispatch and generic programming.

In the background, the `Distributions.jl` package has something like the following implemented

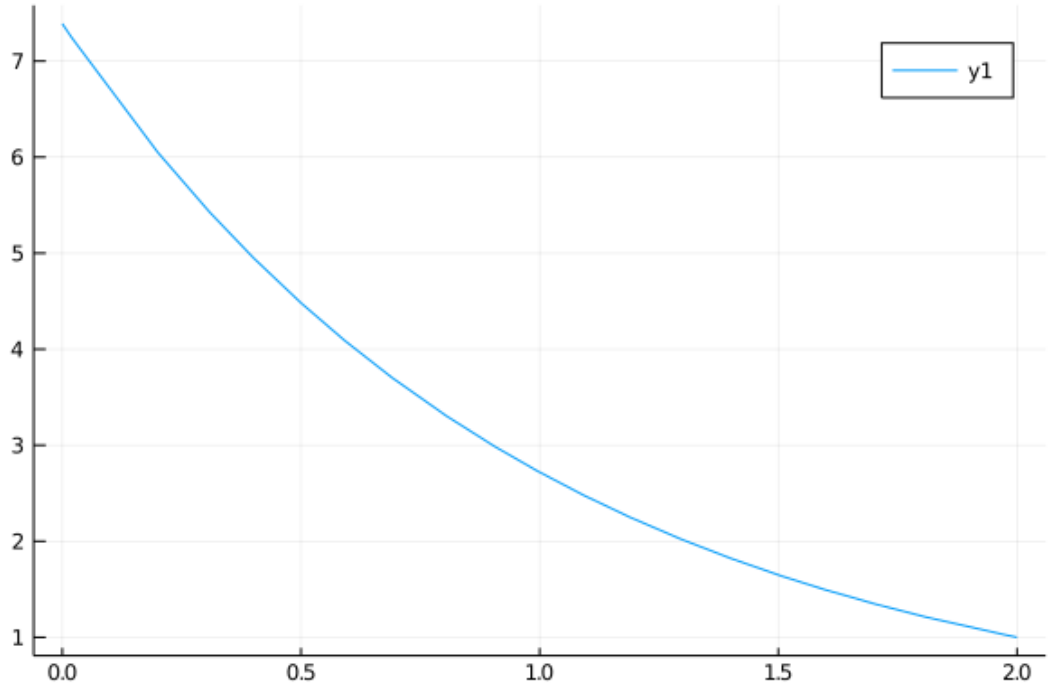
```
Distributions.support(d::Distribution) = RealInterval(minimum(d), maximum(d)
```

Since `OurTruncatedExponential <: Distribution`, and we implemented `minimum` and `maximum`, calls to `support` get this implementation as a fallback.

These functions are enough to use the `StatsPlots.jl` package

```
In [21]: plot(d) # uses the generic code!
```

```
Out[21]:
```



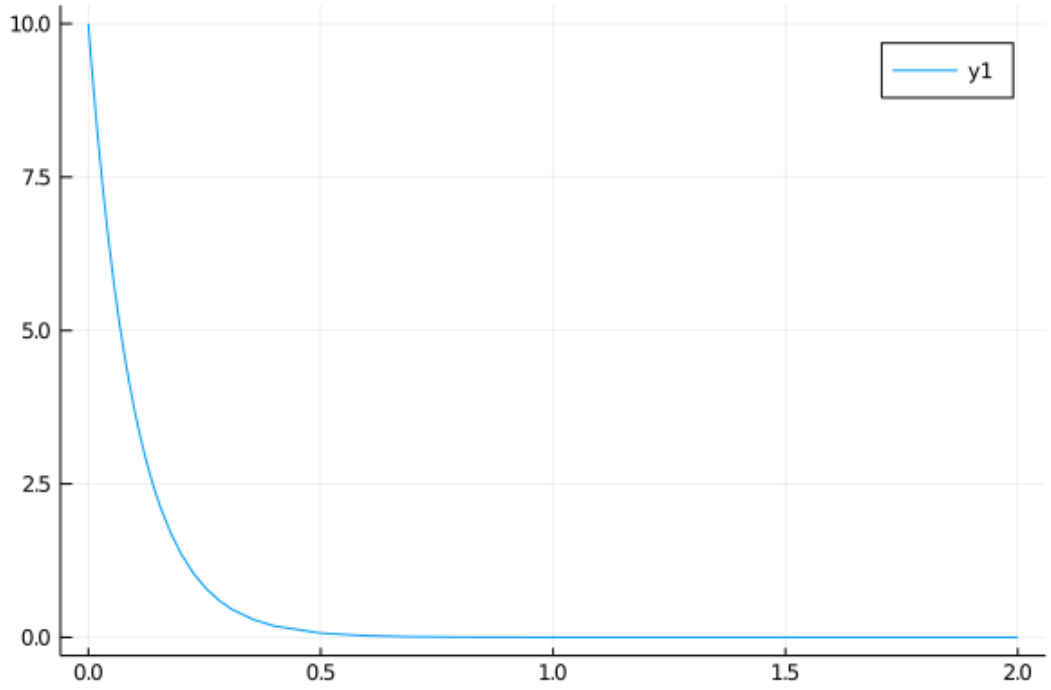
A few things to point out

- Even if it worked for `StatsPlots`, our implementation is incomplete, as we haven't fulfilled all of the requirements of a `Distribution`.
- We also did not implement the `rand` function, which means we are breaking the implicit contract of the `Sampleable` abstract type.
- It turns out that there is a better way to do this precise thing already built into `Distributions`.

```
In [22]: d = Truncated(Exponential(0.1), 0.0, 2.0)
         @show typeof(d)
         plot(d)
```

```
typeof(d) = Truncated{Exponential{Float64},Continuous,Float64}
```

Out[22]:



This is the power of generic programming in general, and Julia in particular: you can combine and compose completely separate packages and code, as long as there is an agreement on abstract types and functions.

7.5 Numbers and Algebraic Structures

Define two binary functions, $+$ and $\cdot$, called addition and multiplication – although the operators can be applied to data structures much more abstract than a `Real`.

In mathematics, a ring is a set with associated additive and multiplicative operators where

- the additive operator is associative and commutative
- the multiplicative operator is associative and distributive with respect to the additive operator
- there is an additive identity element, denoted 0, such that $a + 0 = a$ for any a in the set
- there is an additive inverse of each element, denoted $-a$, such that $a + (-a) = 0$
- there is a multiplicative identity element, denoted 1, such that $a \cdot 1 = a = 1 \cdot a$
- a total or partial ordering is **not** required (i.e., there does not need to be any meaningful $<$ operator defined)
- a multiplicative inverse is **not** required

While this skips over some parts of the mathematical definition, this algebraic structure provides motivation for the abstract `Number` type in Julia

- **Remark:** We use the term "motivation" because they are not formally connected and the mapping is imperfect.

- The main difficulty when dealing with numbers that can be concretely created on a computer is that the requirement that the operators are closed in the set are difficult to ensure (e.g. floating points have finite numbers of bits of information).

Let `typeof(a) = typeof(b) = T <: Number`, then under an informal definition of the **generic interface** for `Number`, the following must be defined

- the additive operator: `a + b`
- the multiplicative operator: `a * b`
- an additive inverse operator: `-a`
- an inverse operation for addition `a - b = a + (-b)`
- an additive identity: `zero(T)` or `zero(a)` for convenience
- a multiplicative identity: `one(T)` or `one(a)` for convenience

The core of generic programming is that, given the knowledge that a value is of type `Number`, we can design algorithms using any of these functions and not concern ourselves with the particular concrete type.

Furthermore, that generality in designing algorithms comes with no compromises on performance compared to carefully designed algorithms written for that particular type.

To demonstrate this for a complex number, where `Complex{Float64} <: Number`

```
In [23]: a = 1.0 + 1.0im
         b = 0.0 + 2.0im
         @show typeof(a)
         @show typeof(a) <: Number
         @show a + b
         @show a * b
         @show -a
         @show a - b
         @show zero(a)
         @show one(a);
```

```
    typeof(a) = Complex{Float64}
typeof(a) <: Number = true
a + b = 1.0 + 3.0im
a * b = -2.0 + 2.0im
-a = -1.0 - 1.0im
a - b = 1.0 - 1.0im
zero(a) = 0.0 + 0.0im
one(a) = 1.0 + 0.0im
```

And for an arbitrary precision integer where `BigInt <: Number` (i.e., a different type than the `Int64` you have worked with, but nevertheless a `Number`)

```
In [24]: a = BigInt(10)
         b = BigInt(4)
         @show typeof(a)
         @show typeof(a) <: Number
         @show a + b
         @show a * b
         @show -a
         @show a - b
         @show zero(a)
         @show one(a);
```

```
    typeof(a) = BigInt
typeof(a) <: Number = true
```

```
a + b = 14
a * b = 40
-a = -10
a - b = 6
zero(a) = 0
one(a) = 1
```

7.5.1 Complex Numbers and Composition of Generic Functions

This allows us to showcase further how different generic packages compose – even if they are only loosely coupled through agreement on common generic interfaces.

The `Complex` numbers require some sort of storage for their underlying real and imaginary parts, which is itself left generic.

This data structure is defined to work with any type `<: Number`, and is parameterized (e.g. `Complex{Float64}` is a complex number storing the imaginary and real parts in `Float64`)

```
In [25]: x = 4.0 + 1.0im
         @show x, typeof(x)

         xbig = BigFloat(4.0) + 1.0im
         @show xbig, typeof(xbig);
```

```
   (x, typeof(x)) = (4.0 + 1.0im, Complex{Float64})
(xbig, typeof(xbig)) = (4.0 + 1.0im, Complex{BigFloat})
```

The implementation of the `Complex` numbers use the underlying operations of storage type, so as long as `+`, `*` etc. are defined – as they should be for any `Number` – the complex operation can be defined

```
In [26]: @which +(x,x)
```

```
Out[26]: +(z::Complex, w::Complex) in Base at complex.jl:275
```

Following that link, the implementation of `+` for complex numbers is

```
+(z::Complex, w::Complex) = Complex(real(z) + real(w), imag(z) + imag(w))
```

`real(z)` and `imag(z)` returns the associated components of the complex number in the underlying storage type (e.g. `Float64` or `BigFloat`).

The rest of the function has been carefully written to use functions defined for any `Number` (e.g. `+` but not `<`, since it is not part of the generic number interface).

To follow another example , look at the implementation of `abs` specialized for complex numbers

```
In [27]: @which abs(x)
```

```
Out[27]: abs(z::Complex) in Base at complex.jl:264
```

The source is

```
abs(z::Complex)  = hypot(real(z), imag(z))
```

In this case, if you look at the generic function to get the hypotenuse, `hypot`, you will see that it has the function signature `hypot(x::T, y::T) where T<:Number`, and hence works for any `Number`.

That function, in turn, relies on the underlying `abs` for the type of `real(z)`.

This would dispatch to the appropriate `abs` for the type

```
In [28]: @which abs(1.0)
```

```
Out[28]: abs(x::Float64) in Base at float.jl:528
```

```
In [29]: @which abs(BigFloat(1.0))
```

```
Out[29]: abs(x::Real) in Base at number.jl:120
```

With implementations

```
abs(x::Real) = ifelse(signbit(x), -x, x)
abs(x::Float64) = abs_float(x)
```

For a `Real` number (which we will discuss in the next section) the fallback implementation calls a function `signbit` to determine if it should flip the sign of the number.

The specialized version for `Float64 <: Real` calls a function called `abs_float` – which turns out to be a specialized implementation at the compiler level.

While we have not completely dissected the tree of function calls, at the bottom of the tree you will end at the most optimized version of the function for the underlying datatype.

Hopefully this showcases the power of generic programming: with a well-designed set of abstract types and functions, the code can both be highly general and composable and still use the most efficient implementation possible.

7.6 Reals and Algebraic Structures

Thinking back to the mathematical motivation, a field is a `ring` with a few additional properties, among them

- a multiplicative inverse: a^{-1}
- an inverse operation for multiplication: $a/b = a \cdot b^{-1}$

Furthermore, we will make it a total ordered field with

- a total ordering binary operator: $a < b$

This type gives some motivation for the operations and properties of the `Real` type.

Of course, `Complex{Float64} <: Number` but not `Real` – since the ordering is not defined for complex numbers in mathematics.

These operations are implemented in any subtype of `Real` through

- the multiplicative inverse: `inv(a)`
- the multiplicative inverse operation: `a / b = a * inv(b)`
- an ordering `a < b`

We have already shown these with the `Float64` and `BigFloat`.

To show this for the `Rational` number type, where `a // b` constructs a rational number $\frac{a}{b}$

```
In [30]: a = 1 // 10
         b = 4 // 6
         @show typeof(a)
         @show typeof(a) <: Number
         @show typeof(a) <: Real
         @show inv(a)
         @show a / b
         @show a < b;
```

```
    typeof(a) = Rational{Int64}
typeof(a) <: Number = true
typeof(a) <: Real = true
inv(a) = 10//1
a / b = 3//20
a < b = true
```

Remark: Here we see where and how the precise connection to the mathematics for number types breaks down for practical reasons, in particular

- `Integer` types (i.e., `Int64 <: Integer`) do not have a a multiplicative inverse with closure in the set.
- However, it is necessary in practice for integer division to be defined, and return back a member of the `Real`'s.
- This is called type promotion, where a type can be converted to another to ensure an operation is possible by direct conversion between types (i.e., it can be independent of the type hierarchy).

Do not think of the break in the connection between the underlying algebraic structures and the code as a failure of the language or design.

Rather, the underlying algorithms for use on a computer do not perfectly fit the algebraic structures in this instance.

Moving further down the tree of types provides more operations more directly tied to the computational implementation than abstract algebra.

For example, floating point numbers have a machine precision, below which numbers become indistinguishable due to lack of sufficient "bits" of information

```
In [31]: @show Float64 <: AbstractFloat
         @show BigFloat <: AbstractFloat
         @show eps(Float64)
         @show eps(BigFloat);
```

```
    Float64 <: AbstractFloat = true
BigFloat <: AbstractFloat = true
eps(Float64) = 2.220446049250313e-16
eps(BigFloat) =
1.72723371101888892507727037256007991422320007288725627700474069403371836063248 5e-
77
```

The `isless` function also has multiple methods.

First let's try with integers

```
In [32]: @which isless(1, 2)
```

```
Out[32]: isless(x::Real, y::Real) in Base at operators.jl:346
```

As we saw previously, the `Real` data type is an *abstract* type, and encompasses both floats and integers.

If we go to the provided link in the source, we see the entirety of the function is

```
isless(x::Real, y::Real) = x<y
```

That is, for any values where `typeof(x) <: Real` and `typeof(y) <: Real`, the definition relies on `<`.

We know that `<` is defined for the types because it is part of the informal interface for the `Real` abstract type.

Note that this is not defined for `Number` because not all `Number` types have the `<` ordering operator defined (e.g. `Complex`).

In order to generate fast code, the implementation details may define specialized versions of these operations.

```
In [33]: isless(1.0, 2.0)  # applied to two floats
         @which isless(1.0, 2.0)
```

```
Out[33]: isless(x::Float64, y::Float64) in Base at float.jl:465
```

Note that the reason `Float64 <: Real` calls this implementation rather than the one given above, is that `Float64 <: Real`, and Julia chooses the most specialized implementation for each function.

The specialized implementations are often more subtle than you may realize due to floating point arithmetic, underflow, etc.

7.7 Functions, and Function-Like Types

Another common example of the separation between data structures and algorithms is the use of functions.

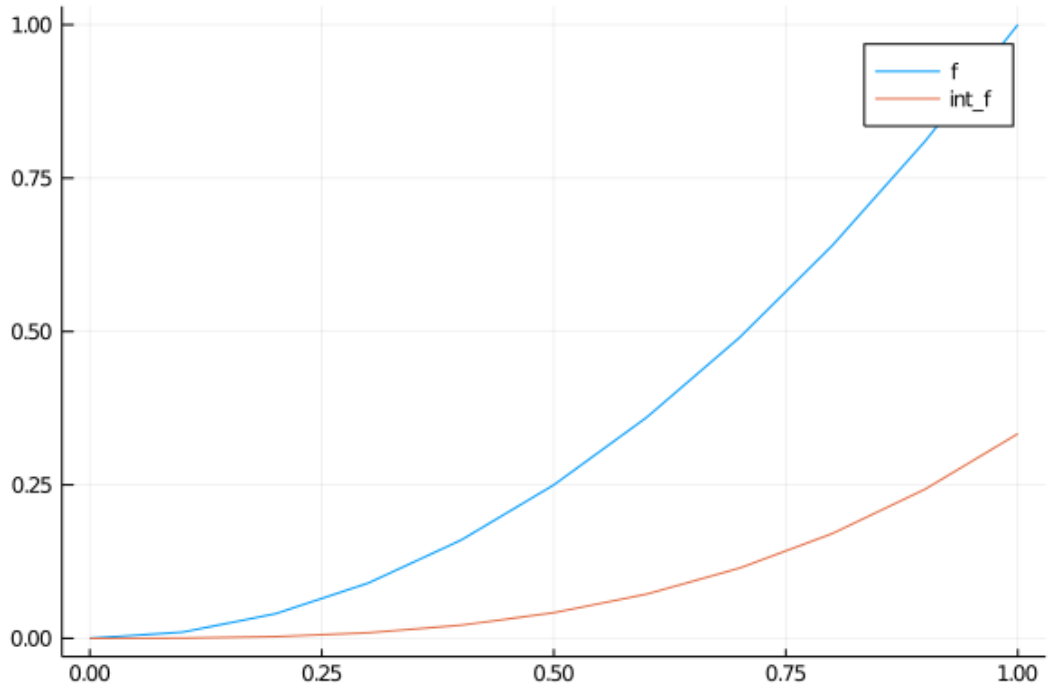
Syntactically, a univariate "function" is any `f` that can call an argument `x` as `f(x)`.

For example, we can use a standard function

In [34]:
```
using QuadGK
f(x) = x^2
@show quadgk(f, 0.0, 1.0)  # integral

function plotfunctions(f)
    intf(x) = quadgk(f, 0.0, x)[1]  # int_0^x f(x) dx

    x = 0:0.1:1.0
    f_x = f.(x)
    plot(x, f_x, label="f")
    plot!(x, intf.(x), label="int_f")
end
plotfunctions(f)  # call with our f
```

```
quadgk(f, 0.0, 1.0) = (0.3333333333333333, 5.551115123125783e-17)
```

Out[34]:



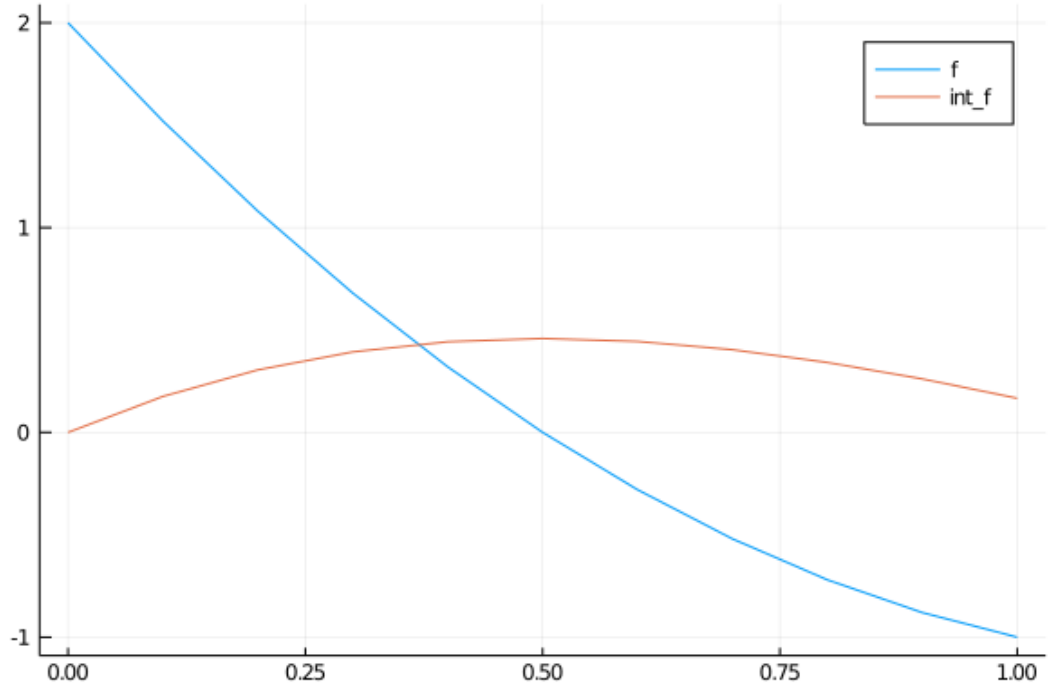
Of course, univariate polynomials are another type of univariate function

In [35]:
```
using Polynomials
p = Polynomial([2, -5, 2], :x)  # :x just gives a symbol for display
```

```
@show p
@show p(1.0) # call like a function

plotfunctions(p)  # same generic function
```

```
   p = Polynomial(2 - 5*x + 2*x^2)
p(1.0) = -1.0
```

Out[35]:

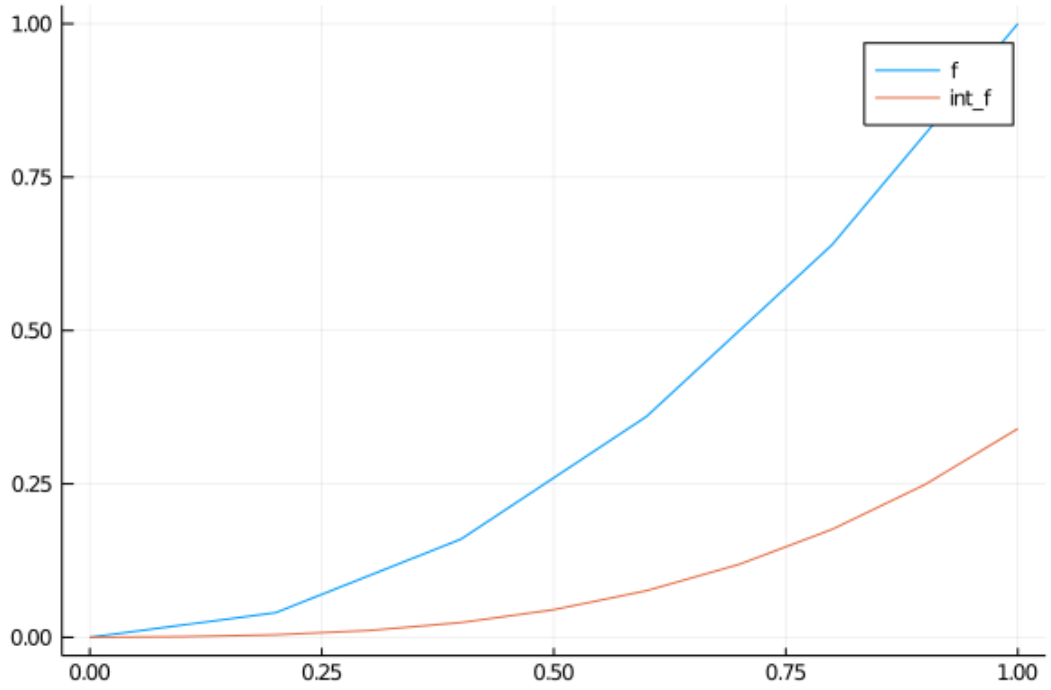


Similarly, the result of interpolating data is also a function

In [36]:
```
using Interpolations
x = 0.0:0.2:1.0
f(x) = x^2
f_int = LinearInterpolation(x, f.(x))  # interpolates the coarse grid
@show f_int(1.0)  # call like a function

plotfunctions(f_int)  # same generic function
```

```
f_int(1.0) = 1.0
```

Out[36]:



Note that the same generic `plotfunctions` could use any variable passed to it that "looks" like a function, i.e., can call `f(x)`.

This approach to design with types – generic, but without any specific type declarations – is called duck typing.

If you need to make an existing type callable, see Function Like Objects.

7.8 Limitations of Dispatching on Abstract Types

You will notice that types in Julia represent a tree with `Any` at the root.

The tree structure has worked well for the above examples, but it doesn't allow us to associate multiple categorizations of types.

For example, a semi-group type would be useful for a writing generic code (e.g. continuous-time solutions for ODEs and matrix-free methods), but cannot be implemented rigorously since the `Matrix` type is a semi-group as well as an `AbstractArray`, but not all semi-groups are `AbstractArray` s.

The main way to implement this in a generic language is with a design approach called "traits".

- See the original discussion and an example of a package to facilitate the pattern.
- A complete description of the traits pattern as the natural evolution of Multiple Dispatch is given in this blog post.

7.9 Exercises

7.9.1 Exercise 1a

In a previous exercise, we discussed the trapezoidal rule for numerical integration.

To summarize, the vector

$$\int_{\underline{x}}^{\bar{x}} f(x)\,dx \approx \omega \cdot \vec{f}$$

where $\vec{f} \equiv \begin{bmatrix} f(x_1) & \dots & f(x_N) \end{bmatrix} \in R^N$ and, for a uniform grid spacing of Δ,

$$\omega \equiv \Delta \begin{bmatrix} \frac{1}{2} & 1 & \dots & 1 & \frac{1}{2} \end{bmatrix} \in R^N$$

The quadrature rule can be implemented easily as

```
In [37]: using LinearAlgebra
         function trap_weights(x)
             return step(x) * [0.5; ones(length(x) - 2); 0.5]
         end
         x = range(0.0, 1.0, length = 100)
         ω = trap_weights(x)
         f(x) = x^2
         dot(f.(x), ω)
```

```
Out[37]: 0.3333503384008434
```

However, in this case the creation of the ω temporary is inefficient as there are no reasons to allocate an entire vector just to iterate through it with the `dot`. Instead, create an iterable by following the interface definition for Iteration, and implement the modified `trap_weights` and integration.

Hint: create a type such as

```
In [38]: struct UniformTrapezoidal
             count::Int
             Δ::Float64
         end
```

and then implement the function `Base.iterate(S::UniformTrapezoidal, state=1)`.

7.9.2 Exercise 1b (Advanced)

Make the `UniformTrapezoidal` type operate as an array with interface definition for AbstractArray. With this, you should be able it go `ω[2]` or `length(ω)` to access the quadrature weights.

7.9.3 Exercise 2 (Advanced)

Implement the same features as Exercise 1a and 1b, but for the non-uniform trapezoidal rule.

Chapter 8

General Purpose Packages

8.1 Contents

8.2 Overview

Julia has both a large number of useful, well written libraries and many incomplete poorly maintained proofs of concept.

A major advantage of Julia libraries is that, because Julia itself is sufficiently fast, there is less need to mix in low level languages like C and Fortran.

As a result, most Julia libraries are written exclusively in Julia.

Not only does this make the libraries more portable, it makes them much easier to dive into, read, learn from and modify.

In this lecture we introduce a few of the Julia libraries that we've found particularly useful for quantitative work in economics.

Also see data and statistical packages and optimization, solver, and related packages for more domain specific packages.

8.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using QuantEcon, QuadGK, FastGaussQuadrature, Distributions, Expectations
        using Interpolations, Plots, LaTeXStrings, ProgressMeter
```

8.3 Numerical Integration

Many applications require directly calculating a numerical derivative and calculating expectations.

8.3.1 Adaptive Quadrature

A high accuracy solution for calculating numerical integrals is QuadGK.

```
In [3]: using QuadGK
        @show value, tol = quadgk(cos, -2π, 2π);
```

```
    (value, tol) = quadgk(cos, -2π, 2π) = (-1.5474478810961125e-14,
5.7846097329025695e-24)
```

This is an adaptive Gauss-Kronrod integration technique that's relatively accurate for smooth functions.

However, its adaptive implementation makes it slow and not well suited to inner loops.

8.3.2 Gaussian Quadrature

Alternatively, many integrals can be done efficiently with (non-adaptive) Gaussian quadrature.

For example, using FastGaussQuadrature.jl

```
In [4]: using FastGaussQuadrature
        x, w = gausslegendre( 100_000 ); # i.e. find 100,000 nodes

        # integrates f(x) = x^2 from -1 to 1
        f(x) = x^2
        @show w ⋅ f.(x); # calculate integral
```

```
    w ⋅ f.(x) = 0.6666666666666667
```

The only problem with the `FastGaussQuadrature` package is that you will need to deal with affine transformations to the non-default domains yourself.

Alternatively, `QuantEcon.jl` has routines for Gaussian quadrature that translate the domains.

```
In [5]: using QuantEcon

        x, w = qnwlege(65, -2π, 2π);
        @show w ⋅ cos.(x); # i.e. on [-2π, 2π] domain
```

```
    w ⋅ cos.(x) = -3.0064051806277455e-15
```

8.3.3 Expectations

If the calculations of the numerical integral is simply for calculating mathematical expectations of a particular distribution, then Expectations.jl provides a convenient interface.

Under the hood, it is finding the appropriate Gaussian quadrature scheme for the distribution using `FastGaussQuadrature`.

In [6]:
```
using Distributions, Expectations
dist = Normal()
E = expectation(dist)
f(x) = x
@show E(f) #i.e. identity

# Or using as a linear operator
f(x) = x^2
x = nodes(E)
w = weights(E)
E * f.(x) == f.(x)  w
```

```
E(f) = -6.991310601309959e-18
```

Out[6]:
```
true
```

8.4 Interpolation

In economics we often wish to interpolate discrete data (i.e., build continuous functions that join discrete sequences of points).

The package we usually turn to for this purpose is Interpolations.jl.

There are a variety of options, but we will only demonstrate the convenient notations.

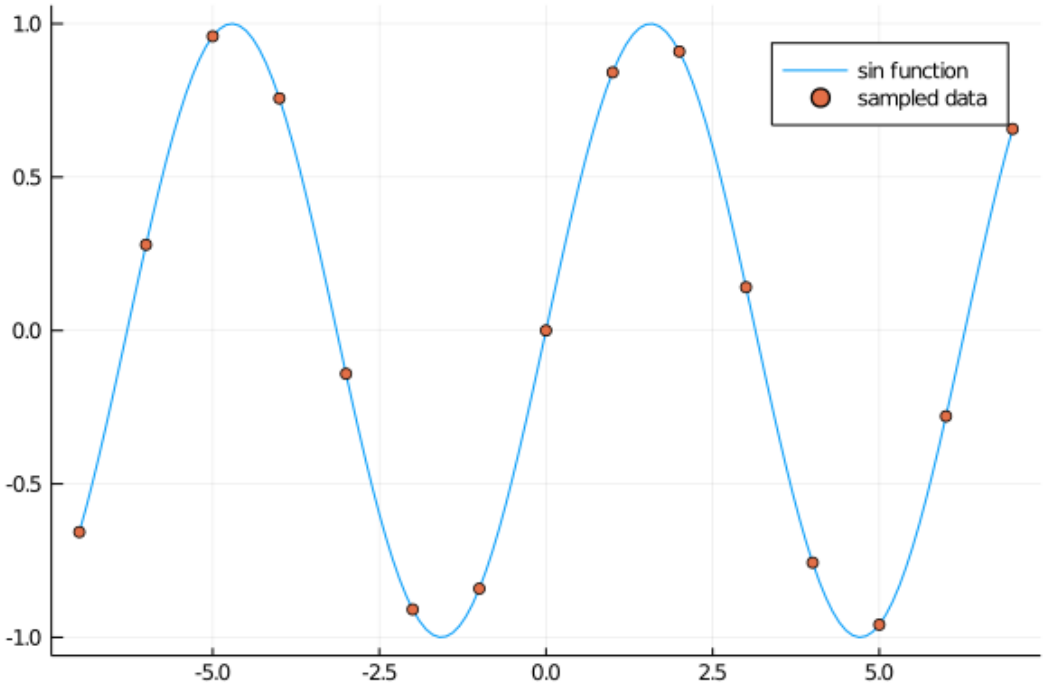
8.4.1 Univariate with a Regular Grid

Let's start with the univariate case.

We begin by creating some data points, using a sine function

In [7]:
```
using Interpolations
using Plots
gr(fmt=:png);

x = -7:7 # x points, coase grid
y = sin.(x) # corresponding y points

xf = -7:0.1:7        # fine grid
plot(xf, sin.(xf), label = "sin function")
scatter!(x, y, label = "sampled data", markersize = 4)
```

Out[7]:

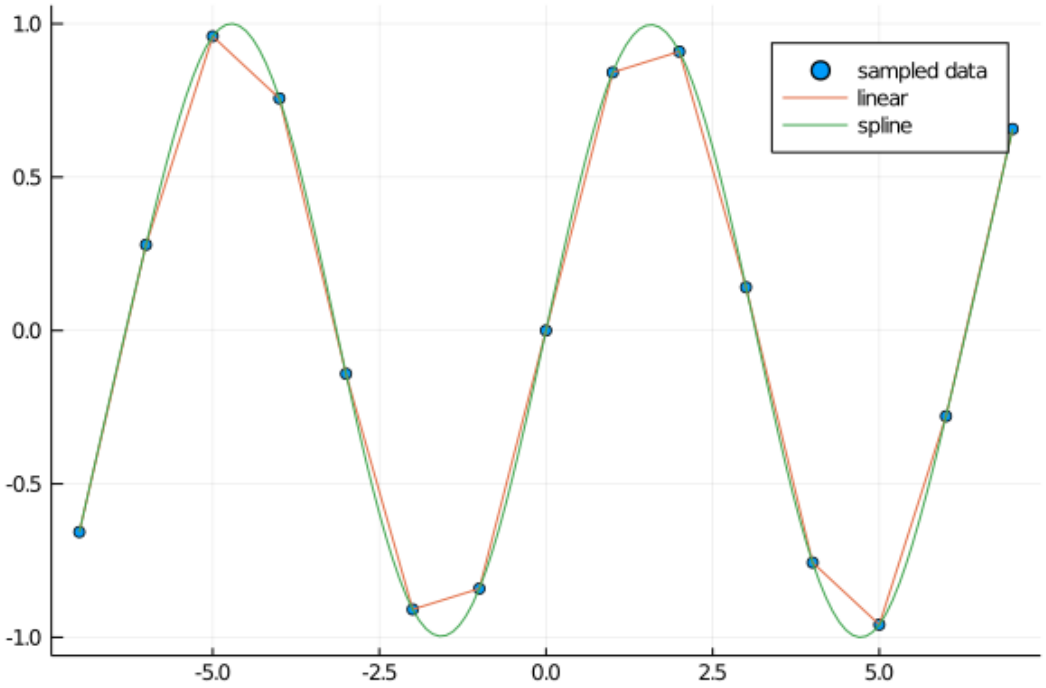


To implement linear and cubic spline interpolation

In [8]:
```
li = LinearInterpolation(x, y)
li_spline = CubicSplineInterpolation(x, y)

@show li(0.3) # evaluate at a single point

scatter(x, y, label = "sampled data", markersize = 4)
plot!(xf, li.(xf), label = "linear")
plot!(xf, li_spline.(xf), label = "spline")
```

```
li(0.3) = 0.25244129544236954
```

Out[8]:



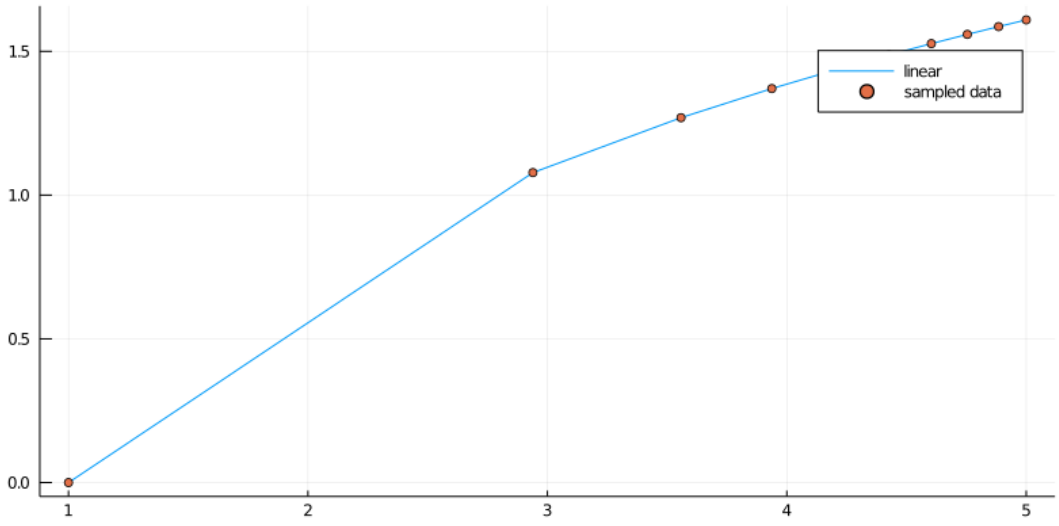
8.4.2 Univariate with Irregular Grid

In the above, the `LinearInterpolation` function uses a specialized function for regular grids since `x` is a `Range` type.

For an arbitrary, irregular grid

```
In [9]: x = log.(range(1, exp(4), length = 10)) .+ 1  # uneven grid
        y = log.(x) # corresponding y points

        interp = LinearInterpolation(x, y)

        xf = log.(range(1,  exp(4), length = 100)) .+ 1 # finer grid

        plot(xf, interp.(xf), label = "linear")
        scatter!(x, y, label = "sampled data", markersize = 4, size = (800, 400))
```

```
Out[9]:
```



At this point, `Interpolations.jl` does not have support for cubic splines with irregular grids, but there are plenty of other packages that do (e.g. Dierckx.jl and GridInterpolations.jl).

8.4.3 Multivariate Interpolation

Interpolating a regular multivariate function uses the same function

In [10]:
```
f(x,y) = log(x+y)
xs = 1:0.2:5
ys = 2:0.1:5
A = [f(x,y) for x in xs, y in ys]

# linear interpolation
interp_linear = LinearInterpolation((xs, ys), A)
@show interp_linear(3, 2) # exactly log(3 + 2)
@show interp_linear(3.1, 2.1) # approximately log(3.1 + 2.1)

# cubic spline interpolation
interp_cubic = CubicSplineInterpolation((xs, ys), A)
@show interp_cubic(3, 2) # exactly log(3 + 2)
@show interp_cubic(3.1, 2.1) # approximately log(3.1 + 2.1);
```

```
   interp_linear(3, 2) = 1.6094379124341003
interp_linear(3.1, 2.1) = 1.6484736801441782
interp_cubic(3, 2) = 1.6094379124341
interp_cubic(3.1, 2.1) = 1.6486586594237707
```

See Interpolations.jl documentation for more details on options and settings.

8.5 Linear Algebra

8.5.1 Standard Library

The standard library contains many useful routines for linear algebra, in addition to standard functions such as `det()`, `inv()`, `factorize()`, etc.

Routines are available for

- Cholesky factorization
- LU decomposition
- Singular value decomposition,
- Schur factorization, etc.

See here for further details.

8.6 General Tools

8.6.1 LaTeXStrings.jl

When you need to properly escape latex code (e.g. for equation labels), use LaTeXStrings.jl.

```
In [11]: using LaTeXStrings
         L"an equation: $1 + \alpha^2$"
```

```
Out[11]: an equation: 1 + α²
```

8.6.2 ProgressMeter.jl

For long-running operations, you can use the ProgressMeter.jl package.

To use the package, you simply put a macro in front of `for` loops, etc.

From the documentation

```
In [12]: using ProgressMeter

         @showprogress 1 "Computing..." for i in 1:50
             sleep(0.1) # some computation....
         end
```

```
Computing…100%|████████████████████████████████████| Time: 0:00:05
```

Chapter 9

Data and Statistics Packages

9.1 Contents

9.2 Overview

This lecture explores some of the key packages for working with data and doing statistics in Julia.

In particular, we will examine the `DataFrame` object in detail (i.e., construction, manipulation, querying, visualization, and nuances like missing data).

While Julia is not an ideal language for pure cookie-cutter statistical analysis, it has many useful packages to provide those tools as part of a more general solution.

This list is not exhaustive, and others can be found in organizations such as JuliaStats, JuliaData, and QueryVerse.

9.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using DataFrames, RDatasets, DataFramesMeta, CategoricalArrays, Query,
  ↪VegaLite
        using GLM
```

9.3 DataFrames

A useful package for working with data is DataFrames.jl.

The most important data type provided is a `DataFrame`, a two dimensional array for storing heterogeneous data.

Although data can be heterogeneous within a `DataFrame`, the contents of the columns must be homogeneous (of the same type).

This is analogous to a `data.frame` in R, a `DataFrame` in Pandas (Python) or, more loosely, a spreadsheet in Excel.

There are a few different ways to create a DataFrame.

9.3.1 Constructing and Accessing a DataFrame

The first is to set up columns and construct a dataframe by assigning names

```
In [3]: using DataFrames, RDatasets  # RDatasets provides good standard data
  ↪examples from R

        # note use of missing
        commodities = ["crude", "gas", "gold", "silver"]
        last_price = [4.2, 11.3, 12.1, missing]
        df = DataFrame(commod = commodities, price = last_price)
```

```
Out[3]: \begin{tabular}{r|cc}
               & commod & price\\
               \hline
               & String & Float64?\\
               \hline
               1 & crude & 4.2 \\
               2 & gas & 11.3 \\
               3 & gold & 12.1 \\
               4 & silver & \emph{missing} \\
       \end{tabular}
```

Columns of the `DataFrame` can be accessed by name using `df.col`, as below

```
In [4]: df.price
```

```
Out[4]: 4-element Array{Union{Missing, Float64},1}:
          4.2
         11.3
         12.1
           missing
```

Note that the type of this array has values `Union{Missing, Float64}` since it was created with a `missing` value.

```
In [5]: df.commod
```

```
Out[5]: 4-element Array{String,1}:
         "crude"
         "gas"
         "gold"
         "silver"
```

The `DataFrames.jl` package provides a number of methods for acting on `DataFrame`'s, such as `describe`.

```
In [6]: DataFrames.describe(df)
```

```
Out[6]: \begin{tabular}{r|cccccccc}
        & variable & mean & min & median & max & nunique & nmissing & eltype\\
        \hline
        & Symbol & …Union & Any & …Union & Any & …Union & …Union & Type\\
        \hline
        1 & commod &  & crude &  & silver & 4 &  & String \\
        2 & price & 9.2 & 4.2 & 11.3 & 12.1 &  & 1 & Union\{Missing, Float64\} \\
\end{tabular}
```

While often data will be generated all at once, or read from a file, you can add to a `DataFrame` by providing the key parameters.

```
In [7]: nt = (commod = "nickel", price= 5.1)
        push!(df, nt)
```

```
Out[7]: \begin{tabular}{r|cc}
        & commod & price\\
        \hline
        & String & Float64?\\
        \hline
        1 & crude & 4.2 \\
        2 & gas & 11.3 \\
        3 & gold & 12.1 \\
        4 & silver & \emph{missing} \\
        5 & nickel & 5.1 \\
\end{tabular}
```

Named tuples can also be used to construct a `DataFrame`, and have it properly deduce all types.

```
In [8]: nt = (t = 1, col1 = 3.0)
        df2 = DataFrame([nt])
        push!(df2, (t=2, col1 = 4.0))
```

```
Out[8]: \begin{tabular}{r|cc}
        & t & col1\\
        \hline
        & Int64 & Float64\\
        \hline
        1 & 1 & 3.0 \\
        2 & 2 & 4.0 \\
\end{tabular}
```

In order to modify a column, access the mutating version by the symbol `df[!, :col]`.

```
In [9]: df[!, :price]
```

```
Out[9]: 5-element Array{Union{Missing, Float64},1}:
          4.2
```

```
 11.3
 12.1
   missing
  5.1
```

Which allows modifications, like other mutating `!` functions in julia.

```
In [10]: df[!, :price] *= 2.0  # double prices
```

```
Out[10]: 5-element Array{Union{Missing, Float64},1}:
           8.4
          22.6
          24.2
            missing
          10.2
```

As discussed in the next section, note that the fundamental types, is propagated, i.e. `missing * 2 === missing`.

9.3.2 Working with Missing

As we discussed in fundamental types, the semantics of `missing` are that mathematical operations will not silently ignore it.

In order to allow `missing` in a column, you can create/load the `DataFrame` from a source with `missing`'s, or call `allowmissing!` on a column.

```
In [11]: allowmissing!(df2, :col1) # necessary to add in a for col1
         push!(df2, (t=3, col1 = missing))
         push!(df2, (t=4, col1 = 5.1))
```

```
Out[11]: \begin{tabular}{r|cc}
                & t & col1\\
                \hline
                & Int64 & Float64?\\
                \hline
                1 & 1 & 3.0 \\
                2 & 2 & 4.0 \\
                3 & 3 & \emph{missing} \\
                4 & 4 & 5.1 \\
         \end{tabular}
```

We can see the propagation of `missing` to caller functions, as well as a way to efficiently calculate with non-missing data.

```
In [12]: @show mean(df2.col1)
         @show mean(skipmissing(df2.col1))
```

```
    mean(df2.col1) = missing
mean(skipmissing(df2.col1)) = 4.033333333333333
```

```
Out[12]: 4.033333333333333
```

And to replace the `missing`

```
In [13]: df2.col1  .= coalesce.(df2.col1, 0.0) # replace all missing with 0.0
```

```
Out[13]: 4-element Array{Union{Missing, Float64},1}:
          3.0
          4.0
          0.0
          5.1
```

9.3.3 Manipulating and Transforming DataFrames

One way to do an additional calculation with a `DataFrame` is to tuse the `@transform` macro from `DataFramesMeta.jl`.

```
In [14]: using DataFramesMeta
         f(x) = x^2
         df2 = @transform(df2, col2 = f.(:col1))
```

```
Out[14]: \begin{tabular}{r|ccc}
                & t & col1 & col2\\
                \hline
                & Int64 & Float64? & Float64\\
                \hline
                1 & 1 & 3.0 & 9.0 \\
                2 & 2 & 4.0 & 16.0 \\
                3 & 3 & 0.0 & 0.0 \\
                4 & 4 & 5.1 & 26.01 \\
         \end{tabular}
```

9.3.4 Categorical Data

For data that is categorical

```
In [15]: using CategoricalArrays
         id = [1, 2, 3, 4]
         y = ["old", "young", "young", "old"]
         y = CategoricalArray(y)
         df = DataFrame(id=id, y=y)
```

```
Out[15]: \begin{tabular}{r|cc}
                & id & y\\
                \hline
                & Int64 & …Cat\\
                \hline
                1 & 1 & old \\
                2 & 2 & young \\
                3 & 3 & young \\
                4 & 4 & old \\
         \end{tabular}
```

```
In [16]: levels(df.y)
```

```
Out[16]: 2-element Array{String,1}:
          "old"
          "young"
```

9.3.5 Visualization, Querying, and Plots

The `DataFrame` (and similar types that fulfill a standard generic interface) can fit into a variety of packages.

One set of them is the QueryVerse.

Note: The QueryVerse, in the same spirit as R's tidyverse, makes heavy use of the pipeline syntax `|>`.

```
In [17]: x = 3.0
         f(x) = x^2
         g(x) = log(x)

         @show g(f(x))
         @show x |> f |> g; # pipes nest function calls
```

```
   g(f(x)) = 2.1972245773362196
(x |> f) |> g = 2.1972245773362196
```

To give an example directly from the source of the LINQ inspired Query.jl

```
In [18]: using Query

         df = DataFrame(name=["John", "Sally", "Kirk"], age=[23., 42., 59.],
        ↪children=[3,5,2])

         x = @from i in df begin
             @where i.age>50
             @select {i.name, i.children}
             @collect DataFrame
         end
```

```
Out[18]: \begin{tabular}{r|cc}
                & name & children\\
                \hline
                & String & Int64\\
                \hline
                1 & Kirk & 2 \\
         \end{tabular}
```

While it is possible to just use the `Plots.jl` library, there may be better options for displaying tabular data – such as VegaLite.jl.

```
In [19]: using RDatasets, VegaLite
         iris = dataset("datasets", "iris")

         iris |> @vlplot(
             :point,
```

```
    x=:PetalLength,
    y=:PetalWidth,
    color=:Species
)
```

```
   WARN Missing type for channel "color", using "nominal" instead.
WARN Missing type for channel "color", using "nominal" instead.
```

Out[19]:

9.4 Statistics and Econometrics

While Julia is not intended as a replacement for R, Stata, and similar specialty languages, it has a growing number of packages aimed at statistics and econometrics.

Many of the packages live in the JuliaStats organization.

A few to point out

- StatsBase has basic statistical functions such as geometric and harmonic means, auto-correlations, robust statistics, etc.
- StatsFuns has a variety of mathematical functions and constants such as pdf and cdf of many distributions, softmax, etc.

9.4.1 General Linear Models

To run linear regressions and similar statistics, use the GLM package.

In [20]:
```
using GLM

x = randn(100)
y = 0.9 .* x + 0.5 * rand(100)
df = DataFrame(x=x, y=y)
ols = lm(@formula(y ~ x), df) # R-style notation
```

Out[20]:
```
StatsModels.TableRegressionModel{LinearModel{GLM.
↪LmResp{Array{Float64,1}},GLM.DensePredC
hol{Float64,Cholesky{Float64,Array{Float64,2}}}},Array{Float64,2}}

y ~ 1 + x

Coefficients:
```

	Estimate	Std. Error	t value	Pr(>|t|)	Lower 95%	Upper 95%
(Intercept)	0.228452	0.01451	15.7445	<1e-27	0.199657	0.257247
x	0.910643	0.0130831	69.6044	<1e-84	0.88468	0.936606

To display the results in a useful tables for LaTeX and the REPL, use RegressionTables for output similar to the Stata package esttab and the R package stargazer.

```
In [21]: using RegressionTables
         regtable(ols)
         # regtable(ols,  renderSettings = latexOutput()) # for LaTex output
```

```
----------------------
                     y
                --------
                     (1)
----------------------
(Intercept)   0.228***
               (0.015)
x             0.911***
               (0.013)
----------------------
Estimator           OLS
----------------------
N                   100
R2                0.980
----------------------
```

9.4.2 Fixed Effects

While Julia may be overkill for estimating a simple linear regression, fixed-effects estimation with dummies for multiple variables are much more computationally intensive.

For a 2-way fixed-effect, taking the example directly from the documentation using cigarette consumption data

```
In [22]: using FixedEffectModels
         cigar = dataset("plm", "Cigar")
         cigar.StateCategorical =  categorical(cigar.State)
         cigar.YearCategorical =  categorical(cigar.Year)
         fixedeffectresults = reg(cigar, @formula(Sales ~ NDI +
↪fe(StateCategorical) +
         fe(YearCategorical)),
                                        weights = :Pop, Vcov.cluster(:State))
         regtable(fixedeffectresults)
```

```
---------------------------
                     Sales
                 ---------
                       (1)
---------------------------
NDI                -0.005***
                    (0.001)
---------------------------
StateCategorical         Yes
YearCategorical          Yes
---------------------------
Estimator                OLS
---------------------------
N                      1,380
R2                     0.803
```

Chapter 10

Solvers, Optimizers, and Automatic Differentiation

10.1 Contents

10.2 Overview

In this lecture we introduce a few of the Julia libraries that we've found particularly useful for quantitative work in economics.

10.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using ForwardDiff, Zygote, Optim, JuMP, Ipopt, BlackBoxOptim, Roots,
  ↪NLsolve,
        LeastSquaresOptim
        using Optim: converged, maximum, maximizer, minimizer, iterations #some
  ↪extra functions
```

10.3 Introduction to Differentiable Programming

The promise of differentiable programming is that we can move towards taking the derivatives of almost arbitrarily complicated computer programs, rather than simply thinking about the derivatives of mathematical functions. Differentiable programming is the natural evolution of automatic differentiation (AD, sometimes called algorithmic differentiation).

Stepping back, there are three ways to calculate the gradient or Jacobian

- Analytic derivatives / Symbolic differentiation
  - You can sometimes calculate the derivative on pen-and-paper, and potentially simplify the expression.
  - In effect, repeated applications of the chain rule, product rule, etc.
  - It is sometimes, though not always, the most accurate and fastest option if there are algebraic simplifications.
  - Sometimes symbolic integration on the computer a good solution, if the package can handle your functions. Doing algebra by hand is tedious and error-prone, but is sometimes invaluable.
- Finite differences
  - Evaluate the function at least $N + 1$ times to get the gradient – Jacobians are even worse.
  - Large Δ is numerically stable but inaccurate, too small of Δ is numerically unstable but more accurate.
  - Choosing the Δ is hard, so use packages such as DiffEqDiffTools.jl.
  - If a function is $R^N \to R$ for a large N, this requires $O(N)$ function evaluations.

$$\partial_{x_i} f(x_1, \dots x_N) \approx \frac{f(x_1, \dots x_i + \Delta, \dots x_N) - f(x_1, \dots x_i, \dots x_N)}{\Delta}$$

- Automatic Differentiation
  - The same as analytic/symbolic differentiation, but where the **chain rule** is calculated **numerically** rather than symbolically.
  - Just as with analytic derivatives, can establish rules for the derivatives of individual functions (e.g. $d\left(sin(x)\right)$ to $cos(x)dx$) for intrinsic derivatives.

AD has two basic approaches, which are variations on the order of evaluating the chain rule: reverse and forward mode (although mixed mode is possible).

1. If a function is $R^N \to R$, then **reverse-mode** AD can find the gradient in $O(1)$ sweep (where a "sweep" is $O(1)$ function evaluations).
2. If a function is $R \to R^N$, then **forward-mode** AD can find the jacobian in $O(1)$ sweeps.

We will explore two types of automatic differentiation in Julia (and discuss a few packages which implement them). For both, remember the chain rule

$$\frac{dy}{dx} = \frac{dy}{dw} \cdot \frac{dw}{dx}$$

Forward-mode starts the calculation from the left with $\frac{dy}{dw}$ first, which then calculates the product with $\frac{dw}{dx}$. On the other hand, reverse mode starts on the right hand side with $\frac{dw}{dx}$ and works backwards.

Take an example a function with fundamental operations and known analytical derivatives

$$f(x_1, x_2) = x_1 x_2 + \sin(x_1)$$

And rewrite this as a function which contains a sequence of simple operations and temporaries.

```
In [3]: function f(x_1, x_2)
            w_1 = x_1
            w_2 = x_2
            w_3 = w_1 * w_2
            w_4 = sin(w_1)
            w_5 = w_3 + w_4
            return w_5
        end
```

```
Out[3]: f (generic function with 1 method)
```

Here we can identify all of the underlying functions (`*, sin, +`), and see if each has an intrinsic derivative. While these are obvious, with Julia we could come up with all sorts of differentiation rules for arbitrarily complicated combinations and compositions of intrinsic operations. In fact, there is even a package for registering more.

10.3.1 Forward-Mode Automatic Differentiation

In forward-mode AD, you first fix the variable you are interested in (called "seeding"), and then evaluate the chain rule in left-to-right order.

For example, with our $f(x_1, f_2)$ example above, if we wanted to calculate the derivative with respect to x_1 then we can seed the setup accordingly. $\frac{\partial w_1}{\partial x_1} = 1$ since we are taking the derivative of it, while $\frac{\partial w_1}{\partial x_1} = 0$.

Following through with these, redo all of the calculations for the derivative in parallel with the function itself.

$f(x_1, x_2)$	$\frac{\partial f(x_1,x_2)}{\partial x_1}$
$w_1 = x_1$	$\frac{\partial w_1}{\partial x_1} = 1$ (seed)
$w_2 = x_2$	$\frac{\partial w_2}{\partial x_1} = 0$ (seed)
$w_3 = w_1 \cdot w_2$	$\frac{\partial w_3}{\partial x_1} = w_2 \cdot \frac{\partial w_1}{\partial x_1} + w_1 \cdot \frac{\partial w_2}{\partial x_1}$
$w_4 = \sin w_1$	$\frac{\partial w_4}{\partial x_1} = \cos w_1 \cdot \frac{\partial w_1}{\partial x_1}$
$w_5 = w_3 + w_4$	$\frac{\partial w_5}{\partial x_1} = \frac{\partial w_3}{\partial x_1} + \frac{\partial w_4}{\partial x_1}$

Since these two could be done at the same time, we say there is "one pass" required for this calculation.

Generalizing a little, if the function was vector-valued, then that single pass would get the entire row of the Jacobian in that single pass. Hence for a $R^N \to R^M$ function, requires N passes to get a dense Jacobian using forward-mode AD.

How can you implement forward-mode AD? It turns out to be fairly easy with a generic programming language to make a simple example (while the devil is in the details for a high-performance implementation).

10.3.2 Forward-Mode with Dual Numbers

One way to implement forward-mode AD is to use dual numbers.

Instead of working with just a real number, e.g. x, we will augment each with an infinitesimal ϵ and use $x + \epsilon$.

From Taylor's theorem,

$$f(x + \epsilon) = f(x) + f'(x)\epsilon + O(\epsilon^2)$$

where we will define the infinitesimal such that $\epsilon^2 = 0$.

With this definition, we can write a general rule for differentiation of $g(x, y)$ as the chain rule for the total derivative

$$g(x + \epsilon, y + \epsilon) = g(x, y) + (\partial_x g(x, y) + \partial_y g(x, y))\epsilon$$

But, note that if we keep track of the constant in front of the ϵ terms (e.g. a x' and y')

$$g(x + x'\epsilon, y + y'\epsilon) = g(x, y) + (\partial_x g(x, y)x' + \partial_y g(x, y)y')\epsilon$$

This is simply the chain rule. A few more examples

$$\begin{aligned}(x + x'\epsilon) + (y + y'\epsilon) &= (x + y) + (x' + y')\epsilon \\ (x + x'\epsilon) \times (y + y'\epsilon) &= (xy) + (x'y + y'x)\epsilon \\ \exp(x + x'\epsilon) &= \exp(x) + (x' \exp(x))\epsilon\end{aligned}$$

Using the generic programming in Julia, it is easy to define a new dual number type which can encapsulate the pair (x, x') and provide a definitions for all of the basic operations. Each definition then has the chain-rule built into it.

With this approach, the "seed" process is simple the creation of the ϵ for the underlying variable.

So if we have the function $f(x_1, x_2)$ and we wanted to find the derivative $\partial_{x_1} f(3.8, 6.9)$ then then we would seed them with the dual numbers $x_1 \to (3.8, 1)$ and $x_2 \to (6.9, 0)$.

If you then follow all of the same scalar operations above with a seeded dual number, it will calculate both the function value and the derivative in a single "sweep" and without modifying any of your (generic) code.

10.3.3 ForwardDiff.jl

Dual-numbers are at the heart of one of the AD packages we have already seen.

```
In [4]: using ForwardDiff
        h(x) = sin(x[1]) + x[1] * x[2] + sinh(x[1] * x[2]) # multivariate.
        x = [1.4 2.2]
        @show ForwardDiff.gradient(h,x) # use AD, seeds from x

        #Or, can use complicated functions of many variables
        f(x) = sum(sin, x) + prod(tan, x) * sum(sqrt, x)
```

```
g = (x) -> ForwardDiff.gradient(f, x); # g() is now the gradient
g(rand(5)) # gradient at a random point
# ForwardDiff.hessian(f,x') # or the hessian
```

```
ForwardDiff.gradient(h, x) = [26.354764961030977 16.663053156992284]
```

```
Out[4]: 5-element Array{Float64,1}:
 1.1951182078800449
 1.653216543645516
 1.2145815673606202
 1.3943366855783785
 1.1889756683992878
```

We can even auto-differentiate complicated functions with embedded iterations.

```
In [5]: function squareroot(x) #pretending we don't know sqrt()
            z = copy(x) # Initial starting point for Newton's method
            while abs(z*z - x) > 1e-13
                z = z - (z*z-x)/(2z)
            end
            return z
        end
        squareroot(2.0)
```

```
Out[5]: 1.4142135623730951
```

```
In [6]: using ForwardDiff
        dsqrt(x) = ForwardDiff.derivative(squareroot, x)
        dsqrt(2.0)
```

```
Out[6]: 0.35355339059327373
```

10.3.4 Zygote.jl

Unlike forward-mode auto-differentiation, reverse-mode is very difficult to implement efficiently, and there are many variations on the best approach.

Many reverse-mode packages are connected to machine-learning packages, since the efficient gradients of $R^N \to R$ loss functions are necessary for the gradient descent optimization algorithms used in machine learning.

One recent package is Zygote.jl, which is used in the Flux.jl framework.

```
In [7]: using Zygote

        h(x, y) = 3x^2 + 2x + 1 + y*x - y
        gradient(h, 3.0, 5.0)
```

```
Out[7]: (25.0, 2.0)
```

Here we see that Zygote has a gradient function as the interface, which returns a tuple.

You could create this as an operator if you wanted to.,

```
In [8]: D(f) = x-> gradient(f, x)[1]  # returns first in tuple

        D_sin = D(sin)
        D_sin(4.0)
```

```
Out[8]: -0.6536436208636119
```

For functions of one (Julia) variable, we can find the by simply using the ' after a function name

```
In [9]: using Statistics
        p(x) = mean(abs, x)
        p'([1.0, 3.0, -2.0])
```

```
Out[9]: 3-element Array{Float64,1}:
          0.3333333333333333
          0.3333333333333333
         -0.3333333333333333
```

Or, using the complicated iterative function we defined for the squareroot,

```
In [10]: squareroot'(2.0)
```

```
Out[10]: 0.3535533905932737
```

Zygote supports combinations of vectors and scalars as the function parameters.

```
In [11]: h(x,n) = (sum(x.^n))^(1/n)
         gradient(h, [1.0, 4.0, 6.0], 2.0)
```

```
Out[11]: ([0.13736056394868904, 0.5494422557947561, 0.8241633836921343], -1.
  ↪2725553130925444 +
         0.0im)
```

The gradients can be very high dimensional. For example, to do a simple nonlinear optimization problem with 1 million dimensions, solved in a few seconds.

```
In [12]: using Optim, LinearAlgebra
         N = 1000000
         y = rand(N)
         λ = 0.01
         obj(x) = sum((x .- y).^2) + λ*norm(x)

         x_iv = rand(N)
         function g!(G, x)
             G .=  obj'(x)
         end

         results = optimize(obj, g!, x_iv, LBFGS()) # or ConjugateGradient()
         println("minimum = $(results.minimum) with in "*
         "$(results.iterations) iterations")
```

```
minimum = 5.773056445151088 with in 2 iterations
```

Caution: while Zygote is the most exciting reverse-mode AD implementation in Julia, it has many rough edges.

- If you write a function, take its gradient, and then modify the function, you need to call `Zygote.refresh()` or else the gradient will be out of sync. This may not apply for Julia 1.3+.
- It provides no features for getting Jacobians, so you would have to ask for each row of the Jacobian separately. That said, you probably want to use `ForwardDiff.jl` for Jacobians if the dimension of the output is similar to the dimension of the input.
- You cannot, in the current release, use mutating functions (e.g. modify a value in an array/etc.) although that feature is in progress.
- Compiling can be very slow for complicated functions.

10.4 Optimization

There are a large number of packages intended to be used for optimization in Julia.

Part of the reason for the diversity of options is that Julia makes it possible to efficiently implement a large number of variations on optimization routines.

The other reason is that different types of optimization problems require different algorithms.

10.4.1 Optim.jl

A good pure-Julia solution for the (unconstrained or box-bounded) optimization of univariate and multivariate function is the Optim.jl package.

By default, the algorithms in `Optim.jl` target minimization rather than maximization, so if a function is called `optimize` it will mean minimization.

Univariate Functions on Bounded Intervals

Univariate optimization defaults to a robust hybrid optimization routine called Brent's method.

```
In [13]: using Optim
         using Optim: converged, maximum, maximizer, minimizer, iterations #some
  ↪extra functions

         result = optimize(x-> x^2, -2.0, 1.0)
```

```
Out[13]: Results of Optimization Algorithm
          * Algorithm: Brent's Method
          * Search Interval: [-2.000000, 1.000000]
          * Minimizer: 0.000000e+00
          * Minimum: 0.000000e+00
          * Iterations: 5
          * Convergence: max(|x - x_upper|, |x - x_lower|) <= 2*(1.5e-08*|x|+2.2e-
16): true
          * Objective Function Calls: 6
```

Always check if the results converged, and throw errors otherwise

```
In [14]: converged(result) || error("Failed to converge in $(iterations(result))
  ↪iterations")
         xmin = result.minimizer
         result.minimum
```

```
Out[14]: 0.0
```

The first line is a logical OR between `converged(result)` and `error("...")`.

If the convergence check passes, the logical sentence is true, and it will proceed to the next line; if not, it will throw the error.

Or to maximize

```
In [15]: f(x) = -x^2
         result = maximize(f, -2.0, 1.0)
         converged(result) || error("Failed to converge in $(iterations(result))
  ↪iterations")
         xmin = maximizer(result)
         fmax = maximum(result)
```

```
Out[15]: -0.0
```

Note: Notice that we call `optimize` results using `result.minimizer`, and `maximize` results using `maximizer(result)`.

Unconstrained Multivariate Optimization

There are a variety of algorithms and options for multivariate optimization.

From the documentation, the simplest version is

```
In [16]: f(x) = (1.0 - x[1])^2 + 100.0 * (x[2] - x[1]^2)^2
         x_iv = [0.0, 0.0]
         results = optimize(f, x_iv) # i.e. optimize(f, x_iv, NelderMead())
```

```
Out[16]:  * Status: success

          * Candidate solution
             Minimizer: [1.00e+00, 1.00e+00]
             Minimum:   3.525527e-09

          * Found with
             Algorithm:     Nelder-Mead
             Initial Point: [0.00e+00, 0.00e+00]

          * Convergence measures
             √(Σ(yᵢ-ȳ)²)/n ≤ 1.0e-08

          * Work counters
             Seconds run:   0  (vs limit Inf)
             Iterations:    60
             f(x) calls:    118
```

The default algorithm in `NelderMead`, which is derivative-free and hence requires many function evaluations.

To change the algorithm type to L-BFGS

```
In [17]: results = optimize(f, x_iv, LBFGS())
         println("minimum = $(results.minimum) with argmin = $(results.minimizer)
 ↪in "*
         "$(results.iterations) iterations")
```

```
  minimum = 5.3784046148998115e-17 with argmin = [0.9999999926662393,
0.9999999853324786] in 24 iterations
```

Note that this has fewer iterations.

As no derivative was given, it used finite differences to approximate the gradient of `f(x)`.

However, since most of the algorithms require derivatives, you will often want to use auto differentiation or pass analytical gradients if possible.

```
In [18]: f(x) = (1.0 - x[1])^2 + 100.0 * (x[2] - x[1]^2)^2
         x_iv = [0.0, 0.0]
         results = optimize(f, x_iv, LBFGS(), autodiff=:forward) # i.e. use
 ↪ForwardDiff.jl
         println("minimum = $(results.minimum) with argmin = $(results.minimizer)
 ↪in "*
         "$(results.iterations) iterations")
```

```
  minimum = 5.191703158437428e-27 with argmin = [0.999999999999928, 0.
↪9999999999998559]
in 24 iterations
```

Note that we did not need to use `ForwardDiff.jl` directly, as long as our `f(x)` function was written to be generic (see the generic programming lecture).

Alternatively, with an analytical gradient

```
In [19]: f(x) = (1.0 - x[1])^2 + 100.0 * (x[2] - x[1]^2)^2
         x_iv = [0.0, 0.0]
         function g!(G, x)
             G[1] = -2.0 * (1.0 - x[1]) - 400.0 * (x[2] - x[1]^2) * x[1]
             G[2] = 200.0 * (x[2] - x[1]^2)
         end

         results = optimize(f, g!, x_iv, LBFGS()) # or ConjugateGradient()
         println("minimum = $(results.minimum) with argmin = $(results.minimizer)
 ↪in "*
         "$(results.iterations) iterations")
```

```
  minimum = 5.191703158437428e-27 with argmin = [0.999999999999928, 0.
↪9999999999998559]
in 24 iterations
```

For derivative-free methods, you can change the algorithm – and have no need to provide a gradient

```
In [20]: f(x) = (1.0 - x[1])^2 + 100.0 * (x[2] - x[1]^2)^2
         x_iv = [0.0, 0.0]
         results = optimize(f, x_iv, SimulatedAnnealing()) # or ParticleSwarm() or
  ↪NelderMead()
```

```
Out[20]:  * Status: failure (reached maximum number of iterations) (line search
  ↪failed)

          * Candidate solution
             Minimizer: [9.15e-01, 8.55e-01]
             Minimum:   3.770761e-02

          * Found with
             Algorithm:     Simulated Annealing
             Initial Point: [0.00e+00, 0.00e+00]

          * Convergence measures
             |x - x'|               = NaN □ 0.0e+00
             |x - x'|/|x'|          = NaN □ 0.0e+00
             |f(x) - f(x')|         = NaN □ 0.0e+00
             |f(x) - f(x')|/|f(x')| = NaN □ 0.0e+00
             |g(x)|                 = NaN □ 1.0e-08

          * Work counters
             Seconds run:   0  (vs limit Inf)
             Iterations:    1000
             f(x) calls:    1001
```

However, you will note that this did not converge, as stochastic methods typically require many more iterations as a tradeoff for their global-convergence properties.

See the maximum likelihood example and the accompanying Jupyter notebook.

10.4.2 JuMP.jl

The JuMP.jl package is an ambitious implementation of a modelling language for optimization problems in Julia.

In that sense, it is more like an AMPL (or Pyomo) built on top of the Julia language with macros, and able to use a variety of different commerical and open source solvers.

If you have a linear, quadratic, conic, mixed-integer linear, etc. problem then this will likely be the ideal "meta-package" for calling various solvers.

For nonlinear problems, the modelling language may make things difficult for complicated functions (as it is not designed to be used as a general-purpose nonlinear optimizer).

See the quick start guide for more details on all of the options.

The following is an example of calling a linear objective with a nonlinear constraint (provided by an external function).

Here `Ipopt` stands for `Interior Point OPTimizer`, a nonlinear solver in Julia

In [21]:
```
using JuMP, Ipopt
# solve
# max( x[1] + x[2] )
# st sqrt(x[1]^2 + x[2]^2) <= 1

function squareroot(x) # pretending we don't know sqrt()
    z = x # Initial starting point for Newton’s method
    while abs(z*z - x) > 1e-13
        z = z - (z*z-x)/(2z)
    end
    return z
end
m = Model(with_optimizer(Ipopt.Optimizer))
# need to register user defined functions for AD
JuMP.register(m,:squareroot, 1, squareroot, autodiff=true)

@variable(m, x[1:2], start=0.5) # start is the initial condition
@objective(m, Max, sum(x))
@NLconstraint(m, squareroot(x[1]^2+x[2]^2) <= 1)
@show JuMP.optimize!(m)
```

```
┌ Warning: `with_optimizer` is deprecated. Adapt the following example to
↪update your
code:
│ `with_optimizer(Ipopt.Optimizer)` becomes `Ipopt.Optimizer`.
│   caller = top-level scope at In[21]:13
└ @ Core In[21]:13



******************************************************************************
This program contains Ipopt, a library for large-scale nonlinear optimization.
 Ipopt is released as open source code under the Eclipse Public License (EPL).
         For more information visit http://projects.coin-or.org/Ipopt
******************************************************************************

This is Ipopt version 3.12.10, running with linear solver mumps.
NOTE: Other linear solvers might be more efficient (see Ipopt documentation).

Number of nonzeros in equality constraint Jacobian…:        0
Number of nonzeros in inequality constraint Jacobian.:        2
Number of nonzeros in Lagrangian Hessian…:        3

Total number of variables…:        2
                     variables with only lower bounds:        0
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints…:        0
Total number of inequality constraints…:        1
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        1

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
   0 -1.0000000e+00 0.00e+00 2.07e-01  -1.0 0.00e+00    -  0.00e+00 0.00e+00   0
   1 -1.4100714e+00 0.00e+00 5.48e-02  -1.7 3.94e-01    -  1.00e+00 7.36e-01f  1
   2 -1.4113851e+00 0.00e+00 2.83e-08  -2.5 9.29e-04    -  1.00e+00 1.00e+00f  1
   3 -1.4140632e+00 0.00e+00 1.50e-09  -3.8 1.89e-03    -  1.00e+00 1.00e+00f  1
   4 -1.4142117e+00 0.00e+00 1.84e-11  -5.7 1.05e-04    -  1.00e+00 1.00e+00f  1
   5 -1.4142136e+00 0.00e+00 8.23e-09  -8.6 1.30e-06    -  1.00e+00 1.00e+00f  1
```

```
Number of Iterations…: 5

                                   (scaled)                 (unscaled)
Objective…:  -1.4142135740093271e+00   -1.4142135740093271e+00
Dual infeasibility…:   8.2280586788385790e-09    8.2280586788385790e-09
Constraint violation…:   0.0000000000000000e+00    0.0000000000000000e+00
Complementarity…:   2.5059035815063646e-09    2.5059035815063646e-09
Overall NLP error…:   8.2280586788385790e-09    8.2280586788385790e-09


Number of objective function evaluations             = 6
Number of objective gradient evaluations             = 6
Number of equality constraint evaluations            = 0
Number of inequality constraint evaluations          = 6
Number of equality constraint Jacobian evaluations   = 0
Number of inequality constraint Jacobian evaluations = 6
Number of Lagrangian Hessian evaluations             = 5
Total CPU secs in IPOPT (w/o function evaluations)   =      1.887
Total CPU secs in NLP function evaluations           =      1.653

EXIT: Optimal Solution Found.
JuMP.optimize!(m) = nothing
```

And this is an example of a quadratic objective

In [22]:
```
# solve
# min (1-x)^2 + 100(y-x^2)^2)
# st x + y >= 10

using JuMP,Ipopt
m = Model(with_optimizer(Ipopt.Optimizer)) # settings for the solver
@variable(m, x, start = 0.0)
@variable(m, y, start = 0.0)

@NLobjective(m, Min, (1-x)^2 + 100(y-x^2)^2)

JuMP.optimize!(m)
println("x = ", value(x), " y = ", value(y))

# adding a (linear) constraint
@constraint(m, x + y == 10)
JuMP.optimize!(m)
println("x = ", value(x), " y = ", value(y))
```

```
┌ Warning: `with_optimizer` is deprecated. Adapt the following example to
↪update your
code:
│ `with_optimizer(Ipopt.Optimizer)` becomes `Ipopt.Optimizer`.
│   caller = top-level scope at In[22]:6
└ @ Core In[22]:6


   This is Ipopt version 3.12.10, running with linear solver mumps.
NOTE: Other linear solvers might be more efficient (see Ipopt documentation).

Number of nonzeros in equality constraint Jacobian…:        0
Number of nonzeros in inequality constraint Jacobian.:        0
```

```
Number of nonzeros in Lagrangian Hessian…:        3

Total number of variables…:        2
                     variables with only lower bounds:        0
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints…:        0
Total number of inequality constraints…:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
   0  1.0000000e+00 0.00e+00 2.00e+00  -1.0 0.00e+00    -  0.00e+00 0.00e+00   0
   1  9.5312500e-01 0.00e+00 1.25e+01  -1.0 1.00e+00    -  1.00e+00 2.50e-01f  3
   2  4.8320569e-01 0.00e+00 1.01e+00  -1.0 9.03e-02    -  1.00e+00 1.00e+00f  1
   3  4.5708829e-01 0.00e+00 9.53e+00  -1.0 4.29e-01    -  1.00e+00 5.00e-01f  2
   4  1.8894205e-01 0.00e+00 4.15e-01  -1.0 9.51e-02    -  1.00e+00 1.00e+00f  1
   5  1.3918726e-01 0.00e+00 6.51e+00  -1.7 3.49e-01    -  1.00e+00 5.00e-01f  2
   6  5.4940990e-02 0.00e+00 4.51e-01  -1.7 9.29e-02    -  1.00e+00 1.00e+00f  1
   7  2.9144630e-02 0.00e+00 2.27e+00  -1.7 2.49e-01    -  1.00e+00 5.00e-01f  2
   8  9.8586451e-03 0.00e+00 1.15e+00  -1.7 1.10e-01    -  1.00e+00 1.00e+00f  1
   9  2.3237475e-03 0.00e+00 1.00e+00  -1.7 1.00e-01    -  1.00e+00 1.00e+00f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
  10  2.3797236e-04 0.00e+00 2.19e-01  -1.7 5.09e-02    -  1.00e+00 1.00e+00f  1
  11  4.9267371e-06 0.00e+00 5.95e-02  -1.7 2.53e-02    -  1.00e+00 1.00e+00f  1
  12  2.8189505e-09 0.00e+00 8.31e-04  -2.5 3.20e-03    -  1.00e+00 1.00e+00f  1
  13  1.0095040e-15 0.00e+00 8.68e-07  -5.7 9.78e-05    -  1.00e+00 1.00e+00f  1
  14  1.3288608e-28 0.00e+00 2.02e-13  -8.6 4.65e-08    -  1.00e+00 1.00e+00f  1

Number of Iterations…: 14

                                   (scaled)                 (unscaled)
Objective…:   1.3288608467480825e-28    1.3288608467480825e-28
Dual infeasibility…:   2.0183854587685121e-13    2.0183854587685121e-13
Constraint violation…:   0.0000000000000000e+00    0.0000000000000000e+00
Complementarity…:   0.0000000000000000e+00    0.0000000000000000e+00
Overall NLP error…:   2.0183854587685121e-13    2.0183854587685121e-13


Number of objective function evaluations             = 36
Number of objective gradient evaluations             = 15
Number of equality constraint evaluations            = 0
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 0
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 14
Total CPU secs in IPOPT (w/o function evaluations)   =      0.085
Total CPU secs in NLP function evaluations           =      0.013

EXIT: Optimal Solution Found.
x = 0.9999999999999899 y = 0.9999999999999792
This is Ipopt version 3.12.10, running with linear solver mumps.
NOTE: Other linear solvers might be more efficient (see Ipopt documentation).

Number of nonzeros in equality constraint Jacobian…:        2
Number of nonzeros in inequality constraint Jacobian.:        0
Number of nonzeros in Lagrangian Hessian…:        3

Total number of variables…:        2
                     variables with only lower bounds:        0
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
```

```
Total number of equality constraints…:        1
Total number of inequality constraints…:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
   0  1.0000000e+00 1.00e+01 1.00e+00  -1.0 0.00e+00    -  0.00e+00 0.00e+00   0
   1  9.6315968e+05 0.00e+00 3.89e+05  -1.0 9.91e+00    -  1.00e+00 1.00e+00h  1
   2  1.6901461e+05 0.00e+00 1.16e+05  -1.0 3.24e+00    -  1.00e+00 1.00e+00f  1
   3  2.5433173e+04 1.78e-15 3.18e+04  -1.0 2.05e+00    -  1.00e+00 1.00e+00f  1
   4  2.6527756e+03 0.00e+00 7.79e+03  -1.0 1.19e+00    -  1.00e+00 1.00e+00f  1
   5  1.1380324e+02 0.00e+00 1.35e+03  -1.0 5.62e-01    -  1.00e+00 1.00e+00f  1
   6  3.3745506e+00 0.00e+00 8.45e+01  -1.0 1.50e-01    -  1.00e+00 1.00e+00f  1
   7  2.8946196e+00 0.00e+00 4.22e-01  -1.0 1.07e-02    -  1.00e+00 1.00e+00f  1
   8  2.8946076e+00 0.00e+00 1.07e-05  -1.7 5.42e-05    -  1.00e+00 1.00e+00f  1
   9  2.8946076e+00 0.00e+00 5.91e-13  -8.6 1.38e-09    -  1.00e+00 1.00e+00f  1

Number of Iterations…: 9

                                   (scaled)                 (unscaled)
Objective…:   2.8946075504894599e+00    2.8946075504894599e+00
Dual infeasibility…:   5.9130478291535837e-13    5.9130478291535837e-13
Constraint violation…:   0.0000000000000000e+00    0.0000000000000000e+00
Complementarity…:   0.0000000000000000e+00    0.0000000000000000e+00
Overall NLP error…:   5.9130478291535837e-13    5.9130478291535837e-13


Number of objective function evaluations             = 10
Number of objective gradient evaluations             = 10
Number of equality constraint evaluations            = 10
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 1
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 9
Total CPU secs in IPOPT (w/o function evaluations)   =      0.003
Total CPU secs in NLP function evaluations           =      0.000

EXIT: Optimal Solution Found.
x = 2.701147124098218 y = 7.2988528759017814
```

10.4.3 BlackBoxOptim.jl

Another package for doing global optimization without derivatives is BlackBoxOptim.jl.

To see an example from the documentation

In [23]:
```
using BlackBoxOptim

  function rosenbrock2d(x)
  return (1.0 - x[1])^2 + 100.0 * (x[2] - x[1]^2)^2
  end

  results = bboptimize(rosenbrock2d; SearchRange = (-5.0, 5.0),
↪NumDimensions = 2);
```

```
  Starting optimization with optimizer
↪DiffEvoOpt{FitPopulation{Float64},RadiusLimitedSe
lector,BlackBoxOptim.
↪AdaptiveDiffEvoRandBin{3},RandomBound{ContinuousRectSearchSpace}}
```

```
0.00 secs, 0 evals, 0 steps

Optimization stopped after 10001 steps and 0.09 seconds
Termination reason: Max number of steps (10000) reached
Steps per second = 115848.82
Function evals per second = 117157.78
Improvements/step = 0.20700
Total function evaluations = 10114


Best candidate found: [1.0, 1.0]

Fitness: 0.000000000
```

An example for parallel execution of the objective is provided.

10.5 Systems of Equations and Least Squares

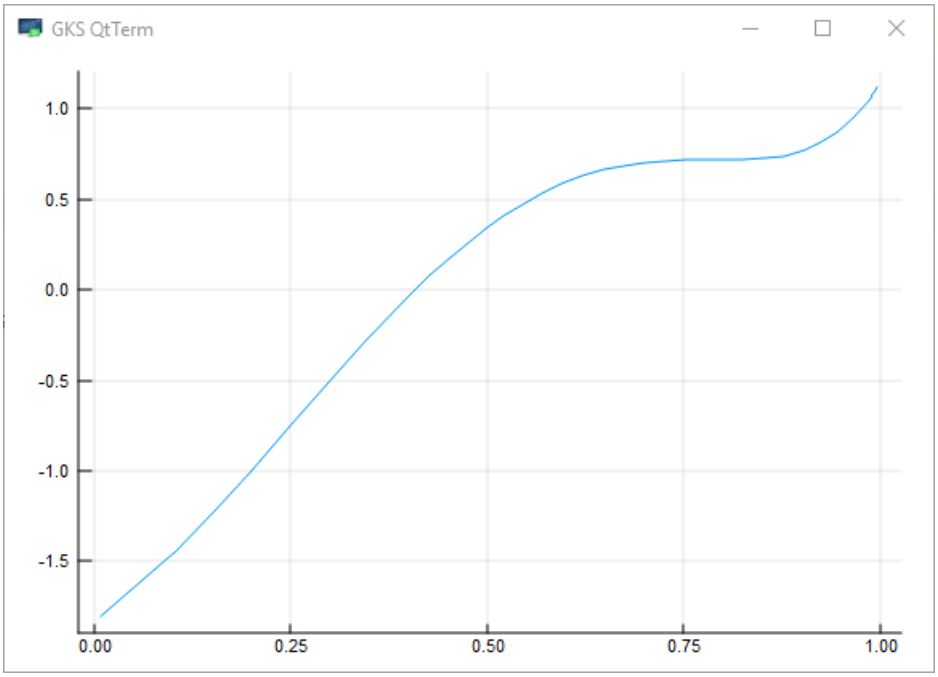
10.5.1 Roots.jl

A root of a real function f on $[a, b]$ is an $x \in [a, b]$ such that $f(x) = 0$.

For example, if we plot the function

$$f(x) = \sin(4(x - 1/4)) + x + x^{20} - 1 \tag{1}$$

with $x \in [0, 1]$ we get



The unique root is approximately 0.408.

The Roots.jl package offers `fzero()` to find roots

```
In [24]: using Roots
         f(x) = sin(4 * (x - 1/4)) + x + x^20 - 1
         fzero(f, 0, 1)
```

```
Out[24]: 0.40829350427936706
```

10.5.2 NLsolve.jl

The NLsolve.jl package provides functions to solve for multivariate systems of equations and fixed points.

From the documentation, to solve for a system of equations without providing a Jacobian

```
In [25]: using NLsolve

         f(x) = [(x[1]+3)*(x[2]^3-7)+18
                 sin(x[2]*exp(x[1])-1)] # returns an array

         results = nlsolve(f, [ 0.1; 1.2])
```

```
Out[25]: Results of Nonlinear Solver Algorithm
          * Algorithm: Trust-region with dogleg and autoscaling
          * Starting Point: [0.1, 1.2]
          * Zero: [-7.775548712324193e-17, 0.9999999999999999]
          * Inf-norm of residuals: 0.000000
          * Iterations: 4
          * Convergence: true
            * |x - x'| < 0.0e+00: false
            * |f(x)| < 1.0e-08: true
          * Function Calls (f): 5
          * Jacobian Calls (df/dx): 5
```

In the above case, the algorithm used finite differences to calculate the Jacobian.

Alternatively, if `f(x)` is written generically, you can use auto-differentiation with a single setting.

```
In [26]: results = nlsolve(f, [ 0.1; 1.2], autodiff=:forward)

         println("converged=$(NLsolve.converged(results)) at root=$(results.zero)
        ↪in "*
         "$(results.iterations) iterations and $(results.f_calls) function calls")
```

```
converged=true at root=[-3.487552479724522e-16, 1.0000000000000002] in 4
↪iterations
and 5 function calls
```

Providing a function which operates inplace (i.e., modifies an argument) may help performance for large systems of equations (and hurt it for small ones).

```
In [27]: function f!(F, x) # modifies the first argument
             F[1] = (x[1]+3)*(x[2]^3-7)+18
```

```
    F[2] = sin(x[2]*exp(x[1])-1)
end

results = nlsolve(f!, [ 0.1; 1.2], autodiff=:forward)

println("converged=$(NLsolve.converged(results)) at root=$(results.zero)
↪in "*
"$(results.iterations) iterations and $(results.f_calls) function calls")
```

```
converged=true at root=[-3.487552479724522e-16, 1.0000000000000002] in 4
↪iterations
and 5 function calls
```

10.6 LeastSquaresOptim.jl

Many optimization problems can be solved using linear or nonlinear least squares.

Let $x \in R^N$ and $F(x) : R^N \to R^M$ with $M \geq N$, then the nonlinear least squares problem is

$$\min_x F(x)^T F(x)$$

While $F(x)^T F(x) \to R$, and hence this problem could technically use any nonlinear optimizer, it is useful to exploit the structure of the problem.

In particular, the Jacobian of $F(x)$, can be used to approximate the Hessian of the objective.

As with most nonlinear optimization problems, the benefits will typically become evident only when analytical or automatic differentiation is possible.

If $M = N$ and we know a root $F(x^*) = 0$ to the system of equations exists, then NLS is the defacto method for solving large **systems of equations**.

An implementation of NLS is given in LeastSquaresOptim.jl.

From the documentation

In [28]:
```
using LeastSquaresOptim
function rosenbrock(x)
    [1 - x[1], 100 * (x[2]-x[1]^2)]
end
LeastSquaresOptim.optimize(rosenbrock, zeros(2), Dogleg())
```

Out[28]:
```
Results of Optimization Algorithm
 * Algorithm: Dogleg
 * Minimizer: [1.0,1.0]
 * Sum of squares at Minimum: 0.000000
 * Iterations: 51
 * Convergence: true
 * |x - x'| < 1.0e-08: false
 * |f(x) - f(x')| / |f(x)| < 1.0e-08: true
 * |g(x)| < 1.0e-08: false
 * Function Calls: 52
 * Gradient Calls: 36
 * Multiplication Calls: 159
```

Note: Because there is a name clash between `Optim.jl` and this package, to use both we need to qualify the use of the `optimize` function (i.e. `LeastSquaresOptim.optimize`).

Here, by default it will use AD with `ForwardDiff.jl` to calculate the Jacobian, but you could also provide your own calculation of the Jacobian (analytical or using finite differences) and/or calculate the function inplace.

```
In [29]: function rosenbrock_f!(out, x)
             out[1] = 1 - x[1]
             out[2] = 100 * (x[2]-x[1]^2)
         end
         LeastSquaresOptim.optimize!(LeastSquaresProblem(x = zeros(2),
                                     f! = rosenbrock_f!, output_length = 2))

         # if you want to use gradient
         function rosenbrock_g!(J, x)
             J[1, 1] = -1
             J[1, 2] = 0
             J[2, 1] = -200 * x[1]
             J[2, 2] = 100
         end
         LeastSquaresOptim.optimize!(LeastSquaresProblem(x = zeros(2),
                                     f! = rosenbrock_f!, g! = rosenbrock_g!,
 ↪output_length =
         2))
```

```
Out[29]: Results of Optimization Algorithm
          * Algorithm: Dogleg
          * Minimizer: [1.0,1.0]
          * Sum of squares at Minimum: 0.000000
          * Iterations: 51
          * Convergence: true
          * |x - x'| < 1.0e-08: false
          * |f(x) - f(x')| / |f(x)| < 1.0e-08: true
          * |g(x)| < 1.0e-08: false
          * Function Calls: 52
          * Gradient Calls: 36
          * Multiplication Calls: 159
```

10.7 Additional Notes

Watch this video from one of Julia's creators on automatic differentiation.

10.8 Exercises

10.8.1 Exercise 1

Doing a simple implementation of forward-mode auto-differentiation is very easy in Julia since it is generic. In this exercise, you will fill in a few of the operations required for a simple AD implementation.

First, we need to provide a type to hold the dual.

```
In [30]: struct DualNumber{T} <: Real
             val::T
             ϵ::T
         end
```

Here we have made it a subtype of `Real` so that it can pass through functions expecting Reals.

We can add on a variety of chain rule definitions by importing in the appropriate functions and adding DualNumber versions. For example

```
In [31]: import Base: +, *, -, ^, exp
         +(x::DualNumber, y::DualNumber) = DualNumber(x.val + y.val, x.ϵ + y.ϵ)  #
 ↪dual addition
         +(x::DualNumber, a::Number) = DualNumber(x.val + a, x.ϵ)  # i.e. scalar
 ↪addition, not
         dual
         +(a::Number, x::DualNumber) = DualNumber(x.val + a, x.ϵ)  # i.e. scalar
 ↪addition, not
         dual
```

```
Out[31]: + (generic function with 265 methods)
```

With that, we can seed a dual number and find simple derivatives,

```
In [32]: f(x, y) = 3.0 + x + y

         x = DualNumber(2.0, 1.0)  # x -> 2.0 + 1.0\epsilon
         y = DualNumber(3.0, 0.0)  # i.e. y = 3.0, no derivative


         # seeded calculates both teh function and the d/dx gradient!
         f(x,y)
```

```
Out[32]: DualNumber{Float64}(8.0, 1.0)
```

For this assignment:

1. Add in AD rules for the other operations: `*, -, ^, exp`.
2. Come up with some examples of univariate and multivariate functions combining those operations and use your AD implementation to find the derivatives.

Chapter 11

Julia Tools and Editors

11.1 Contents

Co-authored with Arnav Sood

While Jupyter notebooks are a great way to get started with the language, eventually you will want to use more powerful tools.

We'll discuss a few of them here, such as

- Text editors like Atom, which come with rich Julia support for debugging, documentation, git integration, plotting and inspecting data, and code execution.
- The Julia REPL, which has specialized modes for package management, shell commands, and help.

Note that we assume you've already completed the getting started and interacting with Julia lectures.

11.2 Preliminary Setup

Follow the instructions for setting up Julia on your local computer.

11.3 The REPL

Previously, we discussed basic use of the Julia REPL ("Read-Evaluate-Print Loop").

Here, we'll consider some more advanced features.

11.3.1 Shell Mode

Hitting `;` brings you into shell mode, which lets you run bash commands (PowerShell on Windows)

```
In [1]: ; pwd
```

```
/home/ubuntu/repos/lecture-source-jl/_build/jupyterpdf/executed/more_julia
```

You can also use Julia variables from shell mode

```
In [2]: x = 2
```

```
Out[2]: 2
```

```
In [3]: ; echo $x
```

```
2
```

11.3.2 Package Mode

Hitting `]` brings you into package mode.

- `] add Expectations` will add a package (here, `Expectations.jl`).
- Likewise, `] rm Expectations` will remove that package.
- `] st` will show you a snapshot of what you have installed.
- `] up` will (intelligently) upgrade versions of your packages.
- `] precompile` will precompile everything possible.
- `] build` will execute build scripts for all packages.
- Running `] preview` before a command (i.e., `] preview up`) will display the changes without executing.

You can get a full list of package mode commands by running

```
In [4]: ] ?
```

```
  Welcome to the Pkg REPL-mode. To return to the julia> prompt,
either press
  backspace when the input line is empty or press Ctrl+C.

  Synopsis

  pkg> cmd [opts] [args]

  Multiple commands can be given on the same line by interleaving a ;
between
  the commands.

  Commands

  activate: set the primary environment the package manager manipulates

  add: add packages to project

  build: run the build script for packages

  develop: clone the full package repo locally for development
```

```
  free: undoes a pin, develop, or stops tracking a repo

  gc: garbage collect packages not used for a significant time

  generate: generate files for a new project

  help: show this message

  instantiate: downloads all the dependencies for the project

  pin: pins the version of packages

  precompile: precompile all the project dependencies

  redo: redo the latest change to the active project

  remove: remove packages from project or manifest

  resolve: resolves to update the manifest from changes in dependencies of
  developed packages

  status: summarize contents of and changes to environment

  test: run tests for packages

  undo: undo the latest change to the active project

  update: update packages in manifest

  registry add: add package registries

  registry remove: remove package registries

  registry status: information about installed registries

  registry update: update package registries
```

On some operating systems (such as OSX) REPL pasting may not work for package mode, and you will need to access it in the standard way (i.e., hit `]` first and then run your commands).

11.3.3 Help Mode

Hitting `?` will bring you into help mode.

The key use case is to find docstrings for functions and macros, e.g.

```
? print
```

Note that objects must be loaded for Julia to return their documentation, e.g.

```
? @test
```

will fail, but

```
using Test
```

```
? @test
```

will succeed.

11.4 Atom

As discussed previously, eventually you will want to use a fully fledged text editor.

The most feature-rich one for Julia development is Atom, with the Juno package.

There are several reasons to use a text editor like Atom, including

- Git integration (more on this in the next lecture).
- Painless inspection of variables and data.
- Easily run code blocks, and drop in custom snippets of code.
- Integration with Julia documentation and plots.

11.4.1 Installation and Configuration

Installing Atom

1. Download and Install Atom from the Atom website.

2. (Optional, but recommended): Change default Atom settings

- Use `Ctrl-,` to get the `Settings` pane
- Choose the `Packages` tab
- Type `line-ending-selector` into the Filter and then click "Settings" for that package
  - Change the default line ending to `LF` (only necessary on Windows)
- Choose the Editor tab
  - Turn on `Soft Wrap`
  - Set the `Tab Length` default to `4`

Installing Juno

1. Use `Ctrl-,` to get the Settings pane.

2. Go to the `Install` tab.

3. Type `uber-juno` into the search box and then click Install on the package that appears.

4. Wait while Juno installs dependencies.

5. When it asks you whether or not to use the standard layout, click `yes`.

At that point, you should see a built-in REPL at the bottom of the screen and be able to start using Julia and Atom.

Troubleshooting

Sometimes, Juno will fail to find the Julia executable (say, if it's installed somewhere non-standard, or you have multiple).

To do this 1. `Ctrl-,` to get Settings pane, and select the Packages tab. 2. Type in `julia-client` and choose Settings. 3. Find the Julia Path, and fill it in with the location of the Julia binary.

    - To find the binary, you could run `Sys.BINDIR` in the REPL, then add in an additional `/julia` to the end of the screen.

- e.g. `C:\Users\YOURUSERNAME\AppData\Local\Julia-1.0.1\bin\julia.exe` on Windows as `/Applications/Julia-1.0.app/Contents/Resources/julia/bin/julia` on OSX.

See the setup instructions for Juno if you have further issues.

If you upgrade Atom and it breaks Juno, run the following in a terminal.

```
apm uninstall ink julia-client
apm install ink julia-client
```

If you aren't able to install `apm` in your PATH, you can do the above by running the following in PowerShell:

```
cd $ENV:LOCALAPPDATA/atom/bin
```

Then navigating to a folder like `C:\Users\USERNAME\AppData\Local\atom\bin` (which will contain the `apm` tool), and running:

```
./apm uninstall ink julia-client
./apm install ink julia-client
```

Upgrading Julia

To get a new release working with Jupyter, run (in the new version's REPL)

```
] add IJulia
] build IJulia
```

This will install (and build) the `IJulia` kernel.

To get it working with Atom, open the command palette and type "Julia Client: Settings."

Then, in the box labelled "Julia Path," enter the path to yor Julia executabe.

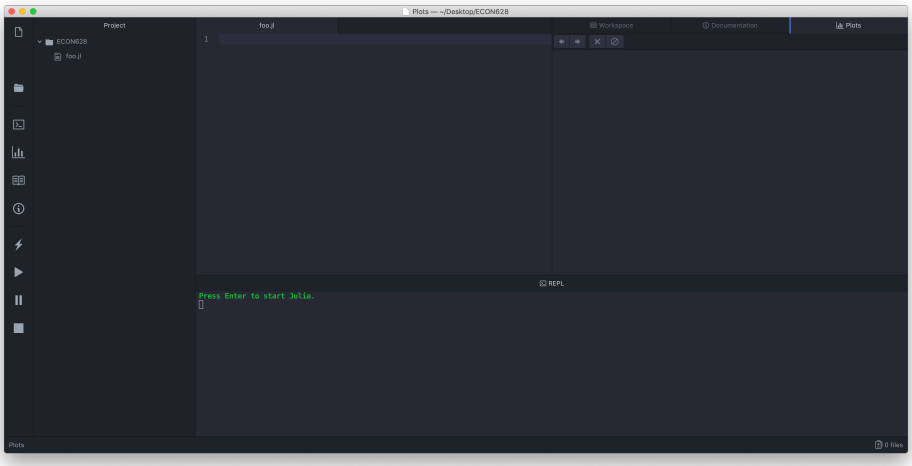
You can find the folder by running `Sys.BINDIR` in a new REPL, and then add the `/julia` at the end to give the exact path.

For example:

11.4.2 Standard Layout

If you follow the instructions, you should see something like this when you open a new file.

If you don't, simply go to the command palette and type "Julia standard layout"



The bottom pane is a standard REPL, which supports the different modes above.

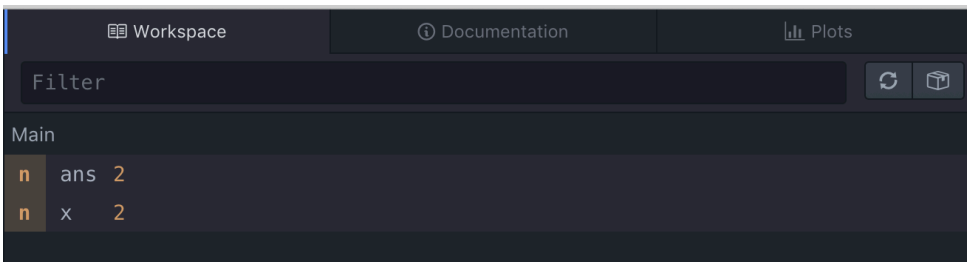
The "workspace" pane is a snapshot of currently-defined objects.

For example, if we define an object in the REPL

```
In [5]: x = 2
```

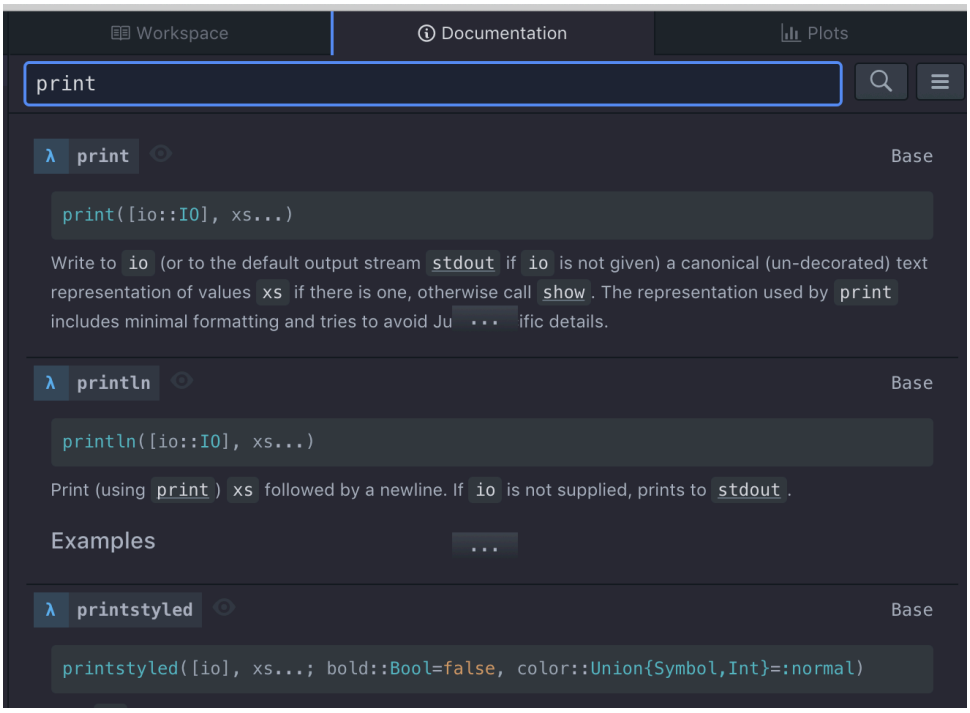
```
Out[5]: 2
```

Our workspace should read



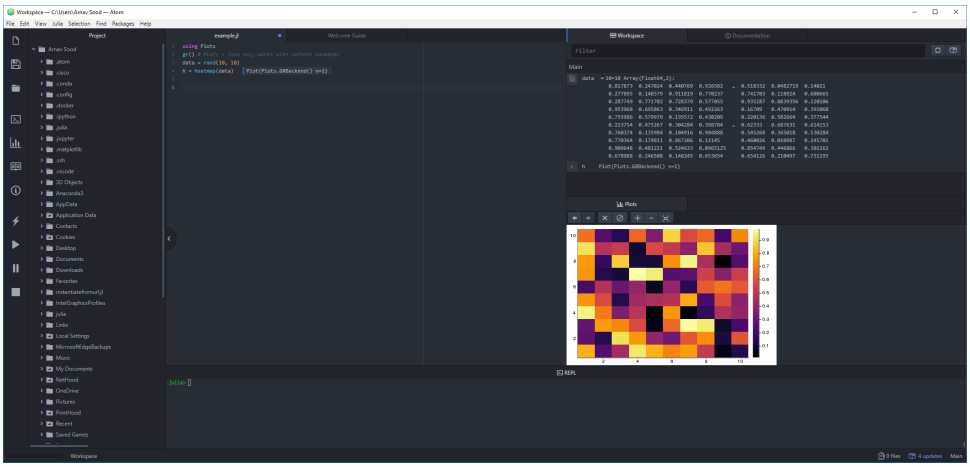
The `ans` variable simply captures the result of the last computation.

The `Documentation` pane simply lets us query Julia documentation



The `Plots` pane captures Julia plots output (the code is as follows)

```
using Plots
gr(fmt = :png);
data = rand(10, 10)
h = heatmap(data)
```



Note: The plots feature is not perfectly reliable across all plotting backends, see the Basic Usage page.

11.4.3 Other Features

- `Shift + Enter` will evaluate a highlighted selection or line (as above).
- The run symbol in the left sidebar (or `Ctrl+Shift+Enter`) will run the whole file.

See basic usage for an exploration of features, and the FAQ for more advanced steps.

11.5 Package Environments

Julia's package manager lets you set up Python-style "virtualenvs," or subsets of packages that draw from an underlying pool of assets on the machine.

This way, you can work with (and specify) the dependencies (i.e., required packages) for one project without worrying about impacts on other projects.

- An `environment` is a set of packages specified by a `Project.toml` (and optionally, a `Manifest.toml`).
- A `registry` is a git repository corresponding to a list of (typically) registered packages, from which Julia can pull (for more on git repositories, see version control).
- A `depot` is a directory, like `~/.julia`, which contains assets (compile caches, registries, package source directories, etc.).

Essentially, an environment is a dependency tree for a project, or a "frame of mind" for Julia's package manager.

- We can see the default (`v1.1`) environment as such

```
In [6]: ] st
```

```
    Status `~/repos/lecture-source-
jl/_build/jupyterpdf/executed/more_julia/Project.toml`
  [2169fc97] AlgebraicMultigrid v0.2.2
  [28f2ccd6] ApproxFun v0.11.13
  [7d9fca2a] Arpack v0.4.0
  [aae01518] BandedMatrices v0.15.7
  [6e4b80f9] BenchmarkTools v0.5.0
  [a134a8b2] BlackBoxOptim v0.5.0
  [ffab5731] BlockBandedMatrices v0.8.4
  [324d7699] CategoricalArrays v0.8.0
  [34da2185] Compat v2.2.0
  [a93c6f00] DataFrames v0.21.0
  [1313f7d8] DataFramesMeta v0.5.1
  [39dd38d3] Dierckx v0.4.1
  [9fdde737] DiffEqOperators v4.10.0
  [31c24e10] Distributions v0.23.2
  [2fe49d83] Expectations v1.1.1
  [a1e7a1ef] Expokit v0.2.0
  [d4d017d3] ExponentialUtilities v1.6.0
  [442a2c76] FastGaussQuadrature v0.4.2
  [1a297f60] FillArrays v0.8.9
  [9d5cd8c9] FixedEffectModels v0.10.7
  [c8885935] FixedEffects v0.7.3
  [587475ba] Flux v0.10.4
  [f6369f11] ForwardDiff v0.10.10
  [38e38edf] GLM v1.3.9
  [28b8d3ca] GR v0.49.1
  [40713840] IncompleteLU v0.1.1
  [43edad99] InstantiateFromURL v0.5.0
```

```
  [a98d9a8b] Interpolations v0.12.9
  [b6b21f68] Ipopt v0.6.1
  [42fd0dbc] IterativeSolvers v0.8.4
  [4076af6c] JuMP v0.21.2
  [5ab0869b] KernelDensity v0.5.1
  [ba0b0d4f] Krylov v0.5.1
  [0b1a1467] KrylovKit v0.4.2
  [b964fa9f] LaTeXStrings v1.1.0
  [5078a376] LazyArrays v0.16.9
  [0fc2ff8b] LeastSquaresOptim v0.7.5
  [093fc24a] LightGraphs v1.3.3
  [7a12625a] LinearMaps v2.6.1
  [5c8ed15e] LinearOperators v1.1.0
  [961ee093] ModelingToolkit v3.6.4
  [76087f3c] NLopt v0.6.0
  [2774e3e8] NLsolve v4.3.0
  [429524aa] Optim v0.20.1
  [1dea7af3] OrdinaryDiffEq v5.38.1
  [d96e819e] Parameters v0.12.1
  [14b8a8f1] PkgTemplates v0.6.4
  [91a5bcdd] Plots v1.2.5
  [f27b6e38] Polynomials v1.0.6
  [af69fa37] Preconditioners v0.3.0
  [92933f4c] ProgressMeter v1.2.0
  [1fd47b50] QuadGK v2.3.1
  [fcd29c91] QuantEcon v0.16.2
  [1a8c2f83] Query v0.12.2
  [ce6b1742] RDatasets v0.6.8
  [d519eb52] RegressionTables v0.4.0
  [295af30f] Revise v2.6.6
  [f2b01f46] Roots v1.0.1
  [47a9eef4] SparseDiffTools v1.8.0
  [684fba80] SparsityDetection v0.3.1
  [90137ffa] StaticArrays v0.12.3
  [2913bbd2] StatsBase v0.32.2
  [3eaba693] StatsModels v0.6.11
  [f3b207a7] StatsPlots v0.14.6
  [789caeaf] StochasticDiffEq v6.20.0
  [a759f4b9] TimerOutputs v0.5.5 #master
(https://github.com/KristofferC/TimerOutputs.jl)
  [112f6efa] VegaLite v2.1.3
  [e88e6eb3] Zygote v0.4.20
  [37e2e46d] LinearAlgebra
  [9a3f8284] Random
  [2f01184e] SparseArrays
  [10745b16] Statistics
  [8dfed614] Test
```

- We can also create and activate a new environment

```
In [7]: ] generate ExampleEnvironment
```

```
  Generating  project ExampleEnvironment:
ExampleEnvironment/Project.toml
ExampleEnvironment/src/ExampleEnvironment.jl
```

- And go to it

```
In [8]: ; cd ExampleEnvironment
```

```
    /home/ubuntu/repos/lecture-source-
jl/_build/jupyterpdf/executed/more_julia/ExampleEnvironment
```

- To activate the directory, simply

```
In [9]: ] activate .
```

```
     Activating environment at `~/repos/lecture-source-
jl/_build/jupyterpdf/executed/more_julia/ExampleEnvironment/Project.toml`
```

where "." stands in for the "present working directory".

- Let's make some changes to this

```
In [10]: ] add Expectations Parameters
```

```
      Updating registry at `~/.julia/registries/General`
```

```
      Updating git-repo
`https://github.com/JuliaRegistries/General.git`
```

```
     Resolving package versions…
   Updating `~/repos/lecture-source-
jl/_build/jupyterpdf/executed/more_julia/ExampleEnvironment/Project.toml`
  [2fe49d83] + Expectations v1.6.0
  [d96e819e] + Parameters v0.12.1
   Updating `~/repos/lecture-source-
jl/_build/jupyterpdf/executed/more_julia/ExampleEnvironment/Manifest.toml`
  [56f22d72] + Artifacts v1.3.0
  [34da2185] + Compat v3.23.0
  [e66e0078] + CompilerSupportLibraries_jll v0.3.4+0
  [9a962f9c] + DataAPI v1.4.0
  [864edb3b] + DataStructures v0.18.8
  [31c24e10] + Distributions v0.23.12
  [2fe49d83] + Expectations v1.6.0
  [442a2c76] + FastGaussQuadrature v0.4.4
  [1a297f60] + FillArrays v0.9.7
  [692b3bcd] + JLLWrappers v1.1.3
  [e1d29d7a] + Missings v0.4.4
  [efe28fd5] + OpenSpecFun_jll v0.5.3+4
  [bac558e1] + OrderedCollections v1.3.2
  [90014a1f] + PDMats v0.10.1
  [d96e819e] + Parameters v0.12.1
  [1fd47b50] + QuadGK v2.4.1
  [79098fc4] + Rmath v0.6.1
  [f50d1b31] + Rmath_jll v0.2.2+1
  [a2af1166] + SortingAlgorithms v0.3.1
  [276daf66] + SpecialFunctions v0.10.3
  [90137ffa] + StaticArrays v0.12.5
```

```
  [2913bbd2] + StatsBase v0.33.2
  [4c63d2b9] + StatsFuns v0.9.6
  [3a884ed6] + UnPack v1.0.2
  [2a0f44e3] + Base64
  [ade2ca70] + Dates
  [8bb1440f] + DelimitedFiles
  [8ba89e20] + Distributed
  [b77e0a4c] + InteractiveUtils
  [76f85450] + LibGit2
  [8f399da3] + Libdl
  [37e2e46d] + LinearAlgebra
  [56ddb016] + Logging
  [d6f4376e] + Markdown
  [a63ad114] + Mmap
  [44cfe95a] + Pkg
  [de0858da] + Printf
  [3fa0cd96] + REPL
  [9a3f8284] + Random
  [ea8e919c] + SHA
  [9e88b42a] + Serialization
  [1a1011a3] + SharedArrays
  [6462fe0b] + Sockets
  [2f01184e] + SparseArrays
  [10745b16] + Statistics
  [4607b0f0] + SuiteSparse
  [8dfed614] + Test
  [cf7118a7] + UUIDs
  [4ec0a83e] + Unicode
```

Note the lack of commas

- To see the changes, simply open the `ExampleEnvironment` directory in an editor like Atom.

The Project TOML should look something like this

```
name = "ExampleEnvironment"
uuid = "14d3e79e-e2e5-11e8-28b9-19823016c34c"
authors = ["QuantEcon User <quanteconuser@gmail.com>"]
version = "0.1.0"

[deps]
Expectations = "2fe49d83-0758-5602-8f54-1f90ad0d522b"
Parameters = "d96e819e-fc66-5662-9728-84c9c7592b0a"
```

We can also

```
In [11]: ] precompile
```

```
    Precompiling project…
┌ Info: Precompiling ExampleEnvironment [d548e192-c78c-496f-9c49-1ae7ad370b2e]
└ @ Base loading.jl:1260
```

Note The TOML files are independent of the actual assets (which live in `~/.julia/packages`, `~/.julia/dev`, and `~/.julia/compiled`).

You can think of the TOML as specifying demands for resources, which are supplied by the `~/.julia` user depot.

- To return to the default Julia environment, simply

```
In [12]: ] activate
```

```
     Activating environment at `~/repos/lecture-source-
jl/_build/jupyterpdf/executed/more_julia/Project.toml`
```

without any arguments.

- Lastly, let's clean up

```
In [13]: ; cd ..
```

```
/home/ubuntu/repos/lecture-source-jl/_build/jupyterpdf/executed/more_julia
```

```
In [14]: ; rm -rf ExampleEnvironment
```

11.5.1 InstantiateFromURL

With this knowledge, we can explain the operation of the setup block

```
In [15]: using InstantiateFromURL
         # optionally add arguments to force installation: instantiate = true,
↪precompile = true
         github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

What this `github_project` function does is activate (and if necessary, download, instantiate and precompile) a particular Julia environment.

Chapter 12

Git, GitHub, and Version Control

12.1 Contents

Co-authored with Arnav Sood

An essential part of modern software engineering is using version control.

We use version control because

- Not all iterations on a file are perfect, and you may want to revert changes.
- We want to be able to see who has changed what and how.
- We want a uniform version scheme to do this between people and machines.
- Concurrent editing on code is necessary for collaboration.
- Version control is an essential part of creating reproducible research.

In this lecture, we'll discuss how to use Git and GitHub.

12.2 Setup

1. Make sure you create an account on GitHub.com.

- If you are a student, be sure to use the GitHub Student Developer Pack.
- Otherwise, see if you qualify for a free Non-Profit/Academic Plan.
- These come with things like unlimited private repositories, testing support, etc.

1. Install `git` and the GitHub Desktop application.

2. Install git.

3. Install the GitHub Desktop application.

4. Optionally (but strongly recommended): On Windows, change the default line-ending by:
5. Opening a Windows/Powershell console, or the "Git Bash" installed in the previous step.
6. Running the following

```
git config --global core.eol lf
git config --global core.autocrlf false
```

12.2.1 Git vs. GitHub vs. GitHub Desktop

To understand the relationship

- Git is an infrastructure for versioning and merging files (it is not specific to GitHub and does not even require an online server).
- GitHub provides an online service to coordinate working with Git repositories, and adds some additional features for managing projects.
- GitHub Desktop is just one of many GUI-based clients to make Git and GitHub easier to use.

Later, you may find yourself using alternatives

- GitHub is the market leader for open source projects and Julia, but there are other options, e.g. GitLab and Bitbucket.
- Instead of the GitHub Desktop, you may directly use the Git command line, GitKraken, or use the Git functionality built into editors such as Atom or VS Code.

Since these lecture notes are intended to provide a minimal path to using the technologies, here we will conflate the workflow of these distinct products.

12.3 Basic Objects

12.3.1 Repositories

The fundamental object in GitHub is a *repository* (or "repo") – this is the master directory for a project.

One example of a repo is the QuantEcon Expectations.jl package.

On the machine, a repo is a normal directory, along with a subdirectory called `.git` which contains the history of changes.

12.3.2 Commits

GitHub stores history as a sequence of changes to text, called *commits*.

Here is an example of a commit, which revises the style guide in a QuantEcon repo.

In particular, commits have the following features

- An ID (formally, an "SHA-1 hash")
- Content (i.e., a before and after state)

- Metadata (author, timestamp, commit message, etc.)

Note: It's crucial to remember that what's stored in a commit is only the actual changes you make to text.

This is a key reason why git can store long and complicated histories without consuming massive amounts of memory.

12.3.3 Common Files

In addition, each GitHub repository typically comes with a few standard text files

- A `.gitignore` file, which lists files/extensions/directories that GitHub shouldn't try to track (e.g., LaTeX compilation byproducts).
- A `README.md` file, which is a Markdown file which GitHub puts on the repository website.
- A `LICENSE.txt` file, which describes the terms under which the repository's contents are made available.

For an example of all three, see the Expectations.jl repo.

Of these, the `README.md` is the most important, as GitHub will display it as Markdown when accessing the repository online.

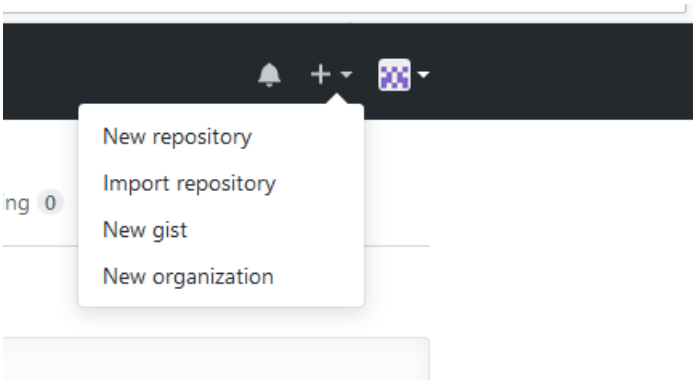
12.4 Individual Workflow

In this section, we'll describe how to use GitHub to version your own projects.

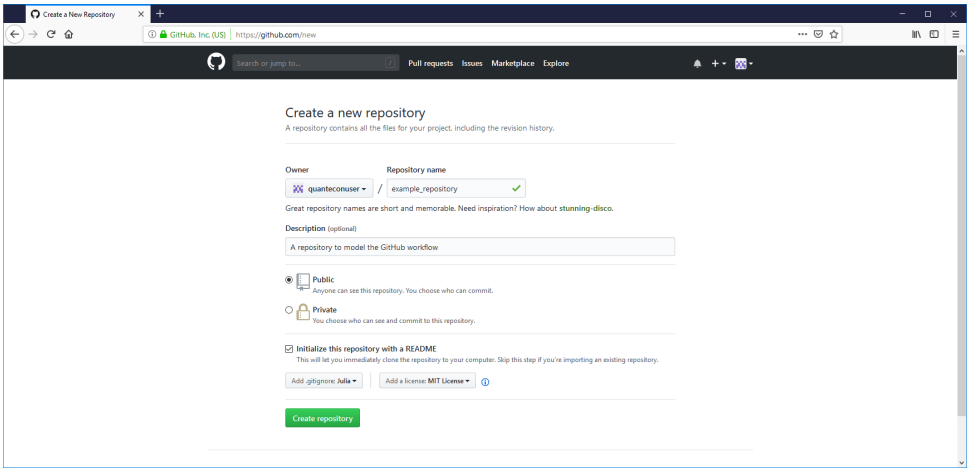
Much of this will carry over to the collaborative section.

12.4.1 Creating a Repository

In general, we will always want to repos for new projects using the following dropdown



We can then configure repository options as such



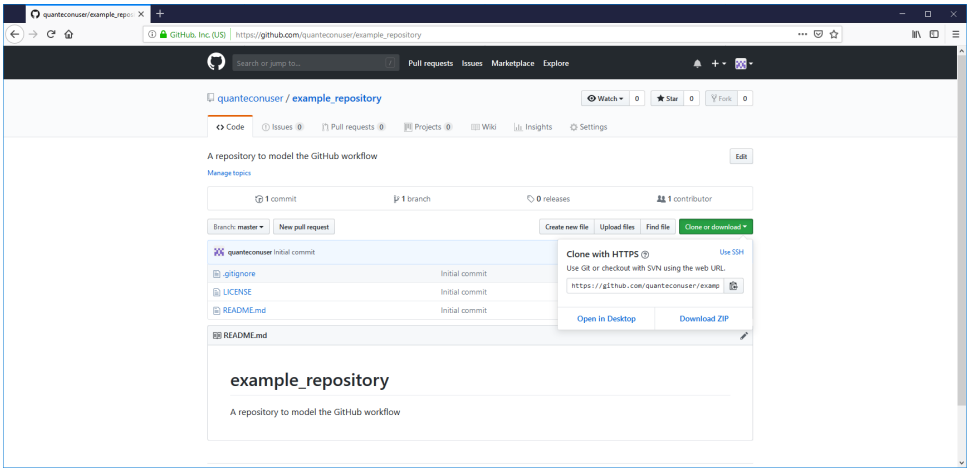
In this case, we're making a public repo `github.com/quantecon_user/example_repository`, which will come with a `README.md`, is licensed under the MIT License, and will ignore Julia compilation byproducts.

Note This workflow is for creating projects *de novo*; the process for turning existing directories into git repos is a bit more complicated.

In particular, in that case we recommend that you create a new repo via this method, then copy in and commit your files (see below), and then delete the old directory.

12.4.2 Cloning a Repository

The next step is to get this to our local machine



This dropdown gives us a few options

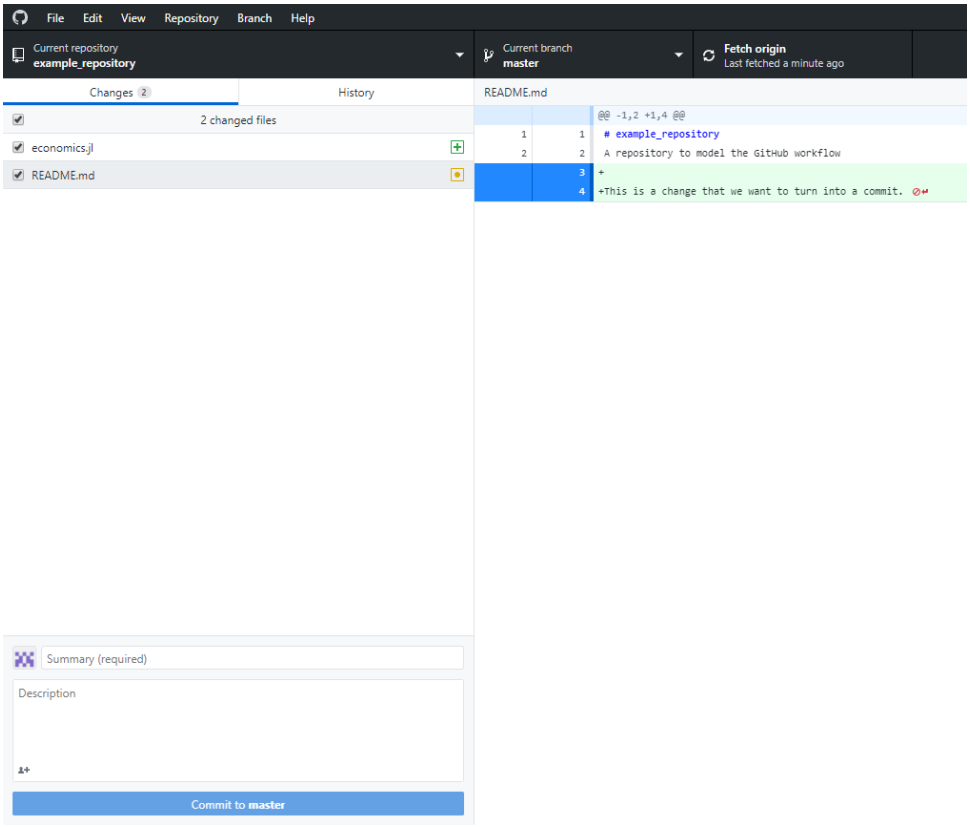
- "Open in Desktop" will call to the GitHub Desktop application that we've installed.
- "Download Zip" will download the directory *without the .git* subdirectory (avoid this option).
- The copy/paste button next to the link lets us use the command line, i.e. `git clone https://github.com/quanteconuser/example_repository.git`.

12.4.3 Making and Managing Changes

Now that we have the repository, we can start working with it.

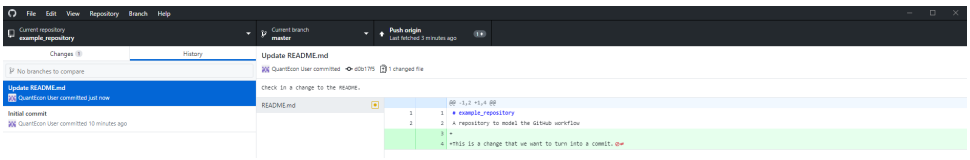
For example, let's say that we've amended the `README.md` (using our editor of choice), and also added a new file `economics.jl` which we're still working on.

Returning to GitHub Desktop, we should see something like



To select individual files for commit, we can use the check boxes to the left of each file.

Let's say you select only the README to commit. Going to the history tab should show you our change



The Julia file is unchanged.

12.4.4 Pushing to the Server

As of now, this commit lives only on our local machine.

To upload it to the server, you can simply click the "Push Origin" button at the top the screen.

The small "1^" to the right of the text indicates we have one commit to upload.

12.4.5 Reading and Reverting History

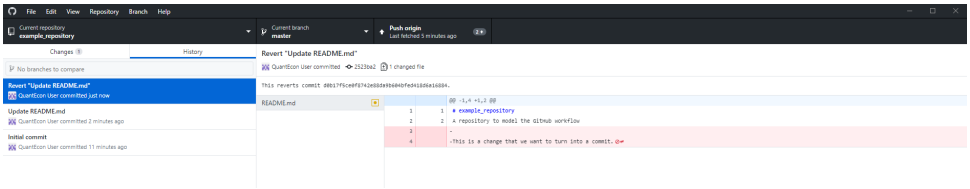
As mentioned, one of the key features of GitHub is the ability to scan through history.

By clicking the "commits" tab on the repo front page, we see this page (as an example).

Clicking an individual commit gives us the difference view, (e.g., example commit).

Sometimes, however, we want to not only inspect what happened before, but reverse the commit.

- If you haven't made the commit yet, just right-click the file in the "changes" tab and hit "discard changes" to reset the file to the last known commit.
- If you have made the commit but haven't pushed to the server yet, go to the "history" tab as above, right click the commit and click "revert this commit." This will create the inverse commit, shown below.



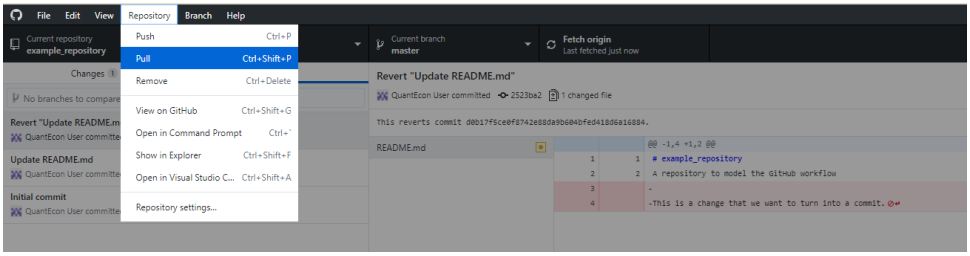
12.4.6 Working across Machines

Generally, you want to work on the same project but across multiple machines (e.g., a home laptop and a lab workstation).

The key is to push changes from one machine, and then to pull changes from the other machine.

Pushing can be done as above.

To pull, simply click pull under the "repository" dropdown at the top of the screen

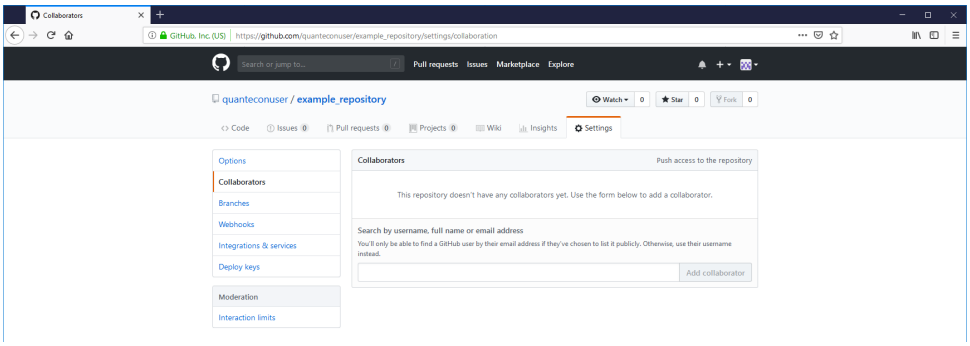


12.5 Collaborative Work

12.5.1 Adding Collaborators

First, let's add a collaborator to the `quanteconuser/example_repository` lecture we created earlier.

We can do this by clicking "settings => collaborators," as follows

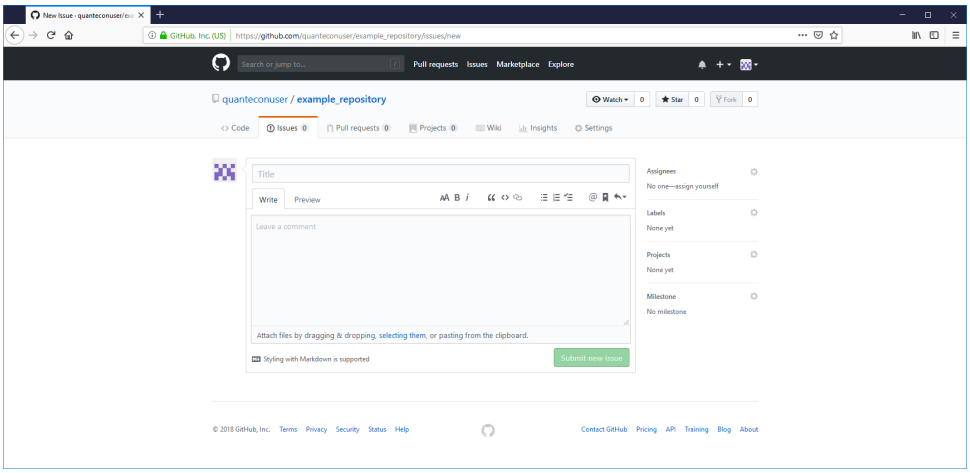


12.5.2 Project Management

GitHub's website also comes with project management tools to coordinate work between people.

The main one is an *issue*, which we can create from the issues tab.

You should see something like this

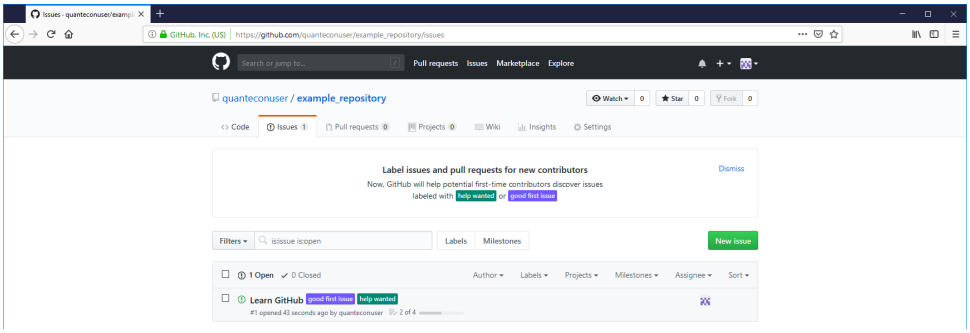


Let's unpack the different components

- The *assignees* dropdown lets you select people tasked to work on the issue.
- The *labels* dropdown lets you tag the issue with labels visible from the issues page, such as "high priority" or "feature request".
- It's possible to tag other issues and collaborators (including in different repos) by linking to them in the comments – this is part of what's called *GitHub-Flavored Markdown*.

For an example of an issue, see here.

You can see open issues at a glance from the general issues tab

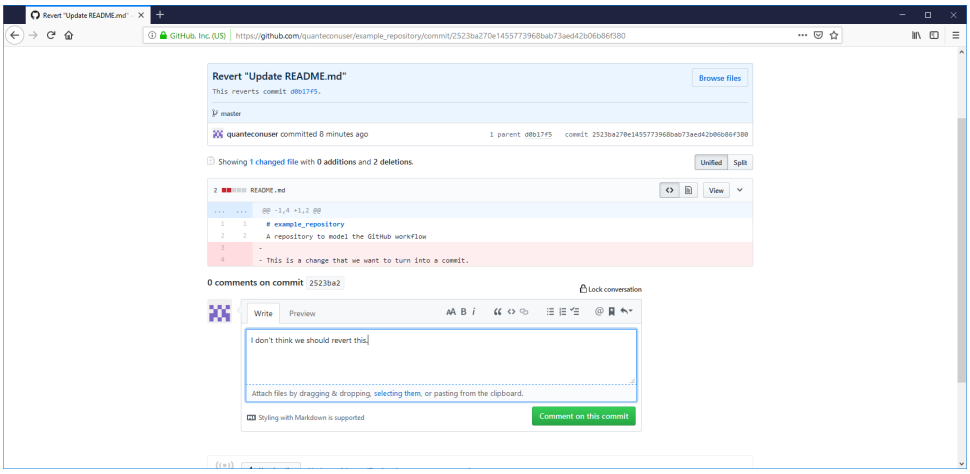


The checkboxes are common in GitHub to manage project tasks.

12.5.3 Reviewing Code

There are a few different ways to review people's code in GitHub

- Whenever people push to a project you're working on, you'll receive an email notification.
- You can also review individual line items or commits by opening commits in the difference view as above.



12.5.4 Merge Conflicts

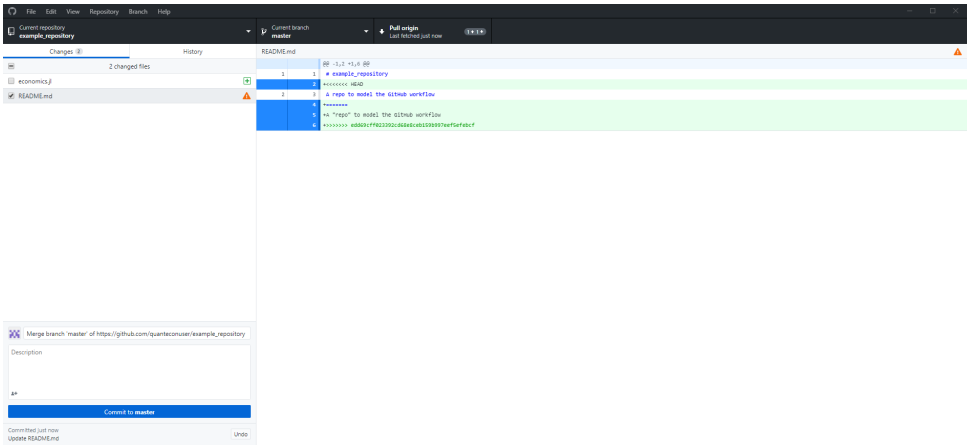
Any project management tool needs to figure out how to reconcile conflicting changes between people.

In GitHub, this event is called a "merge conflict," and occurs whenever people make conflicting changes to the same *line* of code.

Note that this means that two people touching the same file is OK, so long as the differences are compatible.

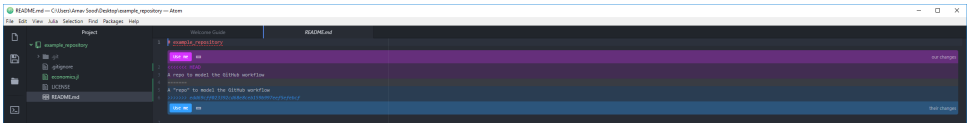
A common use case is when we try to push changes to the server, but someone else has pushed conflicting changes.

GitHub will give us the following window



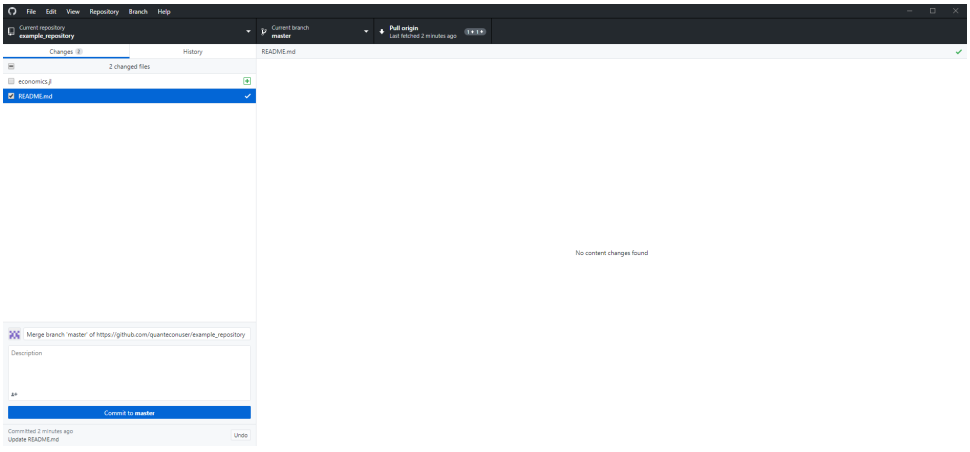
- The warning symbol next to the file indicates the existence of a merge conflict.
- The viewer tries to show us the discrepancy (I changed the word repository to repo, but someone else tried to change it to "repo" with quotes).

To fix the conflict, we can go into a text editor (such as Atom)



Let's say we click the first "use me" (to indicate that my changes should win out), and then save the file.

Returning to GitHub Desktop gives us a pre-formed commit to accept



Clicking "commit to master" will let us push and pull from the server as normal.

12.6 Collaboration via Pull Request

One of the defining features of GitHub is that it is the dominant platform for *open source* code, which anyone can access and use.

However, while anyone can make a copy of the source code, not everyone has access to modify the particular version stored on GitHub.

A maintainer (i.e. someone with "write" access to directly modify a repository) might consider different contributions and "merge" the changes into the main repository if the changes meet their criteria.

A *pull request* ("PR") allows **any** outsiders to suggest changes to open source repositories.

A PR requests the project maintainer to merge ("pull") changes you've worked on into their repository.

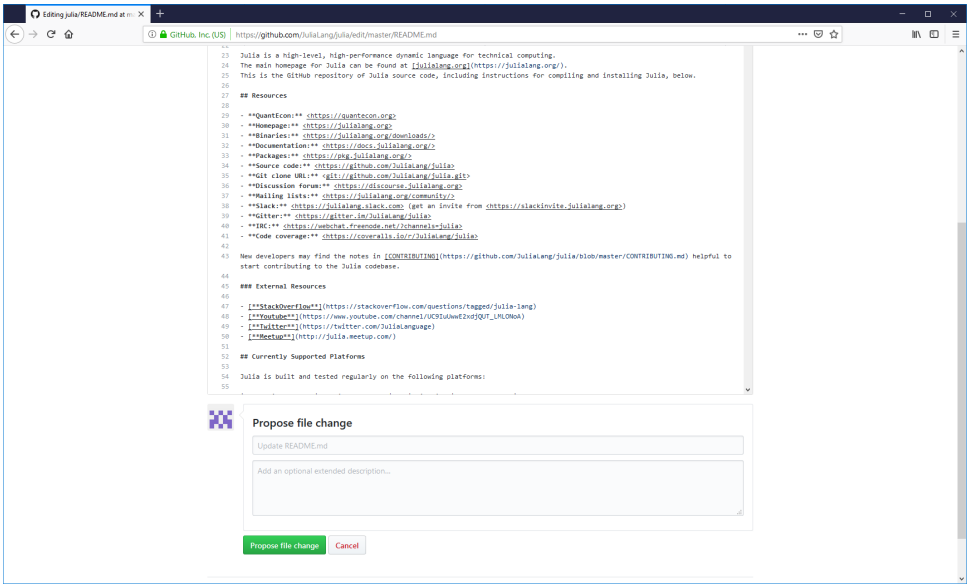
There are a few different workflows for creating and handling PRs, which we'll walk through below.

Note: If the changes are for a Julia Package, you will need to follow a different workflow – described in the testing lecture.

12.6.1 Quick Fixes

GitHub's website provides an online editor for quick and dirty changes, such as fixing typos in documentation.

To use it, open a file in GitHub and click the small pencil to the upper right



Here, we're trying to add the QuantEcon link to the Julia project's `README` file.

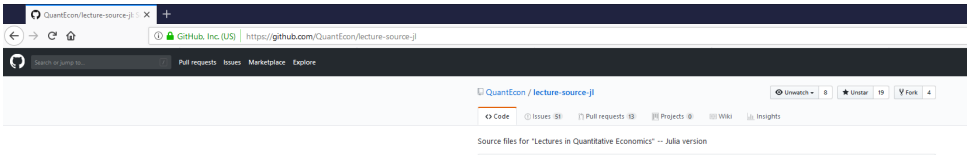
After making our changes, we can then describe and propose them for review by maintainers.

But what if we want to make more in-depth changes?

12.6.2 No-Access Case

A common problem is when we don't have write access (i.e. we can't directly modify) the repo in question.

In that case, click the "Fork" button that lives in the top-right of every repo's main page

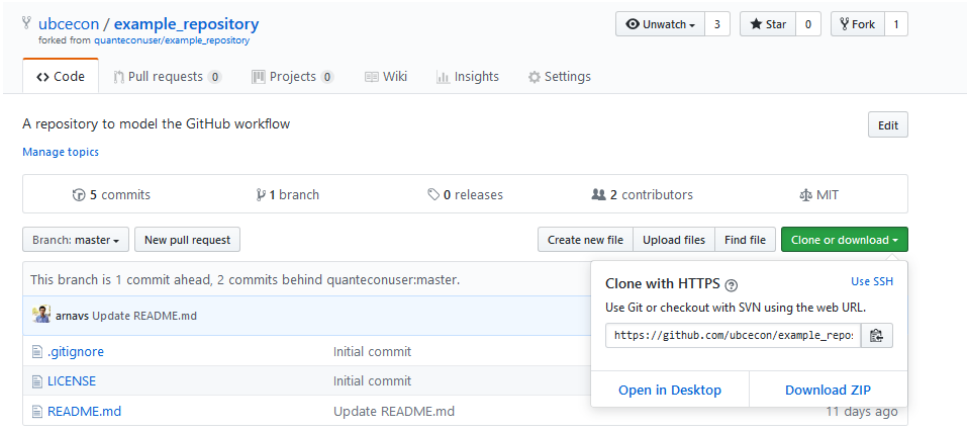


This will copy the repo into your own GitHub account.

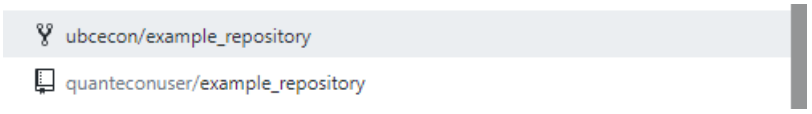
For example, this repo is a fork of our original git setup.

Clone this fork to our desktop and work with it in exactly the same way as we would a repo we own (as the fork is in your account, you now have write access).

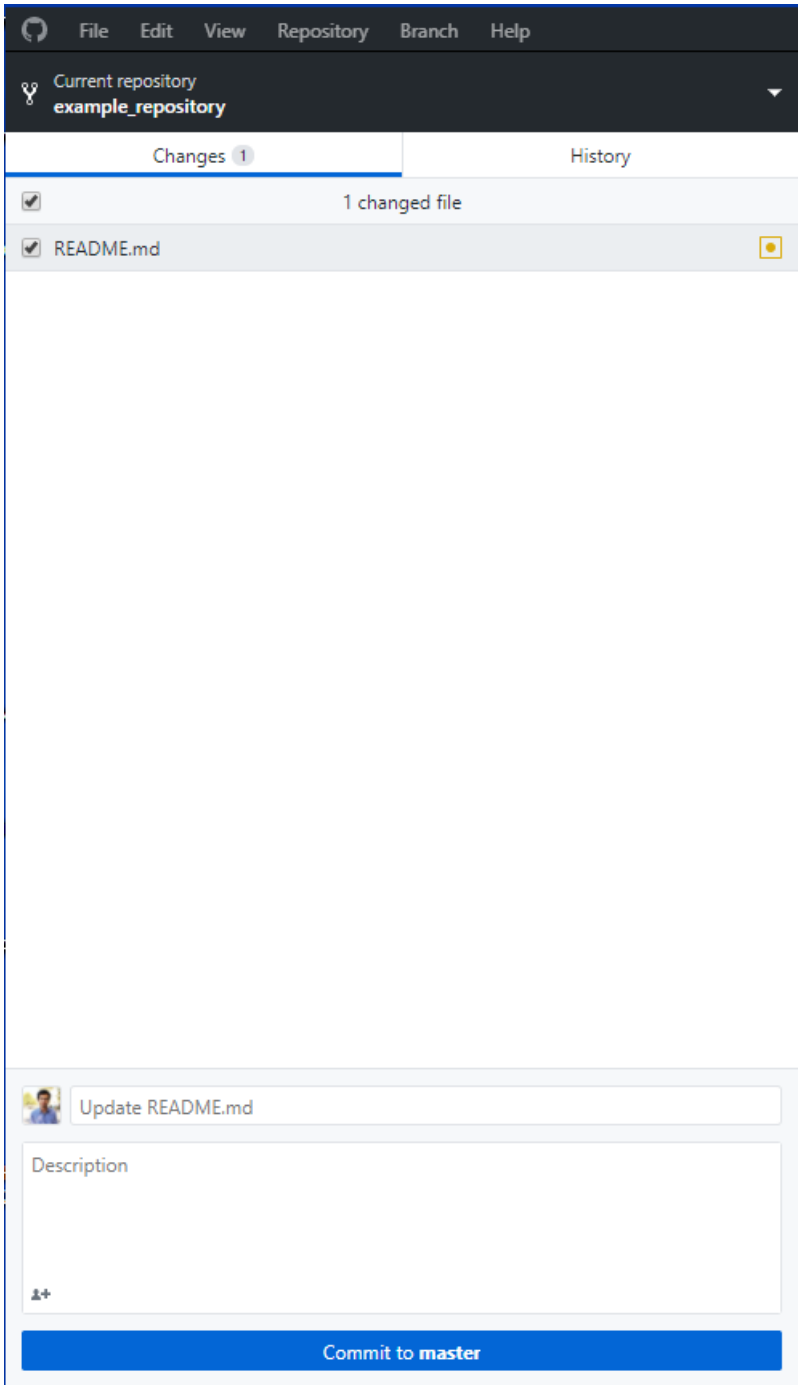
That is, click the "clone" button on our fork



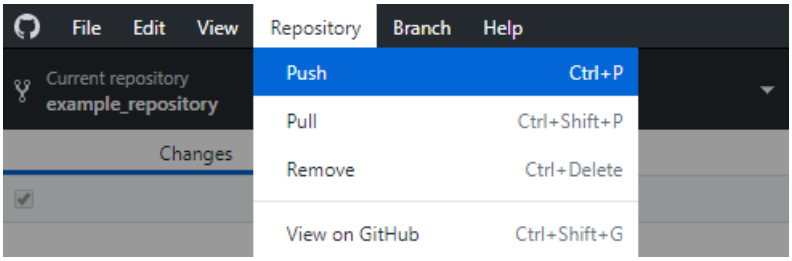
You'll see a new repo with the same name but different URL in your GitHub Desktop repo list, along with a special icon to indicate that it's a fork



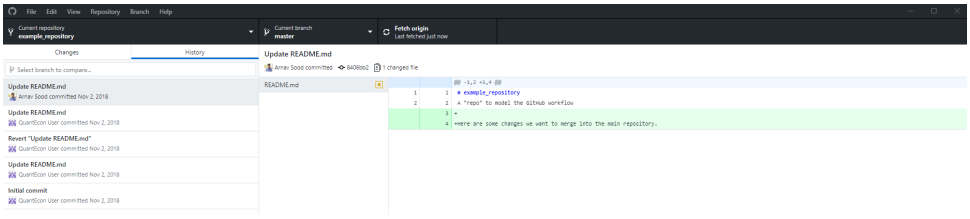
Commit some changes by selecting the files and writing a commit message



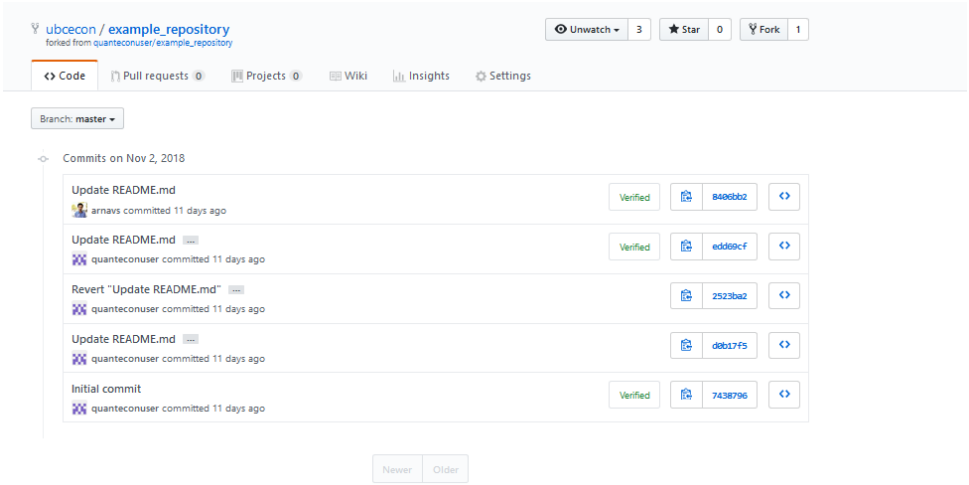
And push by using the dropdown



Below, for example, we've committed and pushed some changes to the fork that we want to upstream into the main repo

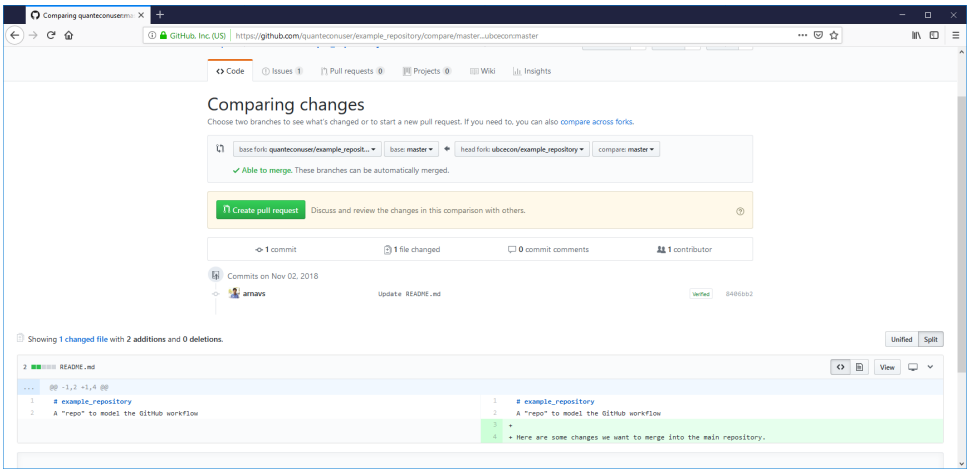


We should make sure that these changes are on the server (which we can get to by going to the fork and clicking "commits")



Next, go to the pull requests menu and click "New Pull Request".

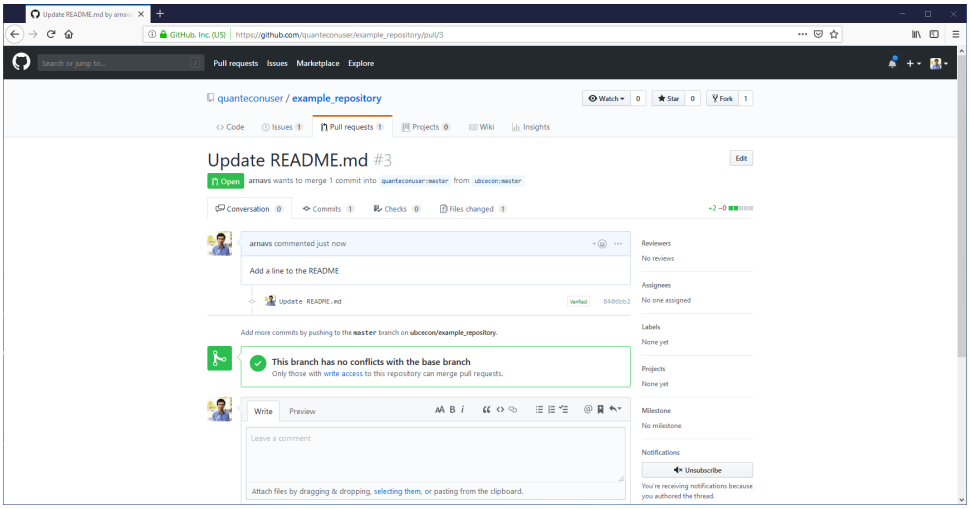
You'll see something like this



This gives us a quick overview of the commits we want to merge in, as well as the overall differences.

Hit create and then click through the following form.

This opens a page like this on the main repo



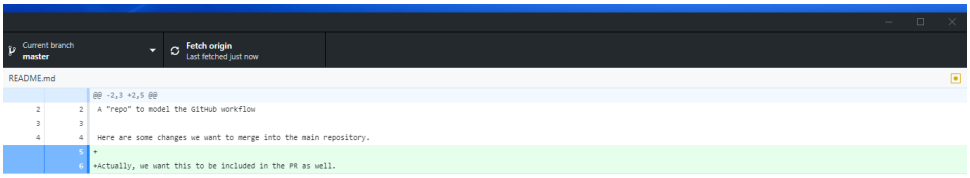
The key pieces are

- A list of the commits we're proposing.
- A list of reviewers, who can approve or modify our changes.
- Labels, Markdown space, assignees, and the ability to tag other git issues and PRs, just as with issues.

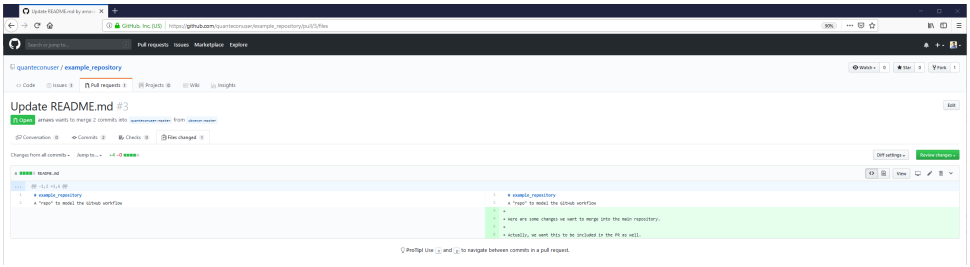
Here's an example pull request.

To edit a PR, simply push changes to the fork you cloned to your desktop.

For example, let's say we commit a new change to the README *after* we create the PR



After pushing to the server, the change is reflected on the PR page



That is, creating a pull request is not like bundling up your changes and delivering them, but rather like opening an *ongoing connection* between two repositories, that is only severed when the PR is closed or merged.

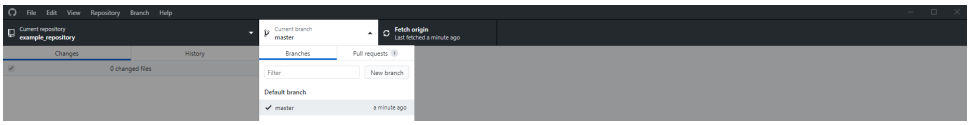
12.6.3 Write Access Case

As you become more familiar with GitHub, and work on larger projects, you will find yourself making PRs even when it isn't strictly required.

If you are a maintainer of the repo (e.g. you created it or are a collaborator) then you don't need to create a fork, but will rather work with a *git branch*.

Branches in git represent parallel development streams (i.e., sequences of commits) that the PR is trying to merge.

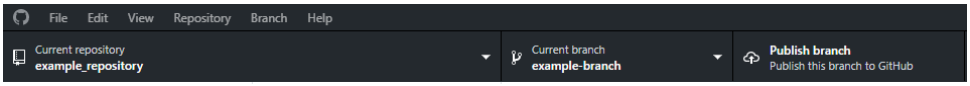
First, load the repo in GitHub Desktop and use the branch dropdown



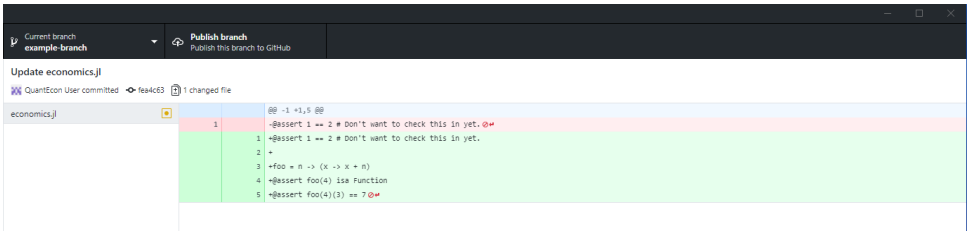
Click "New Branch" and choose an instructive name (make sure there are no spaces or special characters).

This will "check out" a new branch with the same history as the old one (but new commits will be added only to this branch).

We can see the active branch in the top dropdown

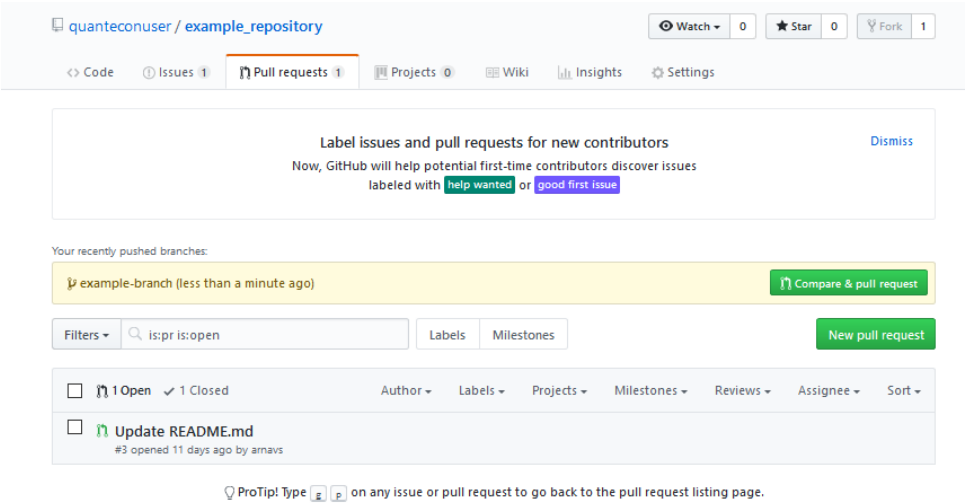


For example, let's say we add some stuff to the Julia code file and commit it



To put this branch (with changes) on the server, we simply need to click "Publish Branch".

Navigating to the repo page, we will see a suggestion about a new branch



At which point the process of creating a PR is identical to the previous case.

12.6.4 Julia Package Case

One special case is when the repo in question is actually a Julia project or package.

We cover that (along with package workflow in general) in the testing lecture.

12.7 Additional Resources and Troubleshooting

You may want to go beyond the scope of this tutorial when working with GitHub.

For example, perhaps you run into a bug, or you're working with a setup that doesn't have GitHub Desktop installed.

Here are some resources to help

- Kate Hudson's excellent git flight rules, which is a near-exhaustive list of situations you could encounter, and command-line fixes.
- The GitHub Learning Lab, an interactive sandbox environment for git.
- The docs for forking on GitHub Desktop and the GitHub Website.

12.7.1 Command-Line Basics

Git also comes with a set of command-line tools.

They're optional, but many people like using them.

Furthermore, in some environments (e.g. JupyterHub installations) you may only have access to the command line.

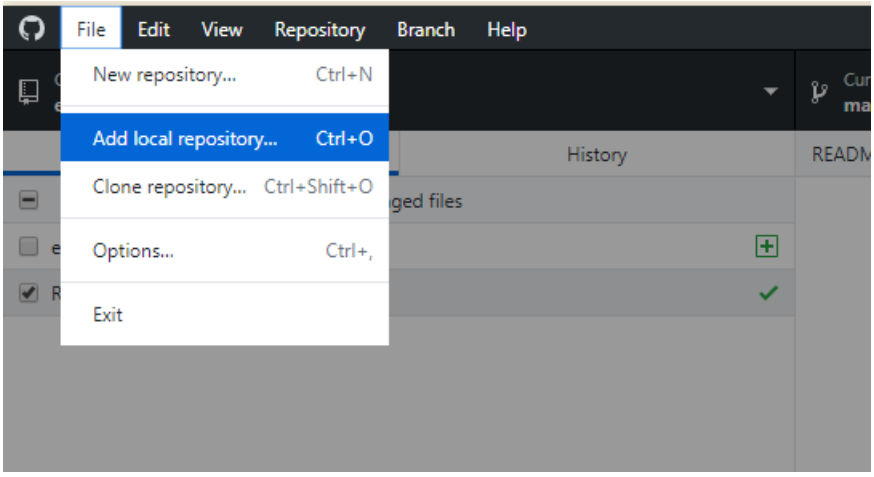
- On Windows, downloading `git` will have installed a program called `git bash`, which installs these tools along with a general Linux-style shell.
- On Linux/MacOS, these tools are integrated into your usual terminal.

To open the terminal in a directory, either right click and hit "open git bash" (in Windows), or use Linux commands like `cd` and `ls` to navigate.

See here for a short introduction to the command line.

As above, you can clone by grabbing the repo URL (say, GitHub's site-policy repo) and running `git clone https://github.com/github/site-policy.git`.

This won't be connected to your GitHub Desktop, so you'd need to use it manually (`File => Add Local Repository`) or drag-and-drop from the file explorer onto the GitHub Desktop



From here, you can get the latest files on the server by `cd`-ing into the directory and running `git pull`.

When you `pull` from the server, it will never overwrite your modified files, so it is impossible to lose local changes.

Instead, to do a hard reset of all files and overwrite any of your local changes, you can run `git reset --hard origin/master`.

12.8 Exercises

12.8.1 Exercise 1a

Follow the instructions to create a new repository for one of your GitHub accounts. In this repository

- Take the code from one of your previous assignments, such as Newton's method in Introductory Examples (either as a `.jl` file or a Jupyter notebook).
- Put in a `README.md` with some text.
- Put in a `.gitignore` file, ignoring the Jupyter files `.ipynb_checkpoints` and the project files, `.projects`.

12.8.2 Exercise 1b

Pair-up with another student who has done Exercise 1a and find out their GitHub ID, and each do the following

- Add the GitHub ID as a collaborators on your repository.

- Clone the repositories to your local desktop.
- Assign each other an issue.
- Submit a commit from GitHub Desktop which references the issue by number.
- Comment on the commits.
- Ensure you can run their code without any modifications.

12.8.3 Exercise 1c

Pair-wise with the results of Exercise 1b examine a merge-conflict by editing the `README.md` file for your repository that you have both setup as collaborators.

Start by ensuring there are multiple lines in the file so that some changes may have conflicts, and some may not.

- Clone the repository to your local desktops.
- Modify **different** lines of code in the file and both commit and push to the server (prior to pulling from each other)–and see how it merges things "automatically".
- Modify **the same** line of code in the file, and deal with the merge conflict.

12.8.4 Exercise 2a

Just using GitHub's web interface, submit a Pull Request for a simple change of documentation to a public repository.

The easiest may be to submit a PR for a typo in the source repository for these notes, i.e. `https://github.com/QuantEcon/lecture-source-jl`.

Note: The source for that repository is in `.rst` files, but you should be able to find spelling mistakes/etc. without much effort.

12.8.5 Exercise 2b

Following the instructions for forking and cloning a public repository to your local desktop, submit a Pull Request to a public repository.

Again, you could submit it for a typo in the source repository for these notes, i.e. `https://github.com/QuantEcon/lecture-source-jl`, but you are also encouraged to instead look for a small change that could help the documentation in another repository.

If you are ambitious, then go to the Exercise Solutions for one of the Exercises in these lecture notes and submit a PR for your own modified version (if you think it is an improvement!).

Chapter 13

Packages, Testing, and Continuous Integration

13.1 Contents

> A complex system that works is invariably found to have evolved from a simple system that worked. The inverse proposition also appears to be true: A complex system designed from scratch never works and cannot be made to work. You have to start over, beginning with a working simple system – Gall's Law.

Co-authored with Arnav Sood

This lecture discusses structuring a project as a Julia module, and testing it with tools from GitHub.

Benefits include

- Specifying dependencies (and their versions) so that your project works across Julia setups and over time.
- Being able to load your project's functions from outside without copy/pasting.
- Writing tests that run locally, *and automatically on the GitHub server.*
- Having GitHub test your project across operating systems, Julia versions, etc.

13.2 Project Setup

13.2.1 Account Setup

Travis CI

As we'll see later, Travis is a service that automatically tests your project on the GitHub server.

First, we need to make sure that your GitHub account is set up with Travis CI and Codecov.

As a reminder, make sure you signed up for the GitHub Student Developer Pack or Academic Plan if eligible.

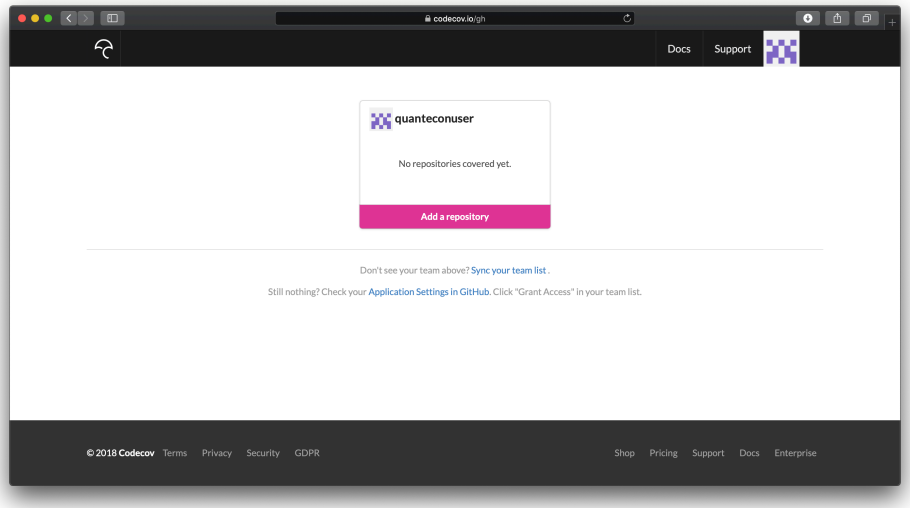
Navigate to the travis-ci.com website and click "sign up with GitHub" – supply your credentials.

If you get stuck, see the Travis tutorial.

Codecov

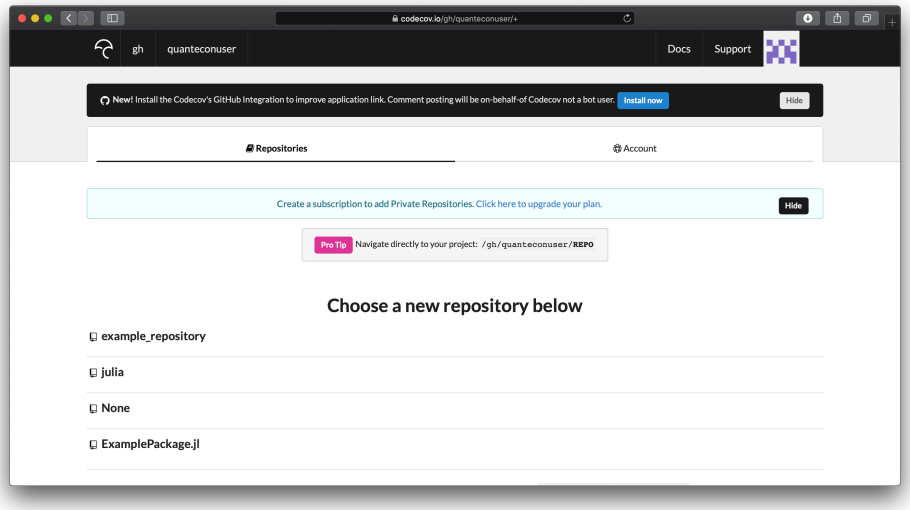
Codecov is a service that tells you how comprehensive your tests are (i.e., how much of your code is actually tested).

To sign up, visit the Codecov website, and click "sign up"



Next, click "add a repository" and *enable private scope* (this allows Codecov to service your private projects).

The result should be



This is all we need for now.

13.2.2 Julia Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

Note: Before these steps, make sure that you've either completed the version control lecture or run.

```
git config --global user.name "Your Name"
```

Note: Throughout this lecture, important points and sequential workflow steps are listed as bullets.

To set up a project on Julia:

- Load the PkgTemplates package.

```
using PkgTemplates
```

- Create a *template* for your project.

This specifies metadata like the license we'll be using (MIT by default), the location (`~/.julia/dev` by default), etc.

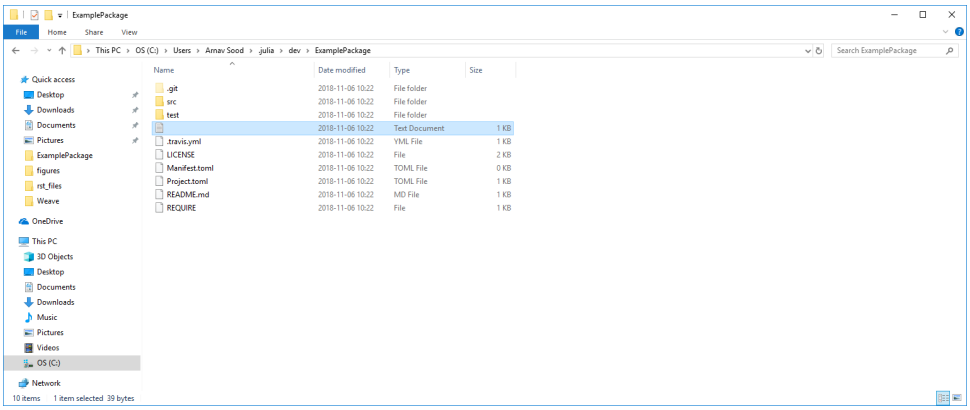
```
ourTemplate = Template(;user="quanteconuser", plugins = [TravisCI(), Codecov()],
```

Note: Make sure you replace the `quanteconuser` with your GitHub ID.

- Create a specific project based off this template

```
generate("ExamplePackage.jl", ourTemplate)
```

If we navigate to the package directory, we should see something like the following.



As a reminder, the location of your `.julia` folder can be found by running `DEPOT_PATH[1]` in a REPL .

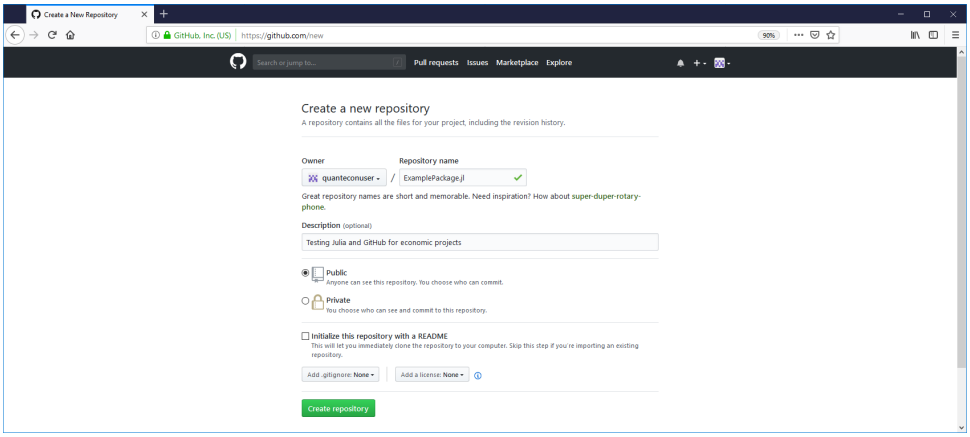
Note: On Mac, this may be hidden; you can either start a terminal, `cd ~` and then `cd .julia`, or make hidden files visible in the Finder.

13.2.3 Adding a Project to Git

The next step is to add this project to Git version control.

- Open the repository screen in your account as discussed previously.

We'll want the following settings



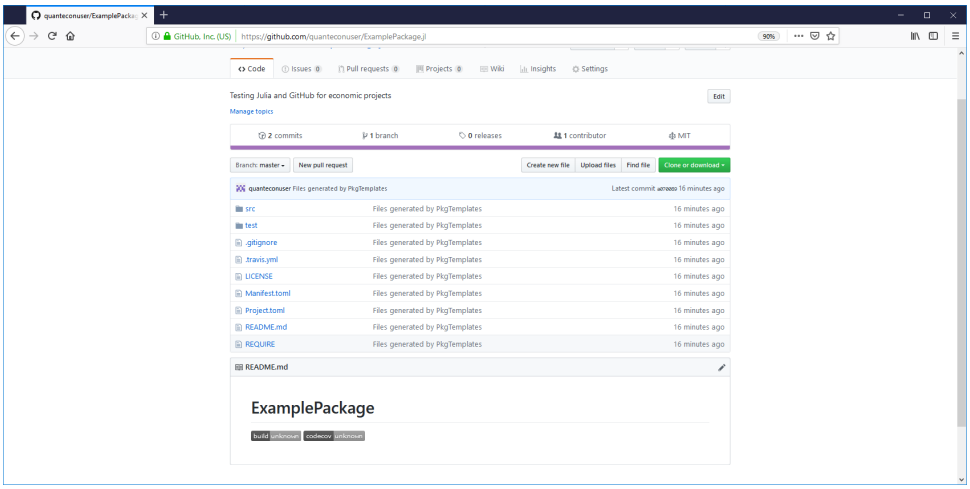
In particular

- The repo you create should have the same name as the project we added.
- We should leave the boxes unchecked for the `README.md`, `LICENSE`, and `.gitignore`, since these are handled by `PkgTemplates`.

Then,

- Drag and drop your folder from your `~/.julia/dev` directory to GitHub Desktop.
- Click the "publish branch" button to upload your files to GitHub.

If you navigate to your git repo (ours is here), you should see something like



Note: Be sure that you don't separately clone the repo you just added to another location (i.e., to your desktop).

A key note is that you have some set of files on your local machine (here in `~/.julia/dev/ExamplePackage.jl`) and git is plugged into those files.

For convenience, you might want to create a shortcut to that location somewhere accessible.

13.2.4 Adding a Project to the Julia Package Manager

We also want Julia's package manager to be aware of the project.

- Open a REPL in the newly created project directory, either by noting the path printed above, or by running the following in a REPL.

```
cd(joinpath(DEPOT_PATH[1], "dev", "ExamplePackage"))
```

Note the lack of `.jl`!

- Run the following

```
] activate
```

to get into the main Julia environment (more on environments in the second half of this lecture).

- And run

```
] dev .
```

to add the package.

You can see the change reflected in our default package list by running

```
] st
```

For more on the package mode, see the tools and editors lecture.

13.2.5 Using the Package Manager

Now, from any Julia terminal in the future, we can run

```
using ExamplePackage
```

To use its exported functions.

We can also get the path to this by running

```
using ExamplePackage
pathof(ExamplePackage) # returns path to src/ExamplePackage.jl
```

13.3 Project Structure

Let's unpack the structure of the generated project

- The first directory, `.git`, holds the version control information.
- The `src` directory contains the project's source code – it should contain only one file (`ExamplePackage.jl`), which reads

```
module ExamplePackage

greet() = print("Hello World!")

end # module
```

- Likewise, the `test` directory should have only one file (`runtests.jl`), which reads

```
using ExamplePackage
using Test

@testset "ExamplePackage.jl" begin
    # Write your own tests here.
end
```

In particular, the workflow is to export objects we want to test (`using ExamplePackage`), and test them using Julia's `Test` module.

The other important text files for now are

- `Project.toml` and `Manifest.toml`, which contain dependency information.

In particular, the `Project.toml` contains a list of dependencies, and the `Manifest.toml` specifies their exact versions and sub-dependencies.

- The `.gitignore` file (which may display as an untitled file), which contains files and paths for `git` to ignore.

13.4 Project Workflow

13.4.1 Dependency Management

Environments

As before, the .toml files define an *environment* for our project, or a set of files which represent the dependency information.

The actual files are written in the TOML language, which is a lightweight format to specify configuration options.

This information is the name of every package we depend on, along with the exact versions of those packages.

This information (in practice, the result of package operations we execute) will be reflected in our `ExamplePackage.jl` directory's TOML, once that environment is activated (selected).

This allows us to share the project with others, who can exactly reproduce the state used to build and test it.

See the Pkg3 docs for more information.

Pkg Operations

For now, let's just try adding a dependency

- Activate the package environment (to be run from the base, `v1.1` environment)

```
] activate ExamplePackage
```

This tells Julia to write the results of package operations to `ExampleProject`'s TOML,

and use the versions of packages specified there.

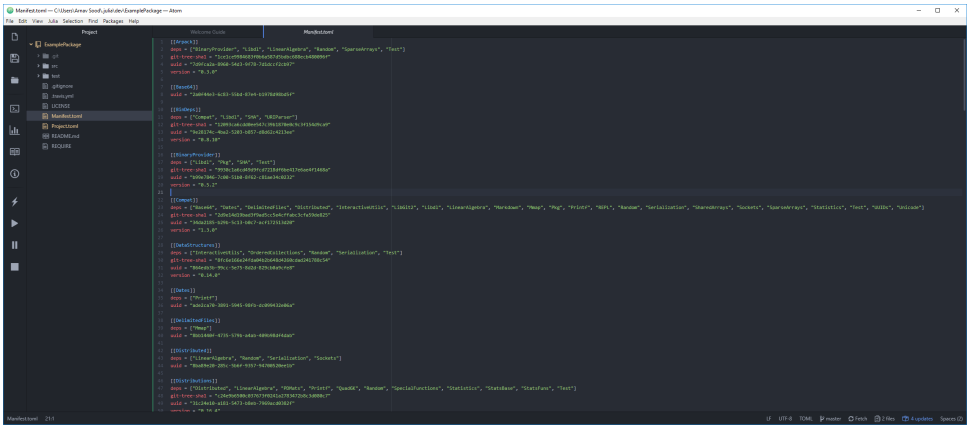
Note that the base environment isn't special, except that it's what's loaded by a freshly-started REPL or Jupyter notebook.

- Add a package

```
] add Expectations
```

We can track changes in the TOML, as before.

Here's the `Manifest.toml`



We can also run other operations, like `] up`, `] precompile`, etc.

Package operations are listed in detail in the tools and editors lecture.

Recall that, to quit the active environment and return to the base `(v1.1)`, simply run

```
] activate
```

13.4.2 Writing Code

The basic idea is to work in `tests/runtests.jl`, while reproducible functions should go in the `src/ExamplePackage.jl`.

For example, let's say we add `Distributions.jl`

```
] activate ExamplePackage
```

```
] add Distributions
```

and edit the source (paste this into the file itself) to read as follows

```
module ExamplePackage

greet() = print("Hello World!")

using Expectations, Distributions

function foo(μ = 1., σ = 2.)
    d = Normal(μ, σ)
    E = expectation(d)
    return E(x -> sin(x))
end

export foo

end # module
```

Let's try calling this

```
] activate
```

```
using ExamplePackage
ExamplePackage.greet()
```

```
foo() # exported, so don't need to qualify the namespace
```

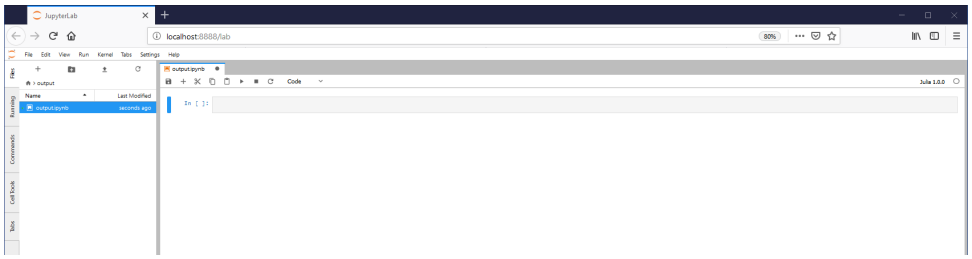
Note: You may need to quit your REPL and load the package again.

13.4.3 Jupyter Workflow

We can also work with the package from a Jupyter notebook.

Let's create a new output directory in our project, and run `jupyter lab` from it.

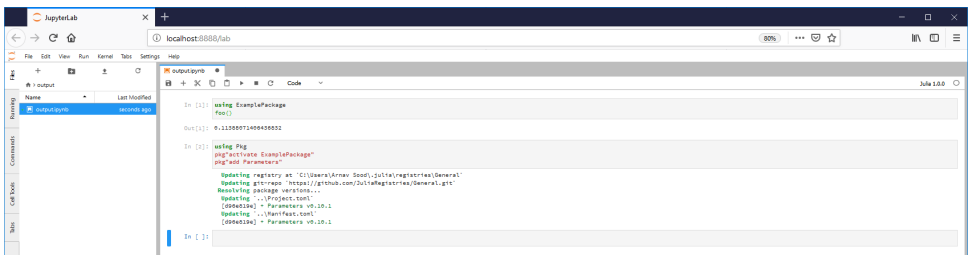
Create a new notebook `output.ipynb`



From here, we can use our package's functions as we would functions from other packages.

This lets us produce neat output documents, without pasting the whole codebase.

We can also run package operations inside the notebook



The change will be reflected in the `Project.toml` file.

Note that, as usual, we had to first activate `ExamplePackage` first before making our dependency changes

```
name = "ExamplePackage"
uuid = "f85830d0-e1f0-11e8-2fad-8762162ab251"
authors = ["QuantEcon User <quanteconuser@gmail.com>"]
```

```
version = "0.1.0"

[deps]
Distributions = "31c24e10-a181-5473-b8eb-7969acd0382f"
Expectations = "2fe49d83-0758-5602-8f54-1f90ad0d522b"
Parameters = "d96e819e-fc66-5662-9728-84c9c7592b0a"

[extras]
Test = "8dfed614-e22c-5e08-85e1-65c5234f0b40"

[targets]
test = ["Test"]
```

There will also be changes in the Manifest as well .

Be sure to add `output/.ipynb_checkpoints` to your `.gitignore` file, so that's not checked in.

Make sure you've activated the project environment (`] activate ExamplePackage`) before you try to propagate changes.

13.4.4 Collaborative Work

For someone else to get the package, they simply need to

- Run the following command

```
] dev https://github.com/quanteconuser/ExamplePackage.jl.git
```

This will place the repository inside their `~/.julia/dev` folder.

- Drag-and-drop the folder to GitHub desktop in the usual way.

Recall that the path to your `~/.julia` folder is

```
In [2]: DEPOT_PATH[1]
```

```
Out[2]: "/home/ubuntu/.julia"
```

They can then collaborate as they would on other git repositories.

In particular, they can run

```
] activate ExamplePackage
```

to load the list of dependencies, and

```
] instantiate
```

to make sure they are installed on the local machine.

13.5 Unit Testing

It's important to make sure that your code is well-tested.

There are a few different kinds of test, each with different purposes

- *Unit testing* makes sure that individual pieces of a project work as expected.
- *Integration testing* makes sure that they fit together as expected.
- *Regression testing* makes sure that behavior is unchanged over time.

In this lecture, we'll focus on unit testing.

In general, well-written unit tests (which also guard against regression, for example by comparing function output to hardcoded values) are sufficient for most small projects.

13.5.1 The `Test` Module

Julia provides testing features through a built-in package called `Test`, which we get by `using Test`.

The basic object is the macro `@test`

```
In [3]: using Test
        @test 1 == 1
        @test 1 ≈ 1
```

```
Out[3]: Test Passed
```

Tests will pass if the condition is `true`, or fail otherwise.

If a test is failing, we should flag it with `@test_broken` as below

```
In [4]: @test_broken 1 == 2
```

```
Out[4]: Test Broken
          Expression: 1 == 2
```

This way, we still have access to information about the test, instead of just deleting it or commenting it out.

There are other test macros, that check for things like error handling and type-stability.

Advanced users can check the Julia docs.

13.5.2 Example

Let's add some unit tests for the `foo()` function we defined earlier.

Our `tests/runtests.jl` file should look like this.

As before, this should be pasted into the file directly

```
using ExamplePackage
using Test
```

```
@test foo() ≈ 0.11388071406436832
@test foo(1, 1.5) ≈ 0.2731856314283442
@test_broken foo(1, 0) # tells us this is broken
```

And run it by typing `] test` into an activated REPL (i.e., a REPL where you've run `] activate ExamplePackage`).

13.5.3 Test Sets

By default, the `runtests.jl` folder starts off with a `@testset`.

This is useful for organizing different batches of tests, but for now we can simply ignore it.

To learn more about test sets, see the docs.

13.5.4 Running Tests

There are a few different ways to run the tests for your package.

- Run the actual `runtests.jl`, say by hitting `shift-enter` on it in Atom.
- From a fresh (`v1.1`) REPL, run `] test ExamplePackage`.
- From an activated (`ExamplePackage`) REPL, simply run `] test` (recall that you can activate with `] activate ExamplePackage`).

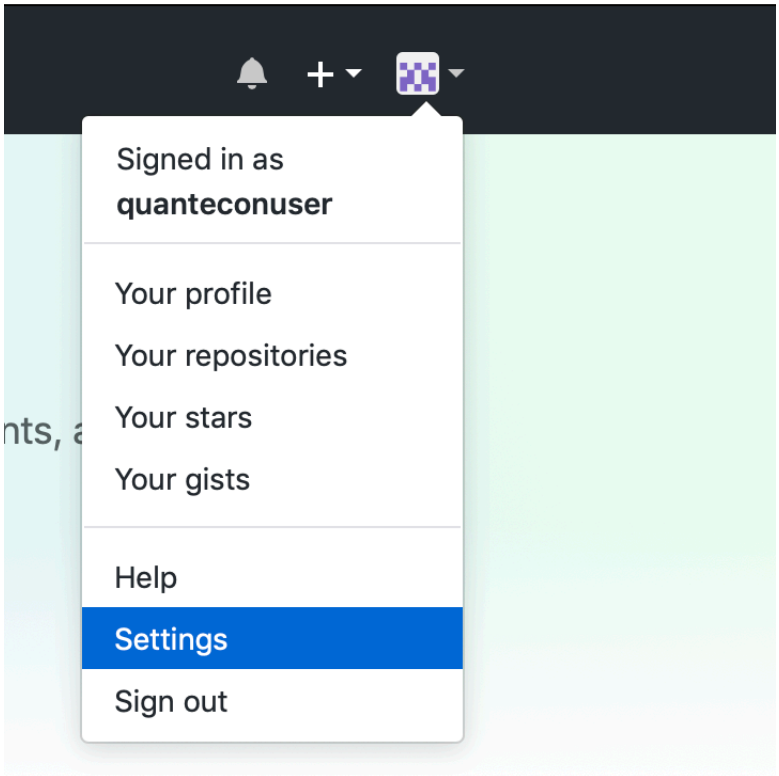
13.6 Continuous Integration with Travis

13.6.1 Setup

By default, Travis should have access to all your repositories and deploy automatically.

This includes private repos if you're on a student developer pack or an academic plan (Travis detects this automatically).

To change this, go to "settings" under your GitHub profile



Click "Applications," then "Travis CI," then "Configure," and choose the repos you want to be tracked.

13.6.2 Build Options

By default, Travis will compile and test your project (i.e., "build" it) for new commits and PRs for every tracked repo with a `.travis.yml` file.

We can see ours by opening it in Atom

```
# Documentation: http://docs.travis-ci.com/user/languages/julia/
language: julia
os:
- linux
- osx
julia:
- 1.1
- nightly
matrix:
allow_failures:
    - julia: nightly
fast_finish: true
notifications:
email: false
after_success:
- julia -e 'using Pkg; Pkg.add("Coverage"); using Coverage; Codecov.submit(proce
```

This is telling Travis to build the project in Julia, on OSX and Linux, using Julia v1.1 and the latest development build ("nightly").

It also says that if the nightly version doesn't work, that shouldn't register as a failure.

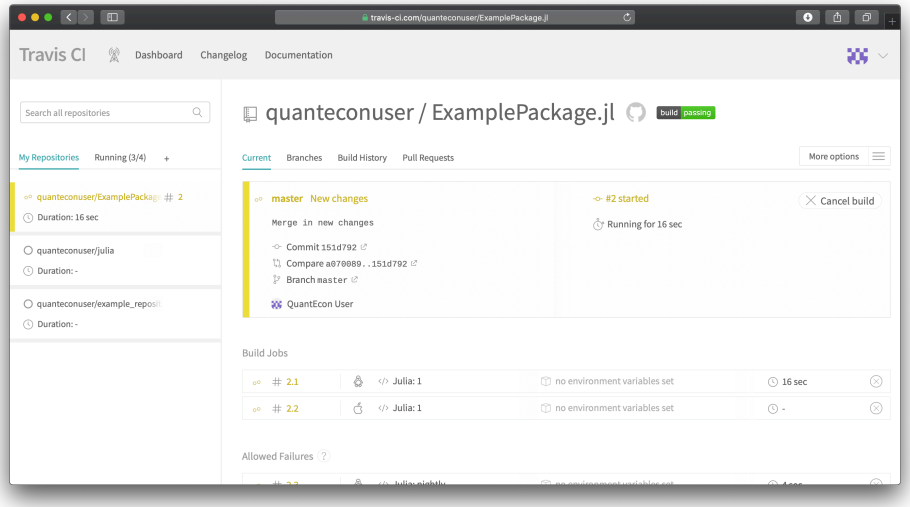
Note You won't need OSX unless you're building something Mac-specific, like iOS or Swift.

You can delete those lines to speed up the build, likewise for the nightly Julia version.

13.6.3 Working with Builds

As above, builds are triggered whenever we push changes or open a pull request.

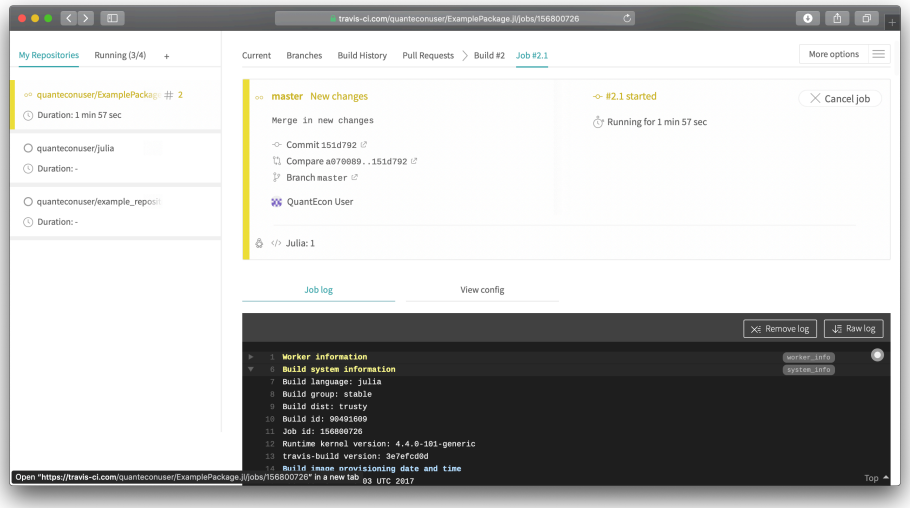
For example, if we push our changes to the server and then click the Travis badge (the one which says "build") on the README, we should see something like



Note that you may need to wait a bit and/or refresh your browser.

This gives us an overview of all the builds running for that commit.

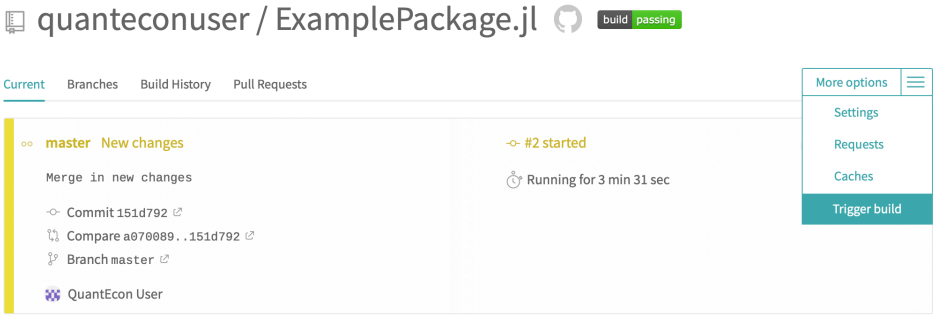
To inspect a build more closely (say, if it fails), we can click on it and expand the log options



Note that the build times here aren't informative, because we can't generally control the hardware to which our job is allocated.

We can also cancel specific jobs, either from their specific pages or by clicking the grey "x" button on the dashboard.

Lastly, we can trigger builds manually (without a new commit or PR) from the Travis overview



To commit *without* triggering a build, simply add "[ci skip]" somewhere inside the commit message.

13.6.4 Travis and Pull Requests

One key feature of Travis is the ability to see at-a-glance whether PRs pass tests before merging them.

This happens automatically when Travis is enabled on a repository.

For an example of this feature, see this PR in the `Games.jl` repository.

13.7 Code Coverage

Beyond the success or failure of our test suite, we also want to know how much of our code the tests cover.

The tool we use to do this is called Codecov.

13.7.1 Setup

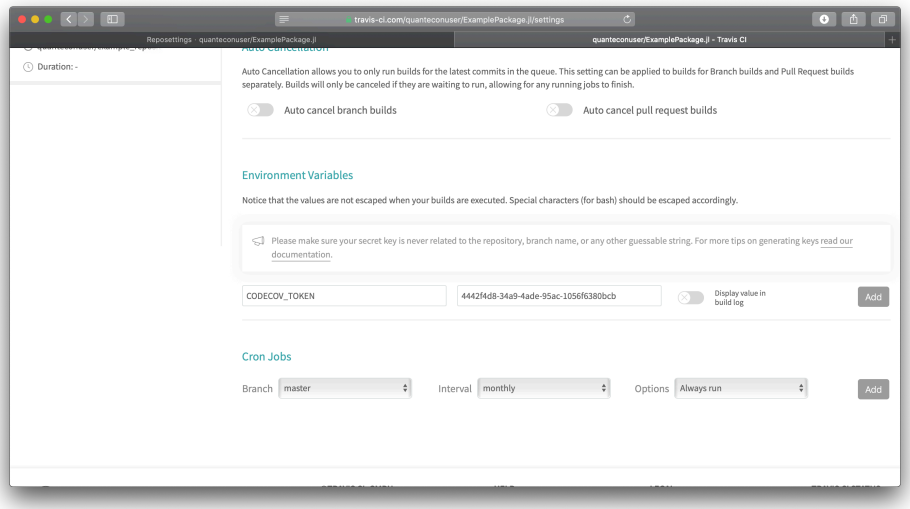
You'll find that Codecov is automatically enabled for public repos with Travis.

For private ones, you'll need to first get an access token.

Add private scope in the Codecov website, just like we did for Travis.

Navigate to the repo settings page (i.e., `https://codecov.io/gh/quanteconuser/ExamplePackage.` for our repo) and copy the token.

Next, go to your Travis settings and add an environment variable as below



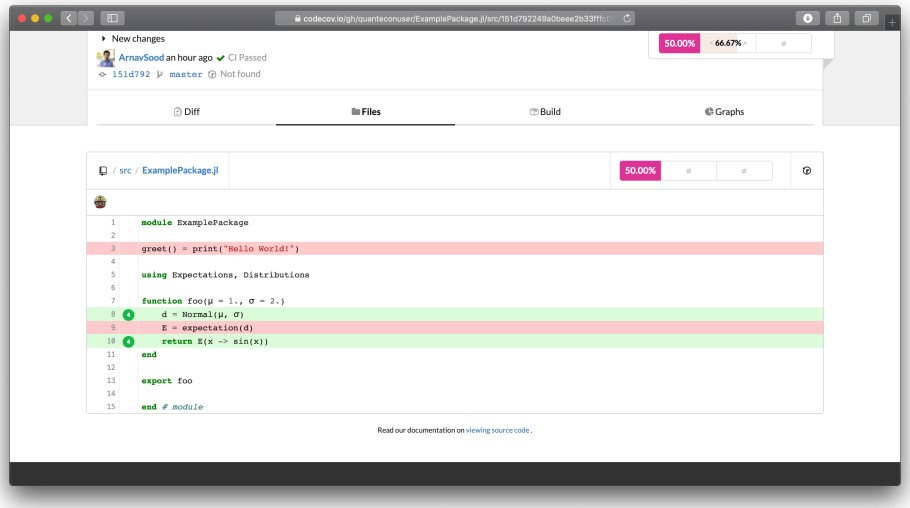
13.7.2 Interpreting Results

Click the Codecov badge to see the build page for your project.

This shows us that our tests cover 50% of our functions in `src//`.

Note: To get a more detailed view, we can click the `src//` and the resultant filename.

Note: Codecov may take a few minutes to run for the first time



This shows us precisely which methods (and parts of methods) are untested.

13.8 Pull Requests to External Julia Projects

As mentioned in version control, sometimes we'll want to work on external repos that are also Julia projects.

- `] dev` the git URL (or package name, if the project is a registered Julia package), which will both clone the git repo to `~/.julia/dev` and sync it with the Julia package manager.

For example, running

```
] dev Expectations
```

will clone the repo `https://github.com/quantecon/Expectations.jl` to `~/.julia/dev/Expectations`.

Make sure you do this from the base Julia environment (i.e., after running `] activate` without arguments).

As a reminder, you can find the location of your `~/.julia` folder (called the "user depot"), by running

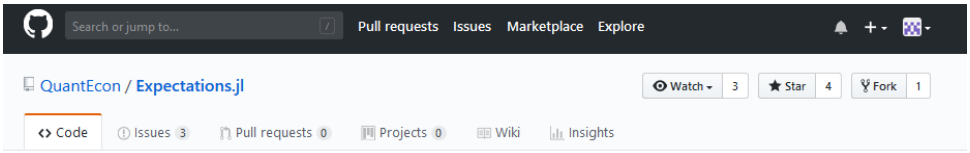
```
In [5]: DEPOT_PATH[1]
```

```
Out[5]: "/home/ubuntu/.julia"
```

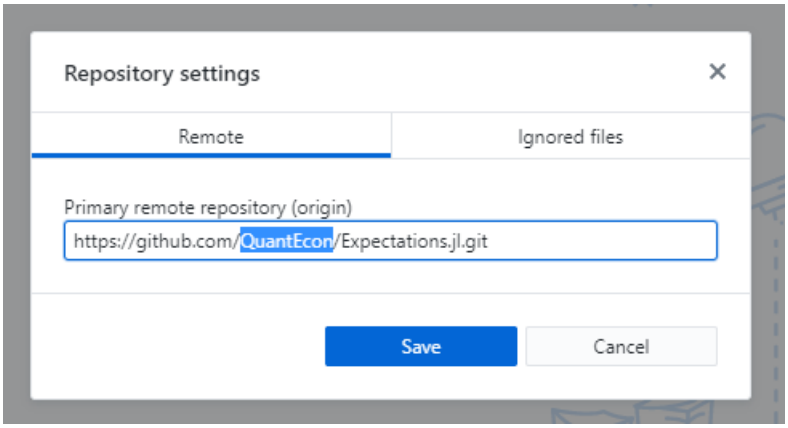
The `] dev` command will also add the target to the package manager, so that whenever we run `using Expectations`, Julia will load our cloned copy from that location

```
using Expectations
pathof(Expectations) # points to our git clone
```

- Drag that folder to GitHub Desktop.
- The next step is to fork the original (external) package from its website (i.e., `https://github.com/quantecon/Expectations.jl`) to your account (`https://github.com/quanteconuser/Expectations.jl` in our case).

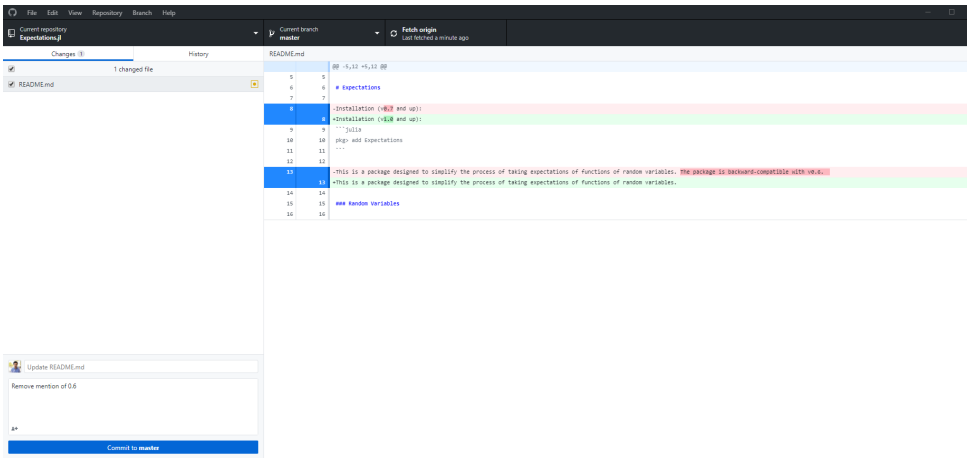


- Edit the settings in GitHub Desktop (from the "Repository" dropdown) to reflect the new URL.



  Here, we'd change the highlighted text to read `quanteconuser`, or whatever our GitHub ID is.
- If you make some changes in a text editor and return to GitHub Desktop, you'll see something like.

Note: As before, we're editing the files directly in `~/.julia/dev`, as opposed to cloning the repo again.

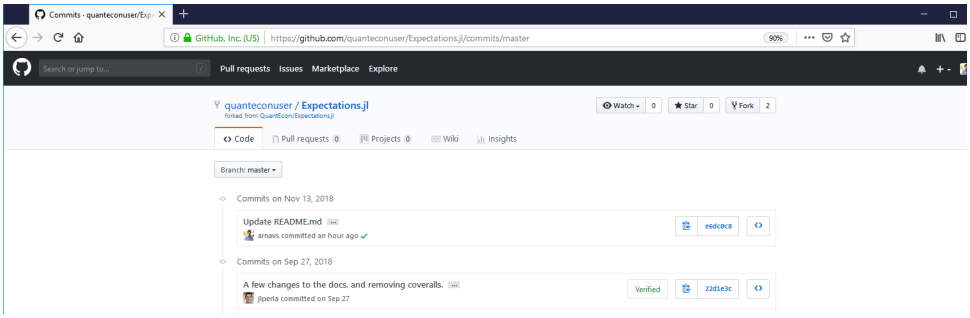


Here, for example, we're revising the README.

- Clicking "commit to master" (recall that the checkboxes next to each file indicate

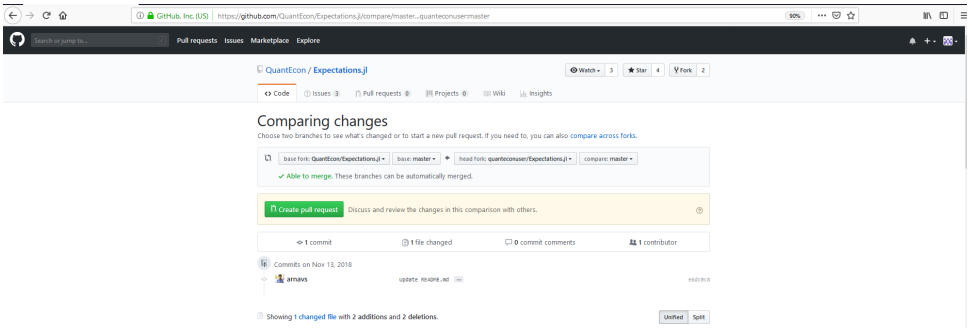
whether it's to be committed) and then pushing (e.g., hitting "push" under the "Repository" dropdown) will add the committed changes to your account.

To confirm this, we can check the history on our account here; for more on working with git repositories, see the version control lecture.



The green check mark indicates that Travis tests passed for this commit.

- Clicking "new pull request" from the pull requests tab will show us a snapshot of the changes, and let us create a pull request for project maintainers to review and approve.



For more on PRs, see the relevant section of the version control lecture.

For more on forking, see the docs on GitHub Desktop and the GitHub Website.

13.8.1 Case with Write Access

If you have write access to the repo, we can skip the preceding steps about forking and changing the URL.

You can use `] dev` on a package name or the URL of the package

```
] dev Expectations
```

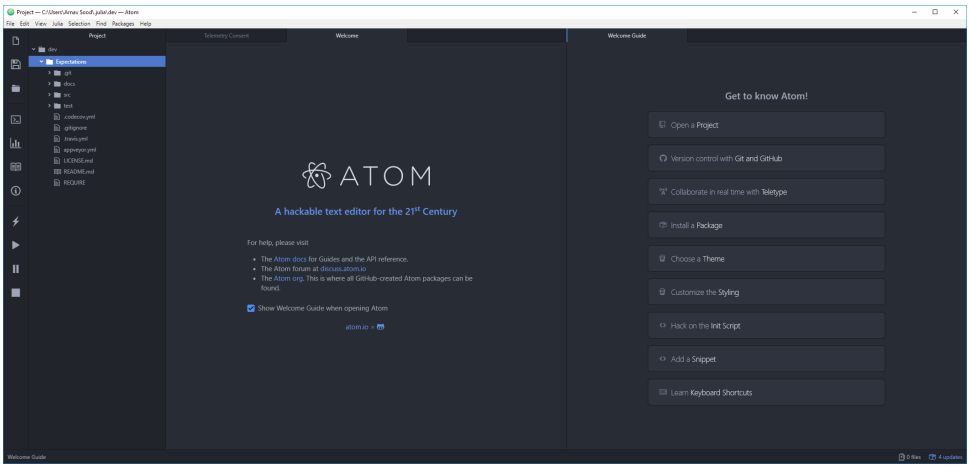
or `] dev https://github.com/quanteconuser/Expectations.jl.git` as an example for an unreleased package by URL.

Which will again clone the repo to `~/.julia/dev`, and use it as a Julia package.

```
using Expectations
pathof(Expectations) # points to our git clone
```

Next, drag that folder to GitHub Desktop as before.

Then, in order to work with the package locally, all we need to do is open the `~/.julia/dev/Expectations` in a text editor (like Atom)



From here, we can edit this package just like we created it ourselves and use GitHub Desktop to track versions of our package files (say, after `] up`, or editing source code, `] add Package`, etc.).

13.8.2 Removing a Julia Package

To "un-dev" a Julia package (say, if we want to use our old `Expectations.jl`), you can simply run

```
] free Expectations
```

To delete it entirely, simply run

```
] rm Expectations
```

From a REPL where that package is in the active environment.

13.9 Benchmarking

Another goal of testing is to make sure that code doesn't slow down significantly from one version to the next.

We can do this using tools provided by the `BenchmarkTools.jl` package.

See the need for speed lecture for more details.

13.10 Additional Notes

- The JuliaCI organization provides more Julia utilities for continuous integration and testing.

13.11 Review

To review the workflow for creating, versioning, and testing a new project end-to-end.

1. Create the local package directory using the `PkgTemplates.jl`.
2. Add that package to the Julia package manager, by opening a Julia REPL in the `~/.julia/dev/ExamplePackage.jl`, making sure the active environment is the default one `(v1.1)`, and hitting `] dev .`.
3. Drag-and-drop that folder to GitHub Desktop.
4. Create an empty repository with the same name on the GitHub server.
5. Push from GitHub Desktop to the server.
6. Open **the original project folder** (e.g., `~/.julia/dev/ExamplePackage.jl`) in Atom.
7. Make changes, test, iterate on it, etc. As a rule, functions like should live in the `src/` directory once they're stable, and you should export them from that file with `export func1, func2`. This will export all methods of `func1`, `func2`, etc.
8. Commit them in GitHub Desktop as you go (i.e., you can and should use version control to track intermediate states).
9. Push to the server, and see the Travis and Codecov results (note that these may take a few minutes the first time).

13.12 Exercises

13.12.1 Exercise 1

Following the instructions for a new project, create a new package on your github account called `NewtonsMethod.jl`.

In this package, you should create a simple package to do Newton's Method using the code you did in the Newton's method exercise in Introductory Examples.

In particular, within your package you should have two functions

- `newtonroot(f, f'; x₀, tol = 1E-7, maxiter = 1000)`
- `newtonroot(f; x₀, tol = 1E-7, maxiter = 1000)`

Where the second function uses Automatic Differentiation to call the first.

The package should include

- implementations of those functions in the `/src` directory
- comprehensive set of tests
- project and manifest files to replicate your development environment
- automated running of the tests with Travis CI in GitHub

For the tests, you should have at the very minimum

- a way to handle non-convergence (e.g. return back `nothing` as discussed in error handling

- several `@test` for the root of a known function, given the `f` and analytical `f'` derivatives
- tests of those roots using the automatic differentiation version of the function
- test of finding those roots with a `BigFloat` and not just a `Float64`
- test of non-convergence for a function without a root (e.g. $f(x) = 2 + x^2$)
- test to ensure that the `maxiter` is working (e.g. what happens if you call `maxiter = 5`
- test to ensure that `tol` is working

And anything else you can think of. You should be able to run `] test` for the project to check that the test-suite is running, and then ensure that it is running automatically on Travis CI.

Push a commit to the repository which breaks one of the tests and see what the Travis CI reports after running the build.

13.12.2 Exercise 2

Watch the youtube video Developing Julia Packages from Chris Rackauckas. The demonstration goes through many of the same concepts as this lecture, but with more background in test-driven development and providing more details for open-source projects..

Chapter 14

The Need for Speed

14.1 Contents

14.2 Overview

Computer scientists often classify programming languages according to the following two categories.

High level languages aim to maximize productivity by

- being easy to read, write and debug
- automating standard tasks (e.g., memory management)
- being interactive, etc.

Low level languages aim for speed and control, which they achieve by

- being closer to the metal (direct access to CPU, memory, etc.)
- requiring a relatively large amount of information from the user (e.g., all data types must be specified)

Traditionally we understand this as a trade off

- high productivity or high performance
- optimized for humans or optimized for machines

One of the great strengths of Julia is that it pushes out the curve, achieving both high productivity and high performance with relatively little fuss.

The word "relatively" is important here, however…

In simple programs, excellent performance is often trivial to achieve.

For longer, more sophisticated programs, you need to be aware of potential stumbling blocks.

This lecture covers the key points.

14.2.1 Requirements

You should read our earlier lecture on types, methods and multiple dispatch before this one.

14.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

14.3 Understanding Multiple Dispatch in Julia

This section provides more background on how methods, functions, and types are connected.

14.3.1 Methods and Functions

The precise data type is important, for reasons of both efficiency and mathematical correctness.

For example consider 1 + 1 vs. 1.0 + 1.0 or [1 0] + [0 1].

On a CPU, integer and floating point addition are different things, using a different set of instructions.

Julia handles this problem by storing multiple, specialized versions of functions like addition, one for each data type or set of data types.

These individual specialized versions are called **methods**.

When an operation like addition is requested, the Julia compiler inspects the type of data to be acted on and hands it out to the appropriate method.

This process is called **multiple dispatch**.

Like all "infix" operators, 1 + 1 has the alternative syntax +(1, 1)

```
In [3]: +(1, 1)
```

```
Out[3]: 2
```

This operator + is itself a function with multiple methods.

We can investigate them using the @which macro, which shows the method to which a given call is dispatched

```
In [4]: x, y = 1.0, 1.0
        @which +(x, y)
```

```
Out[4]: +(x::Float64, y::Float64) in Base at float.jl:401
```

We see that the operation is sent to the `+` method that specializes in adding floating point numbers.

Here's the integer case

```
In [5]: x, y = 1, 1
        @which +(x, y)
```

```
Out[5]: +(x::T, y::T) where T<:Union{Int128, Int16, Int32, Int64, Int8, UInt128,
  ↪UInt16, UInt32,
        UInt64, UInt8} in Base at int.jl:53
```

This output says that the call has been dispatched to the + method responsible for handling integer values.

(We'll learn more about the details of this syntax below)

Here's another example, with complex numbers

```
In [6]: x, y = 1.0 + 1.0im, 1.0 + 1.0im
        @which +(x, y)
```

```
Out[6]: +(z::Complex, w::Complex) in Base at complex.jl:275
```

Again, the call has been dispatched to a + method specifically designed for handling the given data type.

Adding Methods

It's straightforward to add methods to existing functions.

For example, we can't at present add an integer and a string in Julia (i.e. `100 + "100"` is not valid syntax).

This is sensible behavior, but if you want to change it there's nothing to stop you.

```
In [7]: import Base: +  # enables adding methods to the + function

        +(x::Integer, y::String) = x + parse(Int, y)

        @show +(100, "100")
        @show 100 + "100";  # equivalent
```

```
   100 + "100" = 200
100 + "100" = 200
```

14.3.2 Understanding the Compilation Process

We can now be a little bit clearer about what happens when you call a function on given types.

Suppose we execute the function call `f(a, b)` where `a` and `b` are of concrete types `S` and `T` respectively.

The Julia interpreter first queries the types of `a` and `b` to obtain the tuple `(S, T)`.

It then parses the list of methods belonging to `f`, searching for a match.

If it finds a method matching `(S, T)` it calls that method.

If not, it looks to see whether the pair `(S, T)` matches any method defined for *immediate parent types*.

For example, if `S` is `Float64` and `T` is `ComplexF32` then the immediate parents are `AbstractFloat` and `Number` respectively

```
In [8]: supertype(Float64)
```

```
Out[8]: AbstractFloat
```

```
In [9]: supertype(ComplexF32)
```

```
Out[9]: Number
```

Hence the interpreter looks next for a method of the form `f(x::AbstractFloat, y::Number)`.

If the interpreter can't find a match in immediate parents (supertypes) it proceeds up the tree, looking at the parents of the last type it checked at each iteration.

- If it eventually finds a matching method, it invokes that method.
- If not, we get an error.

This is the process that leads to the following error (since we only added the `+` for adding `Integer` and `String` above)

```
In [10]: @show (typeof(100.0) <: Integer) == false
         100.0 + "100"
```

```
(typeof(100.0) <: Integer) == false = true
```

```
MethodError: no method matching +(::Float64, ::String)
Closest candidates are:
  +(::Any, ::Any, !Matched::Any, !Matched::Any…) at operators.jl:
↪529
  +(::Float64, !Matched::Float64) at float.jl:401
  +(::AbstractFloat, !Matched::Bool) at bool.jl:106
  …

Stacktrace:
 [1] top-level scope at In[10]:2
```

Because the dispatch procedure starts from concrete types and works upwards, dispatch always invokes the *most specific method* available.

For example, if you have methods for function `f` that handle

1. `(Float64, Int64)` pairs
2. `(Number, Number)` pairs

and you call `f` with `f(0.5, 1)` then the first method will be invoked.

This makes sense because (hopefully) the first method is optimized for exactly this kind of data.

The second method is probably more of a "catch all" method that handles other data in a less optimal way.

Here's another simple example, involving a user-defined function

```
In [11]: function q(x)  # or q(x::Any)
             println("Default (Any) method invoked")
         end

         function q(x::Number)
             println("Number method invoked")
         end

         function q(x::Integer)
             println("Integer method invoked")
         end

Out[11]: q (generic function with 3 methods)
```

Let's now run this and see how it relates to our discussion of method dispatch above

```
In [12]: q(3)

             Integer method invoked


In [13]: q(3.0)

             Number method invoked


In [14]: q("foo")

             Default (Any) method invoked
```

Since `typeof(3) <: Int64 <: Integer <: Number`, the call `q(3)` proceeds up the tree to `Integer` and invokes `q(x::Integer)`.

On the other hand, `3.0` is a `Float64`, which is not a subtype of `Integer`.

Hence the call `q(3.0)` continues up to `q(x::Number)`.

Finally, `q("foo")` is handled by the function operating on `Any`, since `String` is not a subtype of `Number` or `Integer`.

14.3.3 Analyzing Function Return Types

For the most part, time spent "optimizing" Julia code to run faster is about ensuring the compiler can correctly deduce types for all functions.

The macro `@code_warntype` gives us a hint

```
In [15]: x = [1, 2, 3]
         f(x) = 2x
         @code_warntype f(x)
```

```
  Variables
  #self#::Core.Compiler.Const(f, false)
  x::Array{Int64,1}

Body::Array{Int64,1}
1 — %1 = (2 * x)::Array{Int64,1}
└──      return %1
```

The `@code_warntype` macro compiles `f(x)` using the type of `x` as an example – i.e., the `[1, 2, 3]` is used as a prototype for analyzing the compilation, rather than simply calculating the value.

Here, the `Body::Array{Int64,1}` tells us the type of the return value of the function, when called with types like `[1, 2, 3]`, is always a vector of integers.

In contrast, consider a function potentially returning `nothing`, as in this lecture

```
In [16]: f(x) = x > 0.0 ? x : nothing
         @code_warntype f(1)
```

```
  Variables
  #self#::Core.Compiler.Const(f, false)
  x::Int64

Body::Union{Nothing, Int64}
1 — %1 = (x > 0.0)::Bool
└──      goto #3 if not %1
2 —      return x
3 —      return Main.nothing
```

This states that the compiler determines the return type when called with an integer (like `1`) could be one of two different types, `Body::Union{Nothing, Int64}`.

A final example is a variation on the above, which returns the maximum of `x` and `0`.

```
In [17]: f(x) = x > 0.0 ? x : 0.0
         @code_warntype f(1)
```

```
  Variables
  #self#::Core.Compiler.Const(f, false)
  x::Int64

Body::Union{Float64, Int64}
```

```
1 − %1 = (x > 0.0)::Bool
└──      goto #3 if not %1
2 −      return x
3 −      return 0.0
```

Which shows that, when called with an integer, the type could be that integer or the floating point `0.0`.

On the other hand, if we use change the function to return `0` if x <= 0, it is type-unstable with floating point.

```
In [18]: f(x) = x > 0.0 ? x : 0
         @code_warntype f(1.0)
```

```
  Variables
  #self#::Core.Compiler.Const(f, false)
  x::Float64

Body::Union{Float64, Int64}
1 − %1 = (x > 0.0)::Bool
└──      goto #3 if not %1
2 −      return x
3 −      return 0
```

The solution is to use the `zero(x)` function which returns the additive identity element of type `x`.

On the other hand, if we change the function to return `0` if `x <= 0`, it is type-unstable with floating point.

```
In [19]: @show zero(2.3)
         @show zero(4)
         @show zero(2.0 + 3im)

         f(x) = x > 0.0 ? x : zero(x)
         @code_warntype f(1.0)
```

```
  zero(2.3) = 0.0
zero(4) = 0
zero(2.0 + 3im) = 0.0 + 0.0im
Variables
  #self#::Core.Compiler.Const(f, false)
  x::Float64

Body::Float64
1 − %1 = (x > 0.0)::Bool
└──      goto #3 if not %1
2 −      return x
3 − %4 = Main.zero(x)::Core.Compiler.Const(0.0, false)
└──      return %4
```

14.4 Foundations

Let's think about how quickly code runs, taking as given

- hardware configuration
- algorithm (i.e., set of instructions to be executed)

We'll start by discussing the kinds of instructions that machines understand.

14.4.1 Machine Code

All instructions for computers end up as *machine code*.

Writing fast code — expressing a given algorithm so that it runs quickly — boils down to producing efficient machine code.

You can do this yourself, by hand, if you want to.

Typically this is done by writing assembly, which is a symbolic representation of machine code.

Here's some assembly code implementing a function that takes arguments a, b and returns $2a + 8b$

```
    pushq   %rbp
    movq    %rsp, %rbp
    addq    %rdi, %rdi
    leaq    (%rdi,%rsi,8), %rax
    popq    %rbp
    retq
    nopl    (%rax)
```

Note that this code is specific to one particular piece of hardware that we use — different machines require different machine code.

If you ever feel tempted to start rewriting your economic model in assembly, please restrain yourself.

It's far more sensible to give these instructions in a language like Julia, where they can be easily written and understood.

```
In [20]: function f(a, b)
             y = 2a + 8b
             return y
         end
```

```
Out[20]: f (generic function with 2 methods)
```

or Python

```
def f(a, b):
    y = 2 * a + 8 * b
    return y
```

or even C

```
int f(int a, int b) {
    int y = 2 * a + 8 * b;
    return y;
}
```

In any of these languages we end up with code that is much easier for humans to write, read, share and debug.

We leave it up to the machine itself to turn our code into machine code.

How exactly does this happen?

14.4.2 Generating Machine Code

The process for turning high level code into machine code differs across languages.

Let's look at some of the options and how they differ from one another.

AOT Compiled Languages

Traditional compiled languages like Fortran, C and C++ are a reasonable option for writing fast code.

Indeed, the standard benchmark for performance is still well-written C or Fortran.

These languages compile down to efficient machine code because users are forced to provide a lot of detail on data types and how the code will execute.

The compiler therefore has ample information for building the corresponding machine code ahead of time (AOT) in a way that

- organizes the data optimally in memory and
- implements efficient operations as required for the task in hand

At the same time, the syntax and semantics of C and Fortran are verbose and unwieldy when compared to something like Julia.

Moreover, these low level languages lack the interactivity that's so crucial for scientific work.

Interpreted Languages

Interpreted languages like Python generate machine code "on the fly", during program execution.

This allows them to be flexible and interactive.

Moreover, programmers can leave many tedious details to the runtime environment, such as

- specifying variable types
- memory allocation/deallocation, etc.

But all this convenience and flexibility comes at a cost: it's hard to turn instructions written in these languages into efficient machine code.

For example, consider what happens when Python adds a long list of numbers together.

Typically the runtime environment has to check the type of these objects one by one before it figures out how to add them.

This involves substantial overheads.

There are also significant overheads associated with accessing the data values themselves, which might not be stored contiguously in memory.

The resulting machine code is often complex and slow.

Just-in-time compilation

Just-in-time (JIT) compilation is an alternative approach that marries some of the advantages of AOT compilation and interpreted languages.

The basic idea is that functions for specific tasks are compiled as requested.

As long as the compiler has enough information about what the function does, it can in principle generate efficient machine code.

In some instances, all the information is supplied by the programmer.

In other cases, the compiler will attempt to infer missing information on the fly based on usage.

Through this approach, computing environments built around JIT compilers aim to

- provide all the benefits of high level languages discussed above and, at the same time,
- produce efficient instruction sets when functions are compiled down to machine code

14.5 JIT Compilation in Julia

JIT compilation is the approach used by Julia.

In an ideal setting, all information necessary to generate efficient native machine code is supplied or inferred.

In such a setting, Julia will be on par with machine code from low level languages.

14.5.1 An Example

Consider the function

```
In [21]: function f(a, b)
             y = (a + 8b)^2
             return 7y
         end
```

```
Out[21]: f (generic function with 2 methods)
```

Suppose we call `f` with integer arguments (e.g., `z = f(1, 2)`).

The JIT compiler now knows the types of `a` and `b`.

Moreover, it can infer types for other variables inside the function

- e.g., `y` will also be an integer

It then compiles a specialized version of the function to handle integers and stores it in memory.

We can view the corresponding machine code using the @code_native macro

```
In [22]: @code_native f(1, 2)
```

```
            .text
; ┌ @ In[21]:2 within `f'
; │┌ @ In[21]:2 within `+'
        leaq    (%rdi,%rsi,8), %rcx
; │└
; │┌ @ intfuncs.jl:261 within `literal_pow'
; ││┌ @ int.jl:54 within `*'
        imulq   %rcx, %rcx
; │└└
; │ @ In[21]:3 within `f'
; │┌ @ int.jl:54 within `*'
        leaq    (,%rcx,8), %rax
        subq    %rcx, %rax
; │└
        retq
        nopw    %cs:(%rax,%rax)
        nop
; └
```

If we now call `f` again, but this time with floating point arguments, the JIT compiler will once more infer types for the other variables inside the function.

- e.g., `y` will also be a float

It then compiles a new version to handle this type of argument.

```
In [23]: @code_native f(1.0, 2.0)
```

```
            .text
; ┌ @ In[21]:2 within `f'
        movabsq $139778809481240, %rax  # imm = 0x7F20CA494818
; │┌ @ promotion.jl:312 within `*' @ float.jl:405
        vmulsd  (%rax), %xmm1, %xmm1
; │└
; │┌ @ float.jl:401 within `+'
        vaddsd  %xmm0, %xmm1, %xmm0
; │└
; │┌ @ intfuncs.jl:261 within `literal_pow'
; ││┌ @ float.jl:405 within `*'
        vmulsd  %xmm0, %xmm0, %xmm0
        movabsq $139778809481248, %rax  # imm = 0x7F20CA494820
; │└└
; │ @ In[21]:3 within `f'
; │┌ @ promotion.jl:312 within `*' @ float.jl:405
        vmulsd  (%rax), %xmm0, %xmm0
; │└
        retq
        nopw    %cs:(%rax,%rax)
        nop
; └
```

Subsequent calls using either floats or integers are now routed to the appropriate compiled code.

14.5.2 Potential Problems

In some senses, what we saw above was a best case scenario.

Sometimes the JIT compiler produces messy, slow machine code.

This happens when type inference fails or the compiler has insufficient information to optimize effectively.

The next section looks at situations where these problems arise and how to get around them.

14.6 Fast and Slow Julia Code

To summarize what we've learned so far, Julia provides a platform for generating highly efficient machine code with relatively little effort by combining

1. JIT compilation
2. Optional type declarations and type inference to pin down the types of variables and hence compile efficient code
3. Multiple dispatch to facilitate specialization and optimization of compiled code for different data types

But the process is not flawless, and hiccups can occur.

The purpose of this section is to highlight potential issues and show you how to circumvent them.

14.6.1 BenchmarkTools

The main Julia package for benchmarking is BenchmarkTools.jl.

Below, we'll use the `@btime` macro it exports to evaluate the performance of Julia code.

As mentioned in an earlier lecture, we can also save benchmark results to a file and guard against performance regressions in code.

For more, see the package docs.

14.6.2 Global Variables

Global variables are names assigned to values outside of any function or type definition.

The are convenient and novice programmers typically use them with abandon.

But global variables are also dangerous, especially in medium to large size programs, since

- they can affect what happens in any part of your program
- they can be changed by any function

This makes it much harder to be certain about what some small part of a given piece of code actually commands.

Here's a useful discussion on the topic.

When it comes to JIT compilation, global variables create further problems.

The reason is that the compiler can never be sure of the type of the global variable, or even that the type will stay constant while a given function runs.

To illustrate, consider this code, where b is global

In [24]:
```
b = 1.0
function g(a)
    global b
    for i  1:1_000_000
        tmp = a + b
    end
end
```

Out[24]:
```
g (generic function with 1 method)
```

The code executes relatively slowly and uses a huge amount of memory.

In [25]:
```
using BenchmarkTools

@btime g(1.0)
```

```
    30.018 ms (2000000 allocations: 30.52 MiB)
```

If you look at the corresponding machine code you will see that it's a mess.

In [26]:
```
@code_native g(1.0)
```

```
            .text
; ┌ @ In[24]:3 within `g'
        pushq   %rbp
        movq    %rsp, %rbp
        pushq   %r15
        pushq   %r14
        pushq   %r13
        pushq   %r12
        pushq   %rbx
        andq    $-32, %rsp
        subq    $128, %rsp
        vmovsd  %xmm0, 24(%rsp)
        vxorps  %xmm0, %xmm0, %xmm0
        vmovaps %ymm0, 32(%rsp)
        movq    %fs:0, %rax
        movq    $8, 32(%rsp)
        movq    -15712(%rax), %rcx
        movq    %rcx, 40(%rsp)
        leaq    32(%rsp), %rcx
        movq    %rcx, -15712(%rax)
        leaq    -15712(%rax), %r12
        movl    $1000000, %ebx          # imm = 0xF4240
```

```
        movabsq $jl_system_image_data, %r14
        leaq    88(%rsp), %r15
        nopl    (%rax)
; | @ In[24]:5 within `g'
L112:
        movabsq $139778580060280, %rax  # imm = 0x7F20BC9C9878
        movq    (%rax), %r13
        movq    %r13, 48(%rsp)
        movq    %r12, %rdi
        movl    $1400, %esi             # imm = 0x578
        movl    $16, %edx
        movabsq $jl_gc_pool_alloc, %rax
        vzeroupper
        callq   *%rax
        movabsq $jl_system_image_data, %rcx
        movq    %rcx, -8(%rax)
        vmovsd  24(%rsp), %xmm0         # xmm0 = mem[0],zero
        vmovsd  %xmm0, (%rax)
        movq    %rax, 56(%rsp)
        movq    %rax, 88(%rsp)
        movq    %r13, 96(%rsp)
        movq    %r14, %rdi
        movq    %r15, %rsi
        movl    $2, %edx
        movabsq $jl_apply_generic, %rax
        callq   *%rax
; |┌ @ range.jl:597 within `iterate'
; ||┌ @ promotion.jl:398 within `=='
        addq    $-1, %rbx
; |└└
        jne     L112
        movq    40(%rsp), %rax
        movq    %rax, (%r12)
; | @ In[24]:5 within `g'
        leaq    -40(%rbp), %rsp
        popq    %rbx
        popq    %r12
        popq    %r13
        popq    %r14
        popq    %r15
        popq    %rbp
        retq
        nopw    (%rax,%rax)
; └
```

If we eliminate the global variable like so

```
In [27]: function g(a, b)
             for i  1:1_000_000
                 tmp = a + b
             end
         end
```

```
Out[27]: g (generic function with 2 methods)
```

then execution speed improves dramatically

```
In [28]: @btime g(1.0, 1.0)
```

```
  1.599 ns (0 allocations: 0 bytes)
```

Note that the second run was dramatically faster than the first.

That's because the first call included the time for JIT compilaiton.

Notice also how small the memory footprint of the execution is.

Also, the machine code is simple and clean

```
In [29]: @code_native g(1.0, 1.0)
```

```
            .text
; ┌ @ In[27]:2 within `g'
        retq
        nopw    %cs:(%rax,%rax)
        nopl    (%rax,%rax)
; └
```

Now the compiler is certain of types throughout execution of the function and hence can optimize accordingly.

The `const` keyword

Another way to stabilize the code above is to maintain the global variable but prepend it with `const`

```
In [30]: const b_const = 1.0
         function g(a)
             global b_const
             for i  1:1_000_000
                 tmp = a + b_const
             end
         end
```

```
Out[30]: g (generic function with 2 methods)
```

Now the compiler can again generate efficient machine code.

We'll leave you to experiment with it.

14.6.3 Composite Types with Abstract Field Types

Another scenario that trips up the JIT compiler is when composite types have fields with abstract types.

We met this issue earlier, when we discussed AR(1) models.

Let's experiment, using, respectively,

- an untyped field
- a field with abstract type, and

- parametric typing

As we'll see, the last of these options gives us the best performance, while still maintaining significant flexibility.

Here's the untyped case

```
In [31]: struct Foo_generic
             a
         end
```

Here's the case of an abstract type on the field `a`

```
In [32]: struct Foo_abstract
             a::Real
         end
```

Finally, here's the parametrically typed case

```
In [33]: struct Foo_concrete{T <: Real}
             a::T
         end
```

Now we generate instances

```
In [34]: fg = Foo_generic(1.0)
         fa = Foo_abstract(1.0)
         fc = Foo_concrete(1.0)
```

```
Out[34]: Foo_concrete{Float64}(1.0)
```

In the last case, concrete type information for the fields is embedded in the object

```
In [35]: typeof(fc)
```

```
Out[35]: Foo_concrete{Float64}
```

This is significant because such information is detected by the compiler.

Timing

Here's a function that uses the field `a` of our objects

```
In [36]: function f(foo)
             for i  1:1_000_000
                 tmp = i + foo.a
             end
         end
```

```
Out[36]: f (generic function with 2 methods)
```

Let's try timing our code, starting with the generic case:

```
In [37]: @btime f($fg)
```

```
  39.721 ms (1999489 allocations: 30.51 MiB)
```

The timing is not very impressive.

Here's the nasty looking machine code

```
In [38]: @code_native f(fg)
```

```
        .text
; ┌ @ In[36]:2 within `f'
        pushq   %rbp
        pushq   %r15
        pushq   %r14
        pushq   %r13
        pushq   %r12
        pushq   %rbx
        subq    $56, %rsp
        vxorps  %xmm0, %xmm0, %xmm0
        vmovaps %xmm0, (%rsp)
        movq    $0, 16(%rsp)
        movq    %rsi, 48(%rsp)
        movq    %fs:0, %rax
        movq    $4, (%rsp)
        movq    -15712(%rax), %rcx
        movq    %rcx, 8(%rsp)
        movq    %rsp, %rcx
        movq    %rcx, -15712(%rax)
        leaq    -15712(%rax), %rax
        movq    %rax, 24(%rsp)
        movq    (%rsi), %r13
        movl    $1, %ebx
        movabsq $jl_apply_generic, %r12
        movabsq $jl_system_image_data, %r14
        leaq    32(%rsp), %r15
        nopl    (%rax)
; │ @ In[36]:3 within `f'
; │┌ @ Base.jl:33 within `getproperty'
L128:
        movq    (%r13), %rbp
; │└
        movq    %rbx, %rdi
        movabsq $jl_box_int64, %rax
        callq   *%rax
        movq    %rax, 16(%rsp)
        movq    %rax, 32(%rsp)
        movq    %rbp, 40(%rsp)
        movq    %r14, %rdi
        movq    %r15, %rsi
        movl    $2, %edx
        callq   *%r12
; │┌ @ range.jl:597 within `iterate'
        addq    $1, %rbx
; ││┌ @ promotion.jl:398 within `=='
        cmpq    $1000001, %rbx          # imm = 0xF4241
; │└└
```

```
        jne     L128
        movq    8(%rsp), %rax
        movq    24(%rsp), %rcx
        movq    %rax, (%rcx)
        movabsq $jl_system_image_data, %rax
; | @ In[36]:3 within `f'
        addq    $56, %rsp
        popq    %rbx
        popq    %r12
        popq    %r13
        popq    %r14
        popq    %r15
        popq    %rbp
        retq
        nopw    %cs:(%rax,%rax)
        nopl    (%rax)
; └
```

The abstract case is similar

```
In [39]: @btime f($fa)
```

```
      39.609 ms (1999489 allocations: 30.51 MiB)
```

Note the large memory footprint.

The machine code is also long and complex, although we omit details.

Finally, let's look at the parametrically typed version

```
In [40]: @btime f($fc)
```

```
      1.599 ns (0 allocations: 0 bytes)
```

Some of this time is JIT compilation, and one more execution gets us down to.

Here's the corresponding machine code

```
In [41]: @code_native f(fc)
```

```
            .text
; ┌ @ In[36]:2 within `f'
        retq
        nopw    %cs:(%rax,%rax)
        nopl    (%rax,%rax)
; └
```

Much nicer…

14.6.4 Abstract Containers

Another way we can run into trouble is with abstract container types.

Consider the following function, which essentially does the same job as Julia's `sum()` function but acts only on floating point data

```
In [42]: function sum_float_array(x::AbstractVector{<:Number})
             sum = 0.0
             for i  eachindex(x)
                 sum += x[i]
             end
             return sum
         end
```

```
Out[42]: sum_float_array (generic function with 1 method)
```

Calls to this function run very quickly

```
In [43]: x = range(0,  1, length = Int(1e6))
         x = collect(x)
         typeof(x)
```

```
Out[43]: Array{Float64,1}
```

```
In [44]: @btime sum_float_array($x)
```

```
             1.251 ms (0 allocations: 0 bytes)
```

```
Out[44]: 499999.9999999796
```

When Julia compiles this function, it knows that the data passed in as `x` will be an array of 64 bit floats.

Hence it's known to the compiler that the relevant method for `+` is always addition of floating point numbers.

Moreover, the data can be arranged into continuous 64 bit blocks of memory to simplify memory access.

Finally, data types are stable — for example, the local variable `sum` starts off as a float and remains a float throughout.

Type Inferences

Here's the same function minus the type annotation in the function signature

```
In [45]: function sum_array(x)
             sum = 0.0
             for i  eachindex(x)
                 sum += x[i]
             end
             return sum
         end
```

```
Out[45]: sum_array (generic function with 1 method)
```

When we run it with the same array of floating point numbers it executes at a similar speed as the function with type information.

```
In [46]: @btime sum_array($x)
```

```
  1.251 ms (0 allocations: 0 bytes)
```

```
Out[46]: 499999.9999999796
```

The reason is that when `sum_array()` is first called on a vector of a given data type, a newly compiled version of the function is produced to handle that type.

In this case, since we're calling the function on a vector of floats, we get a compiled version of the function with essentially the same internal representation as `sum_float_array()`.

An Abstract Container

Things get tougher for the interpreter when the data type within the array is imprecise.

For example, the following snippet creates an array where the element type is `Any`

```
In [47]: x = Any[ 1/i for i  1:1e6 ];
```

```
In [48]: eltype(x)
```

```
Out[48]: Any
```

Now summation is much slower and memory management is less efficient.

```
In [49]: @btime sum_array($x)
```

```
  27.232 ms (1000000 allocations: 15.26 MiB)
```

```
Out[49]: 14.392726722864989
```

14.7 Further Comments

Here are some final comments on performance.

14.7.1 Explicit Typing

Writing fast Julia code amounts to writing Julia from which the compiler can generate efficient machine code.

For this, Julia needs to know about the type of data it's processing as early as possible.

We could hard code the type of all variables and function arguments but this comes at a cost.

Our code becomes more cumbersome and less generic.

We are starting to loose the advantages that drew us to Julia in the first place.

Moreover, explicitly typing everything is not necessary for optimal performance.

The Julia compiler is smart and can often infer types perfectly well, without any performance cost.

What we really want to do is

- keep our code simple, elegant and generic
- help the compiler out in situations where it's liable to get tripped up

14.7.2 Summary and Tips

Use functions to segregate operations into logically distinct blocks.

Data types will be determined at function boundaries.

If types are not supplied then they will be inferred.

If types are stable and can be inferred effectively your functions will run fast.

14.7.3 Further Reading

A good next stop for further reading is the relevant part of the Julia documentation.

Part III

Tools and Techniques

Chapter 15

Linear Algebra

15.1 Contents

15.2 Overview

Linear algebra is one of the most useful branches of applied mathematics for economists to invest in.

For example, many applied problems in economics and finance require the solution of a linear system of equations, such as

$$\begin{aligned} y_1 &= ax_1 + bx_2 \\ y_2 &= cx_1 + dx_2 \end{aligned}$$

or, more generally,

$$\begin{aligned} y_1 &= a_{11}x_1 + a_{12}x_2 + \cdots + a_{1k}x_k \\ &\vdots \\ y_n &= a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nk}x_k \end{aligned} \tag{1}$$

The objective here is to solve for the "unknowns" $x_1, \ldots, x_k$ given $a_{11}, \ldots, a_{nk}$ and $y_1, \ldots, y_n$.

When considering such problems, it is essential that we first consider at least some of the following questions

- Does a solution actually exist?
- Are there in fact many solutions, and if so how should we interpret them?
- If no solution exists, is there a best "approximate" solution?

- If a solution exists, how should we compute it?

These are the kinds of topics addressed by linear algebra.

In this lecture we will cover the basics of linear and matrix algebra, treating both theory and computation.

We admit some overlap with this lecture, where operations on Julia arrays were first explained.

Note that this lecture is more theoretical than most, and contains background material that will be used in applications as we go along.

15.3 Vectors

A *vector* is an element of a vector space.

Vectors can be added together and scaled (multiplied) by scalars.

Vectors can be written as $x = [x_1, \ldots, x_n]$.

The set of all n-vectors is denoted by $\mathbb{R}^n$.

For example, $\mathbb{R}^2$ is the plane, and a vector in $\mathbb{R}^2$ is just a point in the plane.

Traditionally, vectors are represented visually as arrows from the origin to the point.

The following figure represents three vectors in this manner.

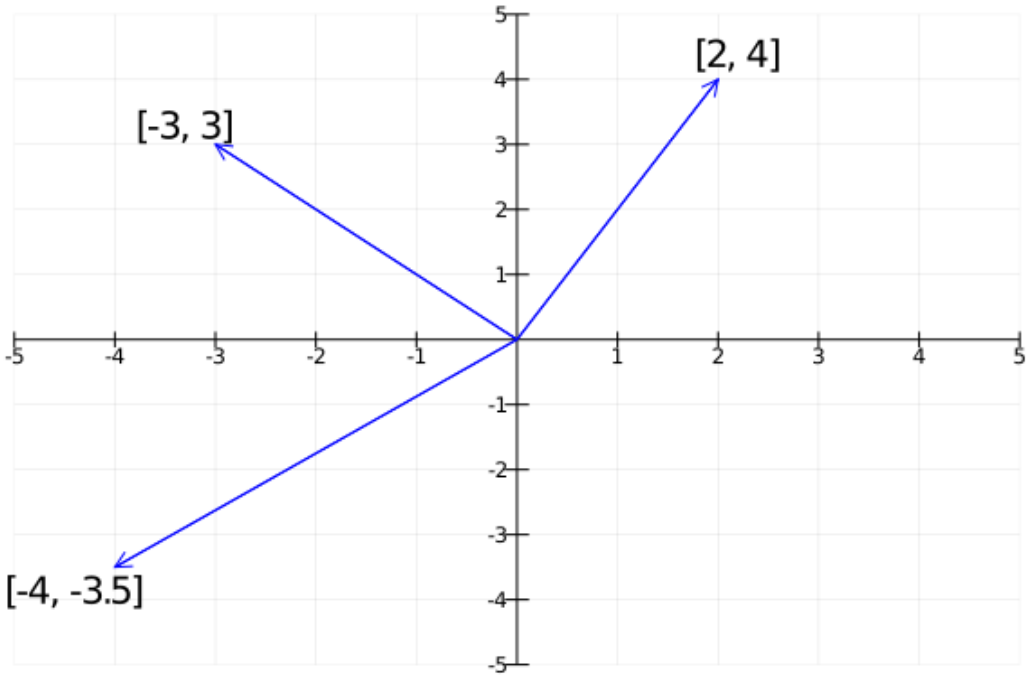
15.3.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, Plots
        gr(fmt=:png);
```

```
In [3]: x_vals = [0 0 0 ; 2 -3 -4]
        y_vals = [0 0 0 ; 4 3 -3.5]

        plot(x_vals, y_vals, arrow = true, color = :blue,
             legend = :none, xlims = (-5, 5), ylims = (-5, 5),
             annotations = [(2.2, 4.4, "[2, 4]"),
                            (-3.3, 3.3, "[-3, 3]"),
                            (-4.4, -3.85, "[-4, -3.5]")],
             xticks = -5:1:5, yticks = -5:1:5,
             framestyle = :origin)
```

Out[3]:



15.3.2 Vector Operations

The two most common operators for vectors are addition and scalar multiplication, which we now describe.

As a matter of definition, when we add two vectors, we add them element by element

$$x + y = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} := \begin{bmatrix} x_1 + y_1 \\ x_2 + y_2 \\ \vdots \\ x_n + y_n \end{bmatrix}$$

Scalar multiplication is an operation that takes a number γ and a vector x and produces

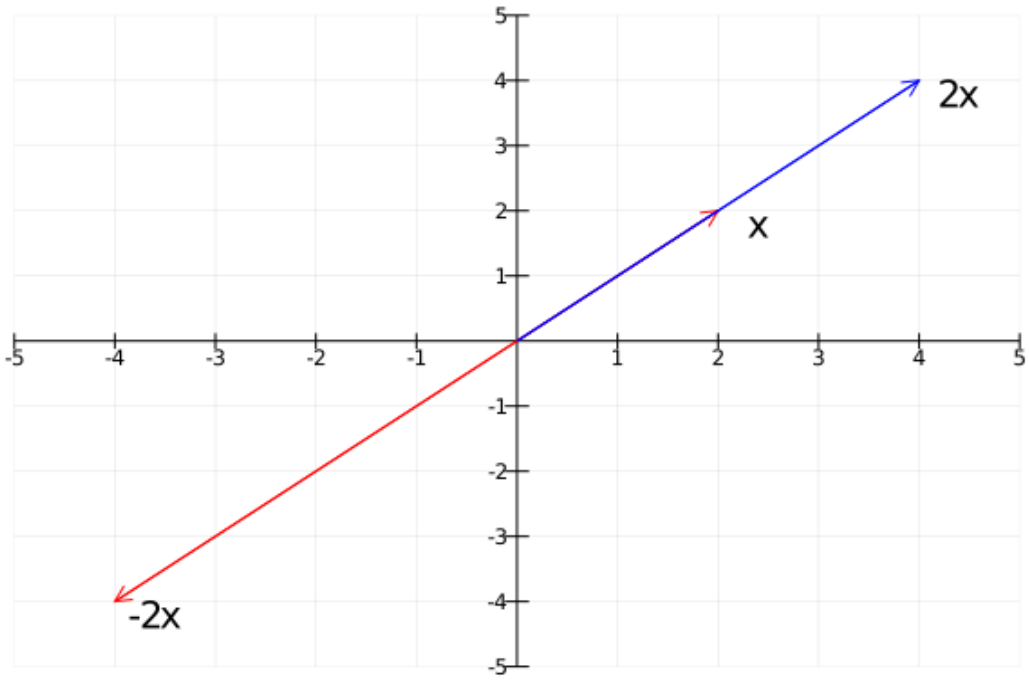
$$\gamma x := \begin{bmatrix} \gamma x_1 \\ \gamma x_2 \\ \vdots \\ \gamma x_n \end{bmatrix}$$

Scalar multiplication is illustrated in the next figure

In [4]:
```
# illustrate scalar multiplication

x = [2]
scalars = [-2 1 2]
vals = [0 0 0; x * scalars]
labels = [(-3.6, -4.2, "-2x"), (2.4, 1.8, "x"), (4.4, 3.8, "2x")]

plot(vals, vals, arrow = true, color = [:red :red :blue],
     legend = :none, xlims = (-5, 5), ylims = (-5, 5),
```

```
        annotations = labels, xticks = -5:1:5, yticks = -5:1:5,
        framestyle = :origin)
```

Out[4]:



In Julia, a vector can be represented as a one dimensional Array.

Julia Arrays allow us to express scalar multiplication and addition with a very natural syntax

```
In [5]: x = ones(3)
```

```
Out[5]: 3-element Array{Float64,1}:
         1.0
         1.0
         1.0
```

```
In [6]: y = [2, 4, 6]
```

```
Out[6]: 3-element Array{Int64,1}:
         2
         4
         6
```

```
In [7]: x + y
```

```
Out[7]: 3-element Array{Float64,1}:
         3.0
         5.0
         7.0
```

```
In [8]: 4x  # equivalent to 4 * x and 4 .* x
```

```
Out[8]: 3-element Array{Float64,1}:
          4.0
          4.0
          4.0
```

15.3.3 Inner Product and Norm

The *inner product* of vectors $x, y \in \mathbb{R}^n$ is defined as

$$x'y := \sum_{i=1}^{n} x_i y_i$$

Two vectors are called *orthogonal* if their inner product is zero.

The *norm* of a vector x represents its "length" (i.e., its distance from the zero vector) and is defined as

$$\|x\| := \sqrt{x'x} := \left(\sum_{i=1}^{n} x_i^2 \right)^{1/2}$$

The expression $\|x - y\|$ is thought of as the distance between x and y.

Continuing on from the previous example, the inner product and norm can be computed as follows

```
In [9]: using LinearAlgebra
```

```
In [10]: dot(x, y)               # Inner product of x and y
```

```
Out[10]: 12.0
```

```
In [11]: sum(prod, zip(x, y))    # Gives the same result
```

```
Out[11]: 12.0
```

```
In [12]: norm(x)                 # Norm of x
```

```
Out[12]: 1.7320508075688772
```

```
In [13]: sqrt(sum(abs2, x))         # Gives the same result
```

```
Out[13]: 1.7320508075688772
```

15.3.4 Span

Given a set of vectors $A := \{a_1, \ldots, a_k\}$ in $\mathbb{R}^n$, it's natural to think about the new vectors we can create by performing linear operations.

New vectors created in this manner are called *linear combinations* of A.

In particular, $y \in \mathbb{R}^n$ is a linear combination of $A := \{a_1, \ldots, a_k\}$ if

$$y = \beta_1 a_1 + \cdots + \beta_k a_k \text{ for some scalars } \beta_1, \ldots, \beta_k$$

In this context, the values $\beta_1, \ldots, \beta_k$ are called the *coefficients* of the linear combination.

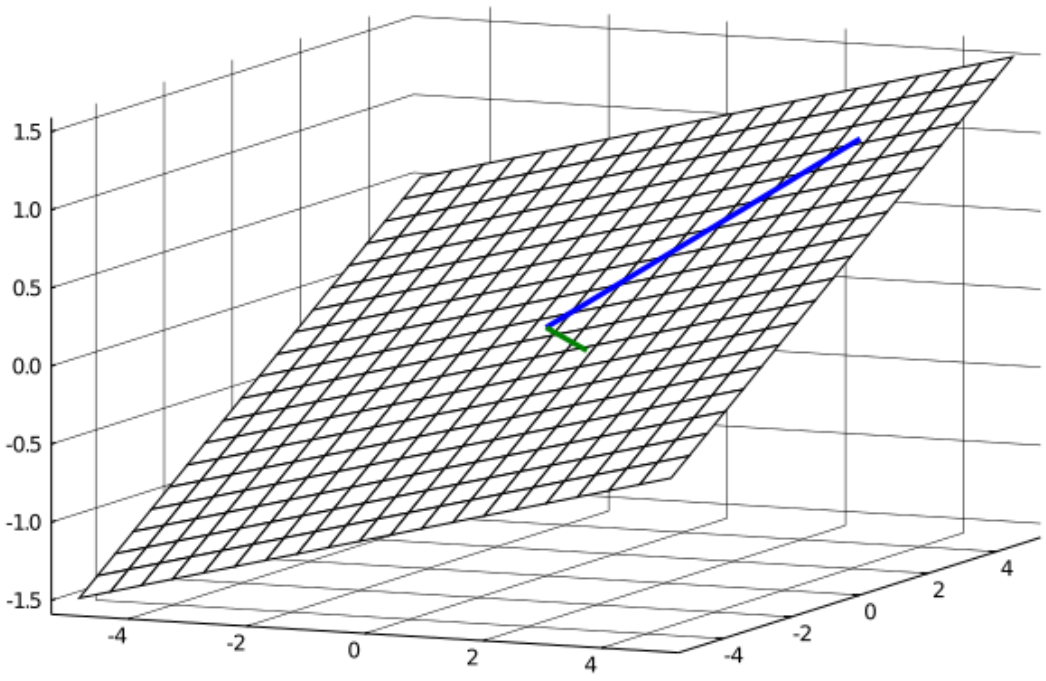
The set of linear combinations of A is called the *span* of A.

The next figure shows the span of $A = \{a_1, a_2\}$ in $\mathbb{R}^3$.

The span is a 2 dimensional plane passing through these two points and the origin.

In [14]:
```
# fixed linear function, to generate a plane
f(x, y) = 0.2x + 0.1y

# lines to vectors
x_vec = [0 0; 3 3]
y_vec = [0 0; 4 -4]
z_vec = [0 0; f(3, 4) f(3, -4)]

# draw the plane
n = 20
grid = range(-5, 5, length = n)
z2 = [ f(grid[row], grid[col]) for row in 1:n, col in 1:n ]
wireframe(grid, grid, z2, fill = :blues, gridalpha =1 )
plot!(x_vec, y_vec, z_vec, color = [:blue :green], linewidth = 3, labels
= "",
      colorbar = false)
```

Out[14]:



Examples

If A contains only one vector $a_1 \in \mathbb{R}^2$, then its span is just the scalar multiples of a_1, which is the unique line passing through both a_1 and the origin.

If $A = \{e_1, e_2, e_3\}$ consists of the *canonical basis vectors* of $\mathbb{R}^3$, that is

$$e_1 := \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad e_2 := \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad e_3 := \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

then the span of A is all of $\mathbb{R}^3$, because, for any $x = (x_1, x_2, x_3) \in \mathbb{R}^3$, we can write

$$x = x_1 e_1 + x_2 e_2 + x_3 e_3$$

Now consider $A_0 = \{e_1, e_2, e_1 + e_2\}$.

If $y = (y_1, y_2, y_3)$ is any linear combination of these vectors, then $y_3 = 0$ (check it).

Hence A_0 fails to span all of $\mathbb{R}^3$.

15.3.5 Linear Independence

As we'll see, it's often desirable to find families of vectors with relatively large span, so that many vectors can be described by linear operators on a few vectors.

The condition we need for a set of vectors to have a large span is what's called linear independence.

In particular, a collection of vectors $A := \{a_1, \ldots, a_k\}$ in $\mathbb{R}^n$ is said to be

- *linearly dependent* if some strict subset of A has the same span as A

- *linearly independent* if it is not linearly dependent

Put differently, a set of vectors is linearly independent if no vector is redundant to the span, and linearly dependent otherwise.

To illustrate the idea, recall the figure that showed the span of vectors $\{a_1, a_2\}$ in $\mathbb{R}^3$ as a plane through the origin.

If we take a third vector a_3 and form the set $\{a_1, a_2, a_3\}$, this set will be

- linearly dependent if a_3 lies in the plane
- linearly independent otherwise

As another illustration of the concept, since $\mathbb{R}^n$ can be spanned by n vectors (see the discussion of canonical basis vectors above), any collection of $m > n$ vectors in $\mathbb{R}^n$ must be linearly dependent.

The following statements are equivalent to linear independence of $A := \{a_1, \dots, a_k\} \subset \mathbb{R}^n$.

1. No vector in A can be formed as a linear combination of the other elements.
2. If $\beta_1 a_1 + \cdots \beta_k a_k = 0$ for scalars $\beta_1, \dots, \beta_k$, then $\beta_1 = \cdots = \beta_k = 0$.

(The zero in the first expression is the origin of $\mathbb{R}^n$)

15.3.6 Unique Representations

Another nice thing about sets of linearly independent vectors is that each element in the span has a unique representation as a linear combination of these vectors.

In other words, if $A := \{a_1, \dots, a_k\} \subset \mathbb{R}^n$ is linearly independent and

$$y = \beta_1 a_1 + \cdots \beta_k a_k$$

then no other coefficient sequence $\gamma_1, \dots, \gamma_k$ will produce the same vector y.

Indeed, if we also have $y = \gamma_1 a_1 + \cdots \gamma_k a_k$, then

$$(\beta_1 - \gamma_1) a_1 + \cdots + (\beta_k - \gamma_k) a_k = 0$$

Linear independence now implies $\gamma_i = \beta_i$ for all i.

15.4 Matrices

Matrices are a neat way of organizing data for use in linear operations.

An $n \times k$ matrix is a rectangular array A of numbers with n rows and k columns:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1k} \\ a_{21} & a_{22} & \cdots & a_{2k} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nk} \end{bmatrix}$$

Often, the numbers in the matrix represent coefficients in a system of linear equations, as discussed at the start of this lecture.

For obvious reasons, the matrix A is also called a vector if either $n = 1$ or $k = 1$.

In the former case, A is called a *row vector*, while in the latter it is called a *column vector*.

If $n = k$, then A is called *square*.

The matrix formed by replacing a_{ij} by a_{ji} for every i and j is called the *transpose* of A, and denoted A' or $A^\top$.

If $A = A'$, then A is called *symmetric*.

For a square matrix A, the i elements of the form a_{ii} for $i = 1, \ldots, n$ are called the *principal diagonal*.

A is called *diagonal* if the only nonzero entries are on the principal diagonal.

If, in addition to being diagonal, each element along the principal diagonal is equal to 1, then A is called the *identity matrix*, and denoted by I.

15.4.1 Matrix Operations

Just as was the case for vectors, a number of algebraic operations are defined for matrices.

Scalar multiplication and addition are immediate generalizations of the vector case:

$$\gamma A = \gamma \begin{bmatrix} a_{11} & \cdots & a_{1k} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nk} \end{bmatrix} := \begin{bmatrix} \gamma a_{11} & \cdots & \gamma a_{1k} \\ \vdots & \vdots & \vdots \\ \gamma a_{n1} & \cdots & \gamma a_{nk} \end{bmatrix}$$

and

$$A + B = \begin{bmatrix} a_{11} & \cdots & a_{1k} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nk} \end{bmatrix} + \begin{bmatrix} b_{11} & \cdots & b_{1k} \\ \vdots & \vdots & \vdots \\ b_{n1} & \cdots & b_{nk} \end{bmatrix} := \begin{bmatrix} a_{11} + b_{11} & \cdots & a_{1k} + b_{1k} \\ \vdots & \vdots & \vdots \\ a_{n1} + b_{n1} & \cdots & a_{nk} + b_{nk} \end{bmatrix}$$

In the latter case, the matrices must have the same shape in order for the definition to make sense.

We also have a convention for *multiplying* two matrices.

The rule for matrix multiplication generalizes the idea of inner products discussed above, and is designed to make multiplication play well with basic linear operations.

If A and B are two matrices, then their product AB is formed by taking as its i, j-th element the inner product of the i-th row of A and the j-th column of B.

There are many tutorials to help you visualize this operation, such as this one, or the discussion on the Wikipedia page.

If A is $n \times k$ and B is $j \times m$, then to multiply A and B we require $k = j$, and the resulting matrix AB is $n \times m$.

As perhaps the most important special case, consider multiplying $n \times k$ matrix A and $k \times 1$ column vector x.

According to the preceding rule, this gives us an $n \times 1$ column vector

$$Ax = \begin{bmatrix} a_{11} & \cdots & a_{1k} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nk} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_k \end{bmatrix} := \begin{bmatrix} a_{11}x_1 + \cdots + a_{1k}x_k \\ \vdots \\ a_{n1}x_1 + \cdots + a_{nk}x_k \end{bmatrix} \tag{2}$$

Note

AB and BA are not generally the same thing.

Another important special case is the identity matrix.

You should check that if A is $n \times k$ and I is the $k \times k$ identity matrix, then $AI = A$.

If I is the $n \times n$ identity matrix, then $IA = A$.

15.4.2 Matrices in Julia

Julia arrays are also used as matrices, and have fast, efficient functions and methods for all the standard matrix operations.

You can create them as follows

```
In [15]: A = [1 2
              3 4]
```

```
Out[15]: 2×2 Array{Int64,2}:
          1  2
          3  4
```

```
In [16]: typeof(A)
```

```
Out[16]: Array{Int64,2}
```

```
In [17]: size(A)
```

```
Out[17]: (2, 2)
```

The `size` function returns a tuple giving the number of rows and columns.

To get the transpose of `A`, use `transpose(A)` or, more simply, `A'`.

There are many convenient functions for creating common matrices (matrices of zeros, ones, etc.) — see here.

Since operations are performed elementwise by default, scalar multiplication and addition have very natural syntax

```
In [18]: A = ones(3, 3)
```

```
Out[18]: 3×3 Array{Float64,2}:
          1.0  1.0  1.0
          1.0  1.0  1.0
          1.0  1.0  1.0
```

```
In [19]: 2I
```

```
Out[19]: UniformScaling{Int64}
         2*I
```

```
In [20]: A + I
```

```
Out[20]: 3×3 Array{Float64,2}:
          2.0  1.0  1.0
          1.0  2.0  1.0
          1.0  1.0  2.0
```

To multiply matrices we use the `*` operator.

In particular, `A * B` is matrix multiplication, whereas `A .* B` is element by element multiplication.

15.4.3 Matrices as Maps

Each $n \times k$ matrix A can be identified with a function $f(x) = Ax$ that maps $x \in \mathbb{R}^k$ into $y = Ax \in \mathbb{R}^n$.

These kinds of functions have a special property: they are *linear*.

A function $f \colon \mathbb{R}^k \to \mathbb{R}^n$ is called *linear* if, for all $x, y \in \mathbb{R}^k$ and all scalars α, β, we have

$$f(\alpha x + \beta y) = \alpha f(x) + \beta f(y)$$

You can check that this holds for the function $f(x) = Ax + b$ when b is the zero vector, and fails when b is nonzero.

In fact, it's known that f is linear if and *only if* there exists a matrix A such that $f(x) = Ax$ for all x.

15.5 Solving Systems of Equations

Recall again the system of equations (1).

If we compare (1) and (2), we see that (1) can now be written more conveniently as

$$y = Ax \tag{3}$$

The problem we face is to determine a vector $x \in \mathbb{R}^k$ that solves (3), taking y and A as given.

This is a special case of a more general problem: Find an x such that $y = f(x)$.

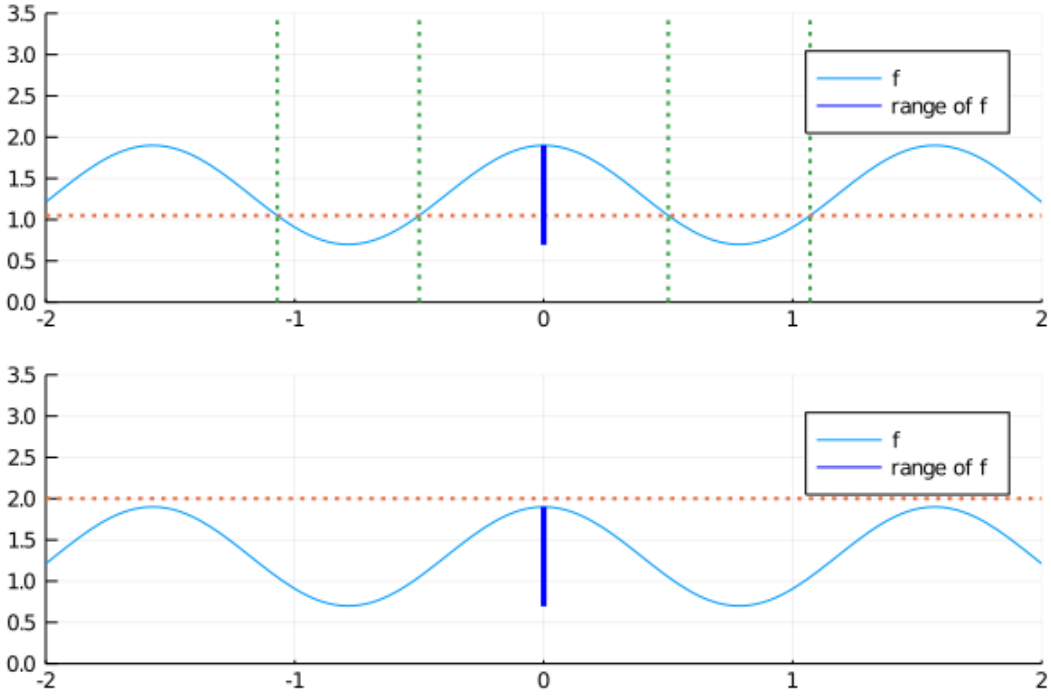
Given an arbitrary function f and a y, is there always an x such that $y = f(x)$?

If so, is it always unique?

The answer to both these questions is negative, as the next figure shows

```
In [21]: f(x) = 0.6cos(4x) + 1.3
         grid = range(-2, 2, length = 100)
         y_min, y_max = extrema( f(x) for x in grid )
         plt1 = plot(f, xlim = (-2, 2), label = "f")
         hline!(plt1, [f(0.5)], linestyle = :dot, linewidth = 2, label = "")
         vline!(plt1, [-1.07, -0.5, 0.5, 1.07], linestyle = :dot, linewidth = 2,
       ↪label = "")
         plot!(plt1, fill(0, 2), [y_min y_min; y_max y_max], lw = 3, color = :blue,
               label = ["range of f" ""])
         plt2 = plot(f, xlim = (-2, 2), label = "f")
         hline!(plt2, [2], linestyle = :dot, linewidth = 2, label = "")
         plot!(plt2, fill(0, 2), [y_min y_min; y_max y_max], lw = 3, color = :blue,
               label = ["range of f" ""])
         plot(plt1, plt2, layout = (2, 1), ylim = (0, 3.5))
```

Out[21]:



In the first plot there are multiple solutions, as the function is not one-to-one, while in the second there are no solutions, since y lies outside the range of f.

Can we impose conditions on A in (3) that rule out these problems?

In this context, the most important thing to recognize about the expression Ax is that it corresponds to a linear combination of the columns of A.

In particular, if $a_1, \ldots, a_k$ are the columns of A, then

$$Ax = x_1 a_1 + \cdots + x_k a_k$$

Hence the range of $f(x) = Ax$ is exactly the span of the columns of A.

We want the range to be large, so that it contains arbitrary y.

As you might recall, the condition that we want for the span to be large is linear independence.

A happy fact is that linear independence of the columns of A also gives us uniqueness.

Indeed, it follows from our earlier discussion that if $\{a_1, \ldots, a_k\}$ are linearly independent and $y = Ax = x_1 a_1 + \cdots + x_k a_k$, then no $z \neq x$ satisfies $y = Az$.

15.5.1 The $n \times n$ Case

Let's discuss some more details, starting with the case where A is $n \times n$.

This is the familiar case where the number of unknowns equals the number of equations.

For arbitrary $y \in \mathbb{R}^n$, we hope to find a unique $x \in \mathbb{R}^n$ such that $y = Ax$.

In view of the observations immediately above, if the columns of A are linearly independent, then their span, and hence the range of $f(x) = Ax$, is all of $\mathbb{R}^n$.

Hence there always exists an x such that $y = Ax$.

Moreover, the solution is unique.

In particular, the following are equivalent

1. The columns of A are linearly independent
2. For any $y \in \mathbb{R}^n$, the equation $y = Ax$ has a unique solution

The property of having linearly independent columns is sometimes expressed as having *full column rank*.

Inverse Matrices

Can we give some sort of expression for the solution?

If y and A are scalar with $A \neq 0$, then the solution is $x = A^{-1}y$.

A similar expression is available in the matrix case.

In particular, if square matrix A has full column rank, then it possesses a multiplicative *inverse matrix* A^{-1}, with the property that $AA^{-1} = A^{-1}A = I$.

As a consequence, if we pre-multiply both sides of $y = Ax$ by A^{-1}, we get $x = A^{-1}y$.

This is the solution that we're looking for.

Determinants

Another quick comment about square matrices is that to every such matrix we assign a unique number called the *determinant* of the matrix — you can find the expression for it here.

If the determinant of A is not zero, then we say that A is *nonsingular*.

Perhaps the most important fact about determinants is that A is nonsingular if and only if A is of full column rank.

This gives us a useful one-number summary of whether or not a square matrix can be inverted.

15.5.2 More Rows than Columns

This is the $n \times k$ case with $n > k$.

This case is very important in many settings, not least in the setting of linear regression (where n is the number of observations, and k is the number of explanatory variables).

Given arbitrary $y \in \mathbb{R}^n$, we seek an $x \in \mathbb{R}^k$ such that $y = Ax$.

In this setting, existence of a solution is highly unlikely.

Without much loss of generality, let's go over the intuition focusing on the case where the columns of A are linearly independent.

It follows that the span of the columns of A is a k-dimensional subspace of $\mathbb{R}^n$.

This span is very "unlikely" to contain arbitrary $y \in \mathbb{R}^n$.

To see why, recall the figure above, where $k = 2$ and $n = 3$.

Imagine an arbitrarily chosen $y \in \mathbb{R}^3$, located somewhere in that three dimensional space.

What's the likelihood that y lies in the span of $\{a_1, a_2\}$ (i.e., the two dimensional plane through these points)?

In a sense it must be very small, since this plane has zero "thickness".

As a result, in the $n > k$ case we usually give up on existence.

However, we can still seek a best approximation, for example an x that makes the distance $\|y - Ax\|$ as small as possible.

To solve this problem, one can use either calculus or the theory of orthogonal projections.

The solution is known to be $\hat{x} = (A'A)^{-1}A'y$ — see for example chapter 3 of these notes

15.5.3 More Columns than Rows

This is the $n \times k$ case with $n < k$, so there are fewer equations than unknowns.

In this case there are either no solutions or infinitely many — in other words, uniqueness never holds.

For example, consider the case where $k = 3$ and $n = 2$.

Thus, the columns of A consists of 3 vectors in $\mathbb{R}^2$.

This set can never be linearly independent, since it is possible to find two vectors that span $\mathbb{R}^2$.

(For example, use the canonical basis vectors)

It follows that one column is a linear combination of the other two.

For example, let's say that $a_1 = \alpha a_2 + \beta a_3$.

Then if $y = Ax = x_1 a_1 + x_2 a_2 + x_3 a_3$, we can also write

$$y = x_1(\alpha a_2 + \beta a_3) + x_2 a_2 + x_3 a_3 = (x_1\alpha + x_2)a_2 + (x_1\beta + x_3)a_3$$

In other words, uniqueness fails.

15.5.4 Linear Equations with Julia

Here's an illustration of how to solve linear equations with Julia's built-in linear algebra facilities

```
In [22]: A = [1.0 2.0; 3.0 4.0];

In [23]: y = ones(2, 1);  # A column vector

In [24]: det(A)

Out[24]: -2.0

In [25]: A_inv = inv(A)

Out[25]: 2×2 Array{Float64,2}:
          -2.0   1.0
           1.5  -0.5

In [26]: x = A_inv * y  # solution

Out[26]: 2×1 Array{Float64,2}:
          -0.9999999999999998
           0.9999999999999999

In [27]: A * x  # should equal y (a vector of ones)

Out[27]: 2×1 Array{Float64,2}:
          1.0
          1.0000000000000004

In [28]: A \ y  # produces the same solution

Out[28]: 2×1 Array{Float64,2}:
          -1.0
           1.0
```

Observe how we can solve for $x = A^{-1}y$ by either via `inv(A) * y`, or using `A \ y`.

The latter method is preferred because it automatically selects the best algorithm for the problem based on the types of `A` and `y`.

If `A` is not square then `A \ y` returns the least squares solution $\hat{x} = (A'A)^{-1}A'y$.

15.6 Eigenvalues and Eigenvectors

Let A be an $n \times n$ square matrix.

If λ is scalar and v is a non-zero vector in $\mathbb{R}^n$ such that

$$Av = \lambda v$$

then we say that λ is an *eigenvalue* of A, and v is an *eigenvector*.

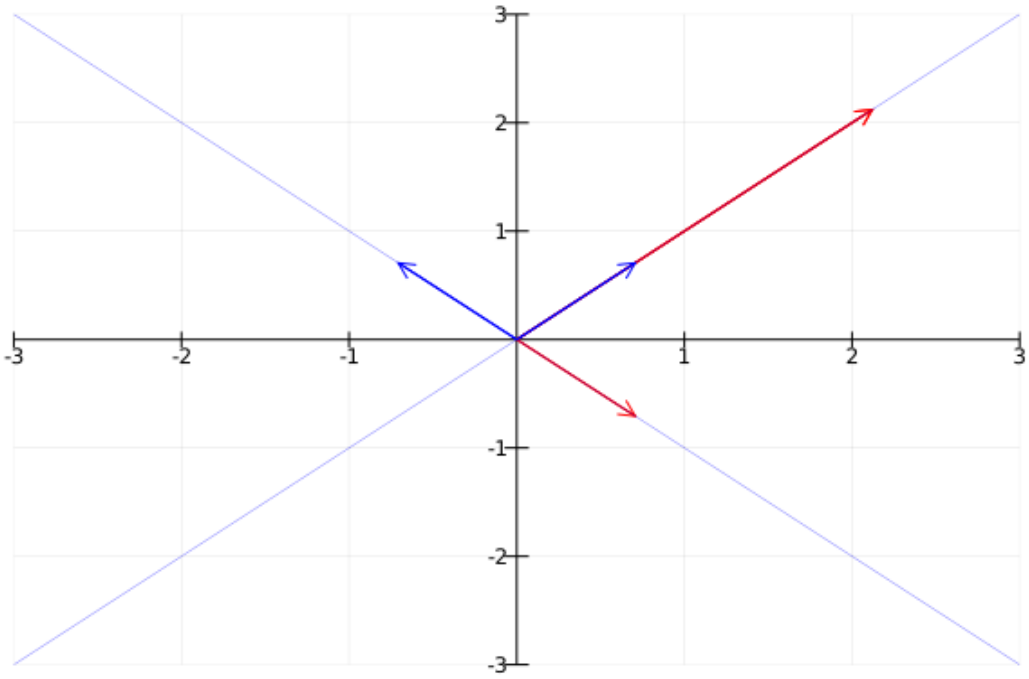
Thus, an eigenvector of A is a vector such that when the map $f(x) = Ax$ is applied, v is merely scaled.

The next figure shows two eigenvectors (blue arrows) and their images under A (red arrows).

As expected, the image Av of each v is just a scaled version of the original

```
In [29]: A = [1 2
              2 1]
         evals, evecs = eigen(A)

         a1, a2 = evals
         eig_1 = [0 0; evecs[:,1]']
         eig_2 = [0 0; evecs[:,2]']
         x = range(-5, 5, length = 10)
         y = -x

         plot(eig_1[:, 2], a1 * eig_2[:, 2], arrow = true, color = :red,
              legend = :none, xlims = (-3, 3), ylims = (-3, 3), xticks = -3:3,
 ↪yticks = -3:3,
              framestyle = :origin)
         plot!(a2 * eig_1[:, 2], a2 * eig_2, arrow = true, color = :red)
         plot!(eig_1, eig_2, arrow = true, color = :blue)
         plot!(x, y, color = :blue, lw = 0.4, alpha = 0.6)
         plot!(x, x, color = :blue, lw = 0.4, alpha = 0.6)
```

Out[29]:



The eigenvalue equation is equivalent to $(A - \lambda I)v = 0$, and this has a nonzero solution v only when the columns of $A - \lambda I$ are linearly dependent.

This in turn is equivalent to stating that the determinant is zero.

Hence to find all eigenvalues, we can look for λ such that the determinant of $A - \lambda I$ is zero.

This problem can be expressed as one of solving for the roots of a polynomial in λ of degree n.

This in turn implies the existence of n solutions in the complex plane, although some might be repeated.

Some nice facts about the eigenvalues of a square matrix A are as follows

1. The determinant of A equals the product of the eigenvalues.
2. The trace of A (the sum of the elements on the principal diagonal) equals the sum of the eigenvalues.
3. If A is symmetric, then all of its eigenvalues are real.
4. If A is invertible and $\lambda_1, \ldots, \lambda_n$ are its eigenvalues, then the eigenvalues of A^{-1} are $1/\lambda_1, \ldots, 1/\lambda_n$.

A corollary of the first statement is that a matrix is invertible if and only if all its eigenvalues are nonzero.

Using Julia, we can solve for the eigenvalues and eigenvectors of a matrix as follows

```
In [30]: A = [1.0 2.0; 2.0 1.0];
```

```
In [31]: evals, evecs = eigen(A);
```

```
In [32]: evals

Out[32]: 2-element Array{Float64,1}:
          -1.0
           3.0

In [33]: evecs

Out[33]: 2×2 Array{Float64,2}:
          -0.707107  0.707107
           0.707107  0.707107
```

Note that the *columns* of `evecs` are the eigenvectors.

Since any scalar multiple of an eigenvector is an eigenvector with the same eigenvalue (check it), the eig routine normalizes the length of each eigenvector to one.

15.6.1 Generalized Eigenvalues

It is sometimes useful to consider the *generalized eigenvalue problem*, which, for given matrices A and B, seeks generalized eigenvalues λ and eigenvectors v such that

$$Av = \lambda Bv$$

This can be solved in Julia via `eigen(A, B)`.

Of course, if B is square and invertible, then we can treat the generalized eigenvalue problem as an ordinary eigenvalue problem $B^{-1}Av = \lambda v$, but this is not always the case.

15.7 Further Topics

We round out our discussion by briefly mentioning several other important topics.

15.7.1 Series Expansions

Recall the usual summation formula for a geometric progression, which states that if $|a| < 1$, then $\sum_{k=0}^{\infty} a^k = (1-a)^{-1}$.

A generalization of this idea exists in the matrix setting.

Matrix Norms

Let A be a square matrix, and let

$$\|A\| := \max_{\|x\|=1} \|Ax\|$$

The norms on the right-hand side are ordinary vector norms, while the norm on the left-hand side is a *matrix norm* — in this case, the so-called *spectral norm*.

For example, for a square matrix S, the condition $\|S\| < 1$ means that S is *contractive*, in the sense that it pulls all vectors towards the origin Section **??**.

Neumann's Theorem

Let A be a square matrix and let $A^k := AA^{k-1}$ with $A^1 := A$.

In other words, A^k is the k-th power of A.

Neumann's theorem states the following: If $\|A^k\| < 1$ for some $k \in \mathbb{N}$, then $I - A$ is invertible, and

$$(I - A)^{-1} = \sum_{k=0}^{\infty} A^k \tag{4}$$

Spectral Radius

A result known as Gelfand's formula tells us that, for any square matrix A,

$$\rho(A) = \lim_{k \to \infty} \|A^k\|^{1/k}$$

Here $\rho(A)$ is the *spectral radius*, defined as $\max_i |\lambda_i|$, where $\{\lambda_i\}_i$ is the set of eigenvalues of A.

As a consequence of Gelfand's formula, if all eigenvalues are strictly less than one in modulus, there exists a k with $\|A^k\| < 1$.

In which case (4) is valid.

15.7.2 Positive Definite Matrices

Let A be a symmetric $n \times n$ matrix.

We say that A is

1. *positive definite* if $x'Ax > 0$ for every $x \in \mathbb{R}^n \quad \{0\}$
2. *positive semi-definite* or *nonnegative definite* if $x'Ax \geq 0$ for every $x \in \mathbb{R}^n$

Analogous definitions exist for negative definite and negative semi-definite matrices.

It is notable that if A is positive definite, then all of its eigenvalues are strictly positive, and hence A is invertible (with positive definite inverse).

15.7.3 Differentiating Linear and Quadratic forms

The following formulas are useful in many economic contexts. Let

- z, x and a all be $n \times 1$ vectors
- A be an $n \times n$ matrix
- B be an $m \times n$ matrix and y be an $m \times 1$ vector

Then

1. $\frac{\partial a'x}{\partial x} = a$

2. $\frac{\partial Ax}{\partial x} = A'$
3. $\frac{\partial x'Ax}{\partial x} = (A + A')x$
4. $\frac{\partial y'Bz}{\partial y} = Bz$
5. $\frac{\partial y'Bz}{\partial B} = yz'$

Exercise 1 below asks you to apply these formulas.

15.7.4 Further Reading

The documentation of the linear algebra features built into Julia can be found here.

Chapters 2 and 3 of the Econometric Theory contains a discussion of linear algebra along the same lines as above, with solved exercises.

If you don't mind a slightly abstract approach, a nice intermediate-level text on linear algebra is [57].

15.8 Exercises

15.8.1 Exercise 1

Let x be a given $n \times 1$ vector and consider the problem

$$v(x) = \max_{y,u} \{-y'Py - u'Qu\}$$

subject to the linear constraint

$$y = Ax + Bu$$

Here

- P is an $n \times n$ matrix and Q is an $m \times m$ matrix
- A is an $n \times n$ matrix and B is an $n \times m$ matrix
- both P and Q are symmetric and positive semidefinite

(What must the dimensions of y and u be to make this a well-posed problem?)

One way to solve the problem is to form the Lagrangian

$$\mathcal{L} = -y'Py - u'Qu + \lambda' [Ax + Bu - y]$$

where λ is an $n \times 1$ vector of Lagrange multipliers.

Try applying the formulas given above for differentiating quadratic and linear forms to obtain the first-order conditions for maximizing $\mathcal{L}$ with respect to y, u and minimizing it with respect to λ.

Show that these conditions imply that

1. $\lambda = -2Py$
2. The optimizing choice of u satisfies $u = -(Q + B'PB)^{-1}B'PAx$
3. The function v satisfies $v(x) = -x'\tilde{P}x$ where $\tilde{P} = A'PA - A'PB(Q + B'PB)^{-1}B'PA$

As we will see, in economic contexts Lagrange multipliers often are shadow prices

Note

If we don't care about the Lagrange multipliers, we can substitute the constraint into the objective function, and then just maximize $-(Ax+Bu)'P(Ax+Bu)-u'Qu$ with respect to u. You can verify that this leads to the same maximizer.

15.9 Solutions

Thanks to Willem Hekman and Guanlong Ren for providing this solution.

15.9.1 Exercise 1

We have an optimization problem:

$$v(x) = \max_{y,u}\{-y'Py - u'Qu\}$$

s.t.

$$y = Ax + Bu$$

with primitives

- P be a symmetric and positive semidefinite $n \times n$ matrix.
- Q be a symmetric and positive semidefinite $m \times m$ matrix.
- A an $n \times n$ matrix.
- B an $n \times m$ matrix.

The associated Lagrangian is :

$$L = -y'Py - u'Qu + \lambda'[Ax + Bu - y]$$

1.

Differentiating Lagrangian equation w.r.t y and setting its derivative equal to zero yields

$$\frac{\partial L}{\partial y} = -(P + P')y - \lambda = -2Py - \lambda = 0\,,$$

since P is symmetric.

Accordingly, the first-order condition for maximizing L w.r.t. y implies

$$\lambda = -2Py\,.$$

2.

Differentiating Lagrangian equation w.r.t. u and setting its derivative equal to zero yields

$$\frac{\partial L}{\partial u} = -(Q + Q')u - B'\lambda = -2Qu + B'\lambda = 0 \,.$$

Substituting $\lambda = -2Py$ gives

$$Qu + B'Py = 0 \,.$$

Substituting the linear constraint $y = Ax + Bu$ into above equation gives

$$Qu + B'P(Ax + Bu) = 0$$

$$(Q + B'PB)u + B'PAx = 0$$

which is the first-order condition for maximizing L w.r.t. u.

Thus, the optimal choice of u must satisfy

$$u = -(Q + B'PB)^{-1}B'PAx \,,$$

which follows from the definition of the first-oder conditions for Lagrangian equation.

3.

Rewriting our problem by substituting the constraint into the objective function, we get

$$v(x) = \max_u \{-(Ax + Bu)'P(Ax + Bu) - u'Qu\} \,.$$

Since we know the optimal choice of u satisfies $u = -(Q + B'PB)^{-1}B'PAx$, then

$$v(x) = -(Ax + Bu)'P(Ax + Bu) - u'Qu \quad with \quad u = -(Q + B'PB)^{-1}B'PAx$$

To evaluate the function

$$\begin{aligned} v(x) &= -(Ax + Bu)'P(Ax + Bu) - u'Qu \\ &= -(x'A' + u'B')P(Ax + Bu) - u'Qu \\ &= -x'A'PAx - u'B'PAx - x'A'PBu - u'B'PBu - u'Qu \\ &= -x'A'PAx - 2u'B'PAx - u'(Q + B'PB)u \end{aligned}$$

For simplicity, denote by $S := (Q + B'PB)^{-1}B'PA$, then $u = -Sx$.

Regarding the second term $-2u'B'PAx$,

$$\begin{aligned} -2u'B'PAx &= -2x'S'B'PAx \\ &= 2x'A'PB(Q + B'PB)^{-1}B'PAx \end{aligned}$$

Notice that the term $(Q + B'PB)^{-1}$ is symmetric as both P and Q are symmetric.

Regarding the third term $-u'(Q + B'PB)u$,

$$\begin{aligned} -u'(Q + B'PB)u &= -x'S'(Q + B'PB)Sx \\ &= -x'A'PB(Q + B'PB)^{-1}B'PAx \end{aligned}$$

Hence, the summation of second and third terms is $x'A'PB(Q + B'PB)^{-1}B'PAx$.

This implies that

$$\begin{aligned} v(x) &= -x'A'PAx - 2u'B'PAx - u'(Q + B'PB)u \\ &= -x'A'PAx + x'A'PB(Q + B'PB)^{-1}B'PAx \\ &= -x'[A'PA - A'PB(Q + B'PB)^{-1}B'PA]x \end{aligned}$$

Therefore, the solution to the optimization problem $v(x) = -x'\tilde{P}x$ follows the above result by denoting $\tilde{P} := A'PA - A'PB(Q + B'PB)^{-1}B'PA$.

Footnotes

[1] Suppose that $\|S\| < 1$. Take any nonzero vector x, and let $r := \|x\|$. We have $\|Sx\| = r\|S(x/r)\| \leq r\|S\| < r = \|x\|$. Hence every point is pulled towards the origin.

Chapter 16

Orthogonal Projections and Their Applications

16.1 Contents

16.2 Overview

Orthogonal projection is a cornerstone of vector space methods, with many diverse applications.

These include, but are not limited to,

- Least squares projection, also known as linear regression
- Conditional expectations for multivariate normal (Gaussian) distributions
- Gram–Schmidt orthogonalization
- QR decomposition
- Orthogonal polynomials
- etc

In this lecture we focus on

- key ideas
- least squares regression

16.2.1 Further Reading

For background and foundational concepts, see our lecture on linear algebra.

For more proofs and greater theoretical detail, see A Primer in Econometric Theory.

For a complete set of proofs in a general setting, see, for example, [90].

For an advanced treatment of projection in the context of least squares prediction, see this book chapter.

16.3 Key Definitions

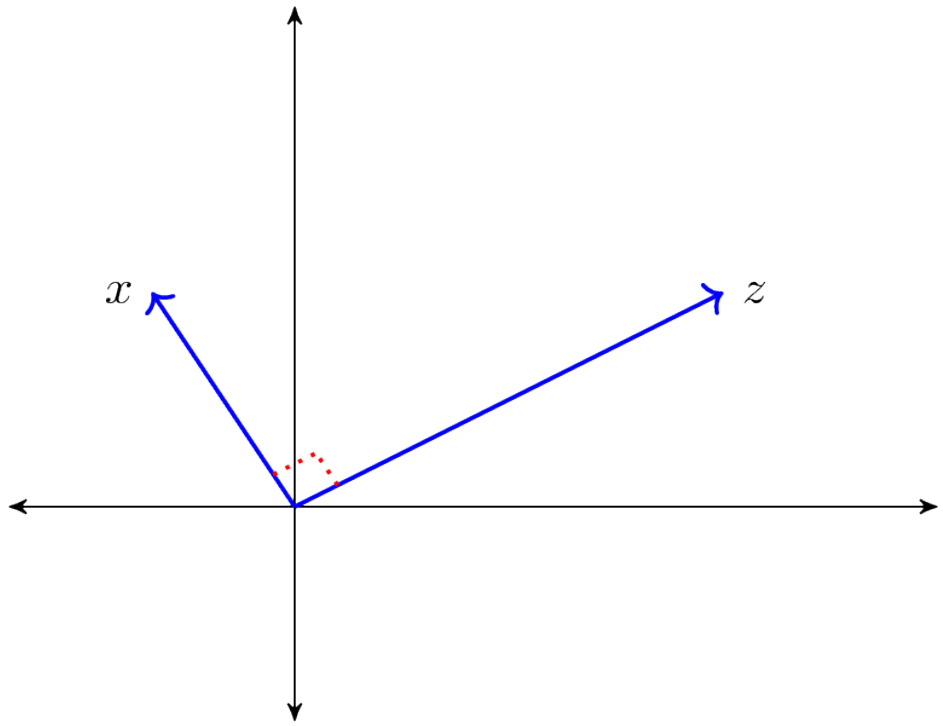
Assume $x, z \in \mathbb{R}^n$.

Define $\langle x, z \rangle = \sum_i x_i z_i$.

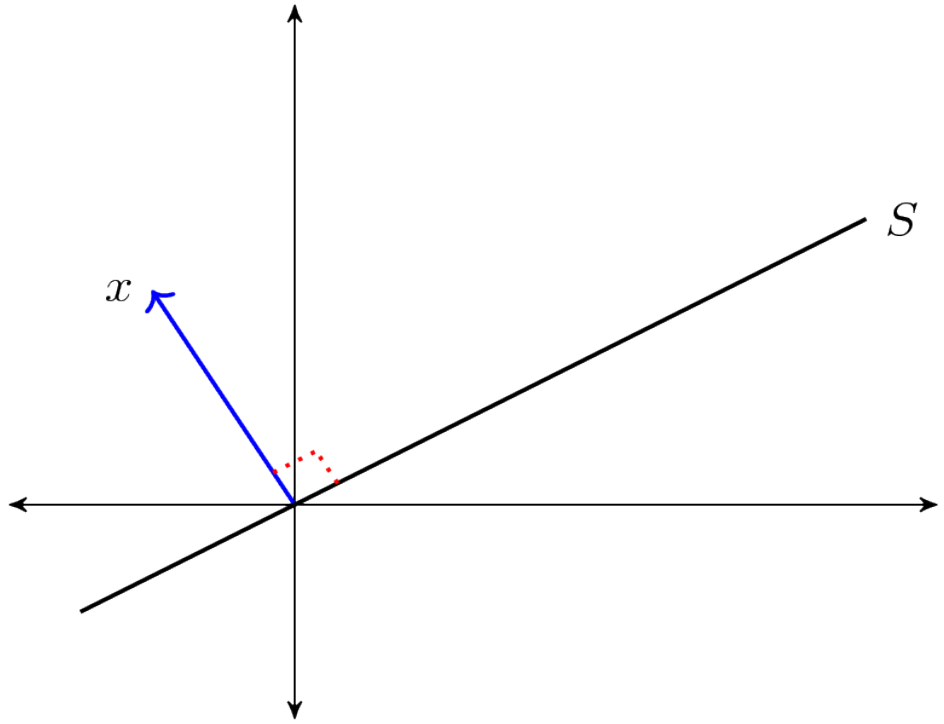
Recall $\|x\|^2 = \langle x, x \rangle$.

The **law of cosines** states that $\langle x, z \rangle = \|x\| \|z\| \cos(\theta)$ where θ is the angle between the vectors x and z.

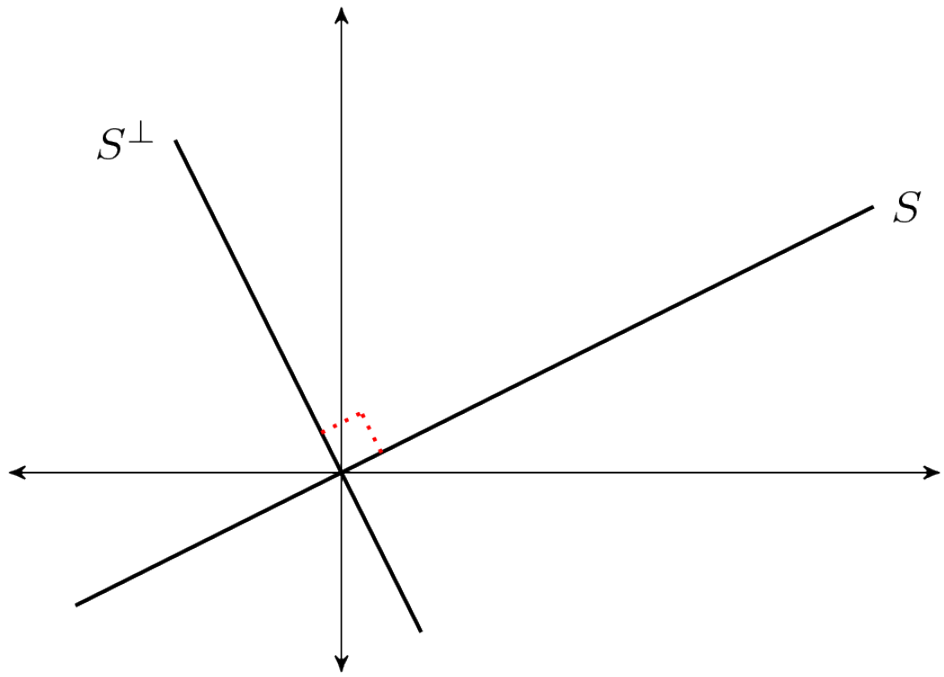
When $\langle x, z \rangle = 0$, then $\cos(\theta) = 0$ and x and z are said to be **orthogonal** and we write $x \perp z$



For a linear subspace $S \subset \mathbb{R}^n$, we call $x \in \mathbb{R}^n$ **orthogonal to** S if $x \perp z$ for all $z \in S$, and write $x \perp S$



The **orthogonal complement** of linear subspace $S \subset \mathbb{R}^n$ is the set $S^\perp := \{x \in \mathbb{R}^n : x \perp S\}$



$S^\perp$ is a linear subspace of $\mathbb{R}^n$

- To see this, fix $x, y \in S^\perp$ and $\alpha, \beta \in \mathbb{R}$.
- Observe that if $z \in S$, then

$$\langle \alpha x + \beta y, z \rangle = \alpha \langle x, z \rangle + \beta \langle y, z \rangle = \alpha \times 0 + \beta \times 0 = 0$$

- Hence $\alpha x + \beta y \in S^\perp$, as was to be shown

A set of vectors $\{x_1, \ldots, x_k\} \subset \mathbb{R}^n$ is called an **orthogonal set** if $x_i \perp x_j$ whenever $i \neq j$.

If $\{x_1, \ldots, x_k\}$ is an orthogonal set, then the **Pythagorean Law** states that

$$\|x_1 + \cdots + x_k\|^2 = \|x_1\|^2 + \cdots + \|x_k\|^2$$

For example, when $k = 2$, $x_1 \perp x_2$ implies

$$\|x_1 + x_2\|^2 = \langle x_1 + x_2, x_1 + x_2 \rangle = \langle x_1, x_1 \rangle + 2\langle x_2, x_1 \rangle + \langle x_2, x_2 \rangle = \|x_1\|^2 + \|x_2\|^2$$

16.3.1 Linear Independence vs Orthogonality

If $X \subset \mathbb{R}^n$ is an orthogonal set and $0 \notin X$, then X is linearly independent.

Proving this is a nice exercise.

While the converse is not true, a kind of partial converse holds, as we'll see below.

16.4 The Orthogonal Projection Theorem

What vector within a linear subspace of $\mathbb{R}^n$ best approximates a given vector in $\mathbb{R}^n$?

The next theorem provides answers this question.

Theorem (OPT) Given $y \in \mathbb{R}^n$ and linear subspace $S \subset \mathbb{R}^n$, there exists a unique solution to the minimization problem

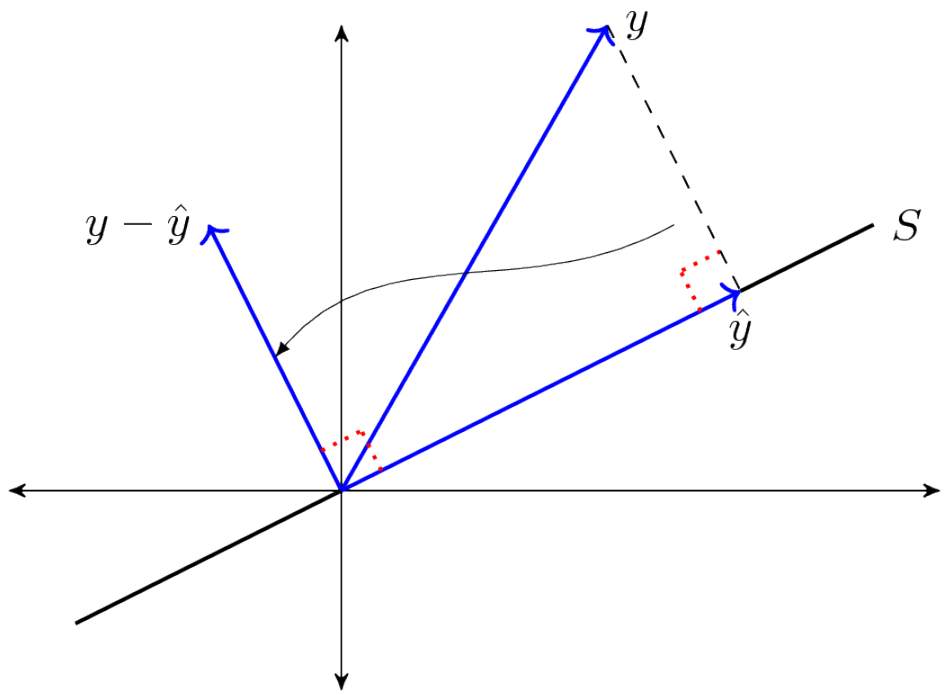
$$\hat{y} := \arg\min_{z \in S} \|y - z\|$$

The minimizer $\hat{y}$ is the unique vector in $\mathbb{R}^n$ that satisfies

- $\hat{y} \in S$
- $y - \hat{y} \perp S$

The vector $\hat{y}$ is called the **orthogonal projection** of y onto S.

The next figure provides some intuition



16.4.1 Proof of sufficiency

We'll omit the full proof.

But we will prove sufficiency of the asserted conditions.

To this end, let $y \in \mathbb{R}^n$ and let S be a linear subspace of $\mathbb{R}^n$.

Let $\hat{y}$ be a vector in $\mathbb{R}^n$ such that $\hat{y} \in S$ and $y - \hat{y} \perp S$.

Let z be any other point in S and use the fact that S is a linear subspace to deduce

$$\|y - z\|^2 = \|(y - \hat{y}) + (\hat{y} - z)\|^2 = \|y - \hat{y}\|^2 + \|\hat{y} - z\|^2$$

Hence $\|y - z\| \geq \|y - \hat{y}\|$, which completes the proof.

16.4.2 Orthogonal Projection as a Mapping

For a linear space Y and a fixed linear subspace S, we have a functional relationship

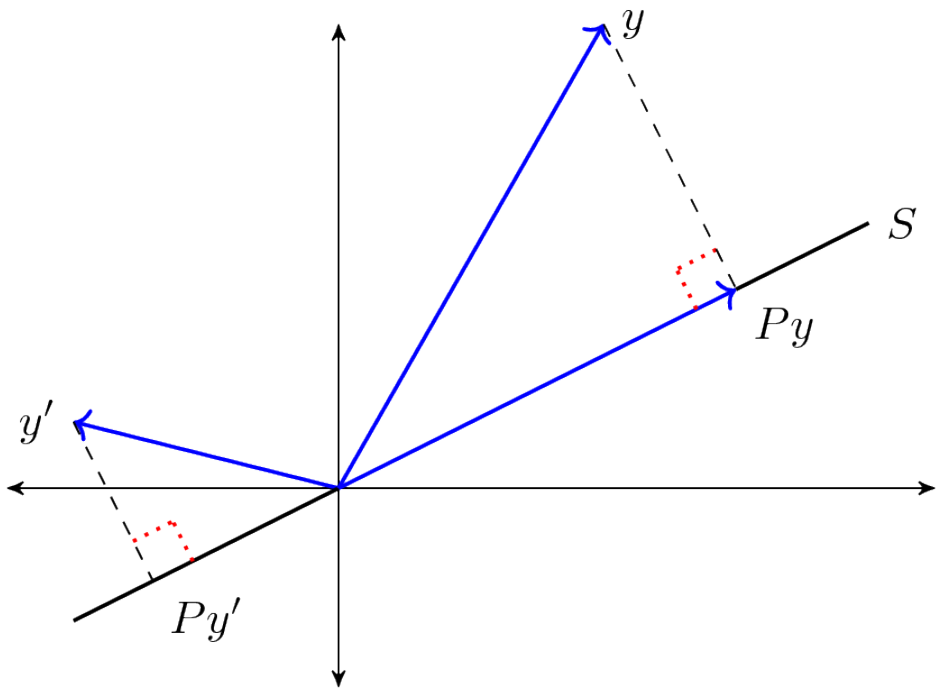
$$y \in Y \;\mapsto\; \text{its orthogonal projection } \hat{y} \in S$$

By the OPT, this is a well-defined mapping or *operator* from $\mathbb{R}^n$ to $\mathbb{R}^n$.

In what follows we denote this operator by a matrix P

- Py represents the projection $\hat{y}$.
- This is sometimes expressed as $\hat{E}_S y = Py$, where $\hat{E}$ denotes a **wide-sense expectations operator** and the subscript S indicates that we are projecting y onto the linear subspace S.

The operator P is called the **orthogonal projection mapping onto** S



It is immediate from the OPT that for any $y \in \mathbb{R}^n$

1. $Py \in S$ and
2. $y - Py \perp S$

From this we can deduce additional useful properties, such as

1. $\|y\|^2 = \|Py\|^2 + \|y - Py\|^2$ and
2. $\|Py\| \leq \|y\|$

For example, to prove 1, observe that $y = Py + y - Py$ and apply the Pythagorean law.

Orthogonal Complement

Let $S \subset \mathbb{R}^n$.

The **orthogonal complement** of S is the linear subspace $S^\perp$ that satisfies $x_1 \perp x_2$ for every $x_1 \in S$ and $x_2 \in S^\perp$.

Let Y be a linear space with linear subspace S and its orthogonal complement $S^\perp$.

We write

$$Y = S \oplus S^\perp$$

to indicate that for every $y \in Y$ there is unique $x_1 \in S$ and a unique $x_2 \in S^\perp$ such that $y = x_1 + x_2$.

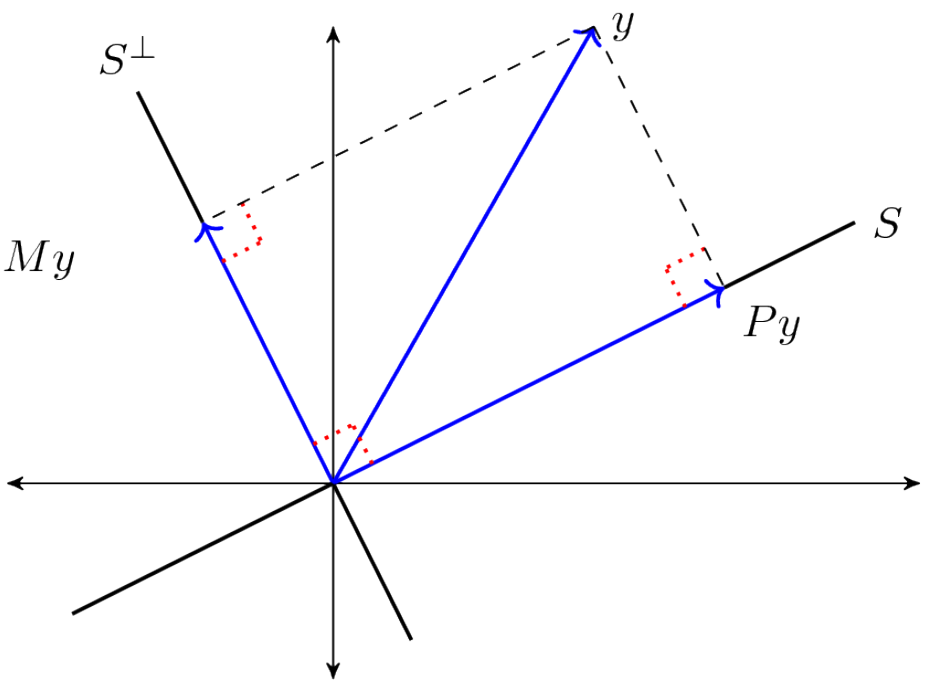
Moreover, $x_1 = \hat{E}_S y$ and $x_2 = y - \hat{E}_S y$.

This amounts to another version of the OPT:

Theorem. If S is a linear subspace of $\mathbb{R}^n$, $\hat{E}_S y = Py$ and $\hat{E}_{S^\perp} y = My$, then

$$Py \perp My \quad \text{and} \quad y = Py + My \quad \text{for all } y \in \mathbb{R}^n$$

The next figure illustrates



16.5 Orthonormal Basis

An orthogonal set of vectors $O \subset \mathbb{R}^n$ is called an **orthonormal set** if $\|u\| = 1$ for all $u \in O$.

Let S be a linear subspace of $\mathbb{R}^n$ and let $O \subset S$.

If O is orthonormal and $\operatorname{span} O = S$, then O is called an **orthonormal basis** of S.

O is necessarily a basis of S (being independent by orthogonality and the fact that no element is the zero vector).

One example of an orthonormal set is the canonical basis $\{e_1, \ldots, e_n\}$ that forms an orthonormal basis of $\mathbb{R}^n$, where e_i is the i th unit vector.

If $\{u_1, \ldots, u_k\}$ is an orthonormal basis of linear subspace S, then

$$x = \sum_{i=1}^{k} \langle x, u_i \rangle u_i \quad \text{for all} \quad x \in S$$

To see this, observe that since $x \in \operatorname{span}\{u_1, \ldots, u_k\}$, we can find scalars $\alpha_1, \ldots, \alpha_k$ that verify

$$x = \sum_{j=1}^{k} \alpha_j u_j \tag{1}$$

Taking the inner product with respect to u_i gives

$$\langle x, u_i \rangle = \sum_{j=1}^{k} \alpha_j \langle u_j, u_i \rangle = \alpha_i$$

Combining this result with (1) verifies the claim.

16.5.1 Projection onto an Orthonormal Basis

When the subspace onto which are projecting is orthonormal, computing the projection simplifies:

Theorem If $\{u_1, \ldots, u_k\}$ is an orthonormal basis for S, then

$$Py = \sum_{i=1}^{k} \langle y, u_i \rangle u_i, \quad \forall \; y \in \mathbb{R}^n \tag{2}$$

Proof: Fix $y \in \mathbb{R}^n$ and let Py be defined as in (2).

Clearly, $Py \in S$.

We claim that $y - Py \perp S$ also holds.

It sufficies to show that $y - Py \perp$ any basis vector u_i (why?).

This is true because

$$\left\langle y - \sum_{i=1}^{k} \langle y, u_i \rangle u_i, u_j \right\rangle = \langle y, u_j \rangle - \sum_{i=1}^{k} \langle y, u_i \rangle \langle u_i, u_j \rangle = 0$$

16.6 Projection Using Matrix Algebra

Let S be a linear subspace of $\mathbb{R}^n$ and let $y \in \mathbb{R}^n$.

We want to compute the matrix P that verifies

$$\hat{E}_S y = Py$$

Evidently Py is a linear function from $y \in \mathbb{R}^n$ to $Py \in \mathbb{R}^n$.

This reference is useful https://en.wikipedia.org/wiki/Linear_map#Matrices.

Theorem. Let the columns of $n \times k$ matrix X form a basis of S. Then

$$P = X(X'X)^{-1}X'$$

Proof: Given arbitrary $y \in \mathbb{R}^n$ and $P = X(X'X)^{-1}X'$, our claim is that

1. $Py \in S$, and
2. $y - Py \perp S$

Claim 1 is true because

$$Py = X(X'X)^{-1}X'y = Xa \quad \text{when} \quad a := (X'X)^{-1}X'y$$

An expression of the form Xa is precisely a linear combination of the columns of X, and hence an element of S.

Claim 2 is equivalent to the statement

$$y - X(X'X)^{-1}X'y \perp Xb \quad \text{for all} \quad b \in \mathbb{R}^K$$

This is true: If $b \in \mathbb{R}^K$, then

$$(Xb)'[y - X(X'X)^{-1}X'y] = b'[X'y - X'y] = 0$$

The proof is now complete.

16.6.1 Starting with X

It is common in applications to start with $n \times k$ matrix X with linearly independent columns and let

$$S := \operatorname{span} X := \operatorname{span}\{\underset{1}{\operatorname{col}} X, \ldots, \underset{k}{\operatorname{col}} X\}$$

Then the columns of X form a basis of S.

From the preceding theorem, $P = X(X'X)^{-1}X'y$ projects y onto S.

In this context, P is often called the **projection matrix**.

- The matrix $M = I - P$ satisfies $My = \hat{E}_{S^\perp} y$ and is sometimes called the **annihilator matrix**.

16.6.2 The Orthonormal Case

Suppose that U is $n \times k$ with orthonormal columns.

Let $u_i := \operatorname{col} U_i$ for each i, let $S := \operatorname{span} U$ and let $y \in \mathbb{R}^n$.

We know that the projection of y onto S is

$$Py = U(U'U)^{-1}U'y$$

Since U has orthonormal columns, we have $U'U = I$.

Hence

$$Py = UU'y = \sum_{i=1}^{k} \langle u_i, y \rangle u_i$$

We have recovered our earlier result about projecting onto the span of an orthonormal basis.

16.6.3 Application: Overdetermined Systems of Equations

Let $y \in \mathbb{R}^n$ and let X is $n \times k$ with linearly independent columns.

Given X and y, we seek $b \in \mathbb{R}^k$ satisfying the system of linear equations $Xb = y$.

If $n > k$ (more equations than unknowns), then b is said to be **overdetermined**.

Intuitively, we may not be able find a b that satisfies all n equations.

The best approach here is to

- Accept that an exact solution may not exist
- Look instead for an approximate solution

By approximate solution, we mean a $b \in \mathbb{R}^k$ such that Xb is as close to y as possible.

The next theorem shows that the solution is well defined and unique.

The proof uses the OPT.

Theorem The unique minimizer of $\|y - Xb\|$ over $b \in \mathbb{R}^K$ is

$$\hat{\beta} := (X'X)^{-1}X'y$$

Proof: Note that

$$X\hat{\beta} = X(X'X)^{-1}X'y = Py$$

Since Py is the orthogonal projection onto $\text{span}(X)$ we have

$$\|y - Py\| \leq \|y - z\| \text{ for any } z \in \text{span}(X)$$

Because $Xb \in \text{span}(X)$

$$\|y - X\hat{\beta}\| \leq \|y - Xb\| \text{ for any } b \in \mathbb{R}^K$$

This is what we aimed to show.

16.7 Least Squares Regression

Let's apply the theory of orthogonal projection to least squares regression.

This approach provides insights about many geometric properties of linear regression.

We treat only some examples.

16.7.1 Squared risk measures

Given pairs $(x, y) \in \mathbb{R}^K \times \mathbb{R}$, consider choosing $f \colon \mathbb{R}^K \to \mathbb{R}$ to minimize the **risk**

$$R(f) := \mathbb{E}\left[(y - f(x))^2\right]$$

If probabilities and hence $\mathbb{E}$ are unknown, we cannot solve this problem directly.

However, if a sample is available, we can estimate the risk with the **empirical risk**:

$$\min_{f \in \mathcal{F}} \frac{1}{N} \sum_{n=1}^{N} (y_n - f(x_n))^2$$

Minimizing this expression is called **empirical risk minimization**.

The set $\mathcal{F}$ is sometimes called the hypothesis space.

The theory of statistical learning tells us that to prevent overfitting we should take the set $\mathcal{F}$ to be relatively simple.

If we let $\mathcal{F}$ be the class of linear functions $1/N$, the problem is

$$\min_{b \in \mathbb{R}^K} \sum_{n=1}^{N} (y_n - b' x_n)^2$$

This is the sample **linear least squares problem**.

16.7.2 Solution

Define the matrices

$$y := \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix}, \quad x_n := \begin{pmatrix} x_{n1} \\ x_{n2} \\ \vdots \\ x_{nK} \end{pmatrix} = \text{n-th obs on all regressors}$$

and

$$X := \begin{pmatrix} x_1' \\ x_2' \\ \vdots \\ x_N' \end{pmatrix} :=: \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1K} \\ x_{21} & x_{22} & \cdots & x_{2K} \\ \vdots & \vdots & & \vdots \\ x_{N1} & x_{N2} & \cdots & x_{NK} \end{pmatrix}$$

We assume throughout that $N > K$ and X is full column rank.

If you work through the algebra, you will be able to verify that $\|y - Xb\|^2 = \sum_{n=1}^{N} (y_n - b' x_n)^2$.

Since monotone transforms don't affect minimizers, we have

$$\operatorname*{arg\,min}_{b \in \mathbb{R}^K} \sum_{n=1}^{N} (y_n - b' x_n)^2 = \operatorname*{arg\,min}_{b \in \mathbb{R}^K} \|y - Xb\|$$

By our results about overdetermined linear systems of equations, the solution is

$$\hat{\beta} := (X'X)^{-1}X'y$$

Let P and M be the projection and annihilator associated with X:

$$P := X(X'X)^{-1}X' \quad \text{and} \quad M := I - P$$

The **vector of fitted values** is

$$\hat{y} := X\hat{\beta} = Py$$

The **vector of residuals** is

$$\hat{u} := y - \hat{y} = y - Py = My$$

Here are some more standard definitions:

- The **total sum of squares** is $:= \|y\|^2$.
- The **sum of squared residuals** is $:= \|\hat{u}\|^2$.
- The **explained sum of squares** is $:= \|\hat{y}\|^2$.

TSS = ESS + SSR.

We can prove this easily using the OPT.

From the OPT we have $y = \hat{y} + \hat{u}$ and $\hat{u} \perp \hat{y}$.

Applying the Pythagorean law completes the proof.

16.8 Orthogonalization and Decomposition

Let's return to the connection between linear independence and orthogonality touched on above.

A result of much interest is a famous algorithm for constructing orthonormal sets from linearly independent sets.

The next section gives details.

16.8.1 Gram-Schmidt Orthogonalization

Theorem For each linearly independent set $\{x_1, \ldots, x_k\} \subset \mathbb{R}^n$, there exists an orthonormal set $\{u_1, \ldots, u_k\}$ with

$$\text{span}\{x_1, \ldots, x_i\} = \text{span}\{u_1, \ldots, u_i\} \quad \text{for} \quad i = 1, \ldots, k$$

The **Gram-Schmidt orthogonalization** procedure constructs an orthogonal set $\{u_1, u_2, \ldots, u_n\}$.

One description of this procedure is as follows:

- For $i = 1, \ldots, k$, form $S_i := \text{span}\{x_1, \ldots, x_i\}$ and $S_i^\perp$
- Set $v_1 = x_1$
- For $i \geq 2$ set $v_i := \hat{E}_{S_{i-1}^\perp} x_i$ and $u_i := v_i / \|v_i\|$

The sequence $u_1, \ldots, u_k$ has the stated properties.

A Gram-Schmidt orthogonalization construction is a key idea behind the Kalman filter described in A First Look at the Kalman filter.

In some exercises below you are asked to implement this algorithm and test it using projection.

16.8.2 QR Decomposition

The following result uses the preceding algorithm to produce a useful decomposition.

Theorem If X is $n \times k$ with linearly independent columns, then there exists a factorization $X = QR$ where

- R is $k \times k$, upper triangular, and nonsingular
- Q is $n \times k$ with orthonormal columns

Proof sketch: Let

- $x_j := \text{col}_j(X)$
- $\{u_1, \ldots, u_k\}$ be orthonormal with same span as $\{x_1, \ldots, x_k\}$ (to be constructed using Gram–Schmidt)
- Q be formed from cols u_i

Since $x_j \in \text{span}\{u_1, \ldots, u_j\}$, we have

$$x_j = \sum_{i=1}^{j} \langle u_i, x_j \rangle u_i \quad \text{for } j = 1, \ldots, k$$

Some rearranging gives $X = QR$.

16.8.3 Linear Regression via QR Decomposition

For matrices X and y that overdetermine *beta* in the linear equation system $y = X\beta$, we found the least squares approximator $\hat{\beta} = (X'X)^{-1}X'y$.

Using the QR decomposition $X = QR$ gives

$$\begin{aligned} \hat{\beta} &= (R'Q'QR)^{-1}R'Q'y \\ &= (R'R)^{-1}R'Q'y \\ &= R^{-1}(R')^{-1}R'Q'y = R^{-1}Q'y \end{aligned}$$

Numerical routines would in this case use the alternative form $R\hat{\beta} = Q'y$ and back substitution.

16.9 Exercises

16.9.1 Exercise 1

Show that, for any linear subspace $S \subset \mathbb{R}^n$, $S \cap S^\perp = \{0\}$.

16.9.2 Exercise 2

Let $P = X(X'X)^{-1}X'$ and let $M = I - P$. Show that P and M are both idempotent and symmetric. Can you give any intuition as to why they should be idempotent?

16.9.3 Exercise 3

Using Gram-Schmidt orthogonalization, produce a linear projection of y onto the column space of X and verify this using the projection matrix $P := X(X'X)^{-1}X'$ and also using QR decomposition, where:

$$y := \begin{pmatrix} 1 \\ 3 \\ -3 \end{pmatrix},$$

and

$$X := \begin{pmatrix} 1 & 0 \\ 0 & -6 \\ 2 & 2 \end{pmatrix}$$

16.10 Solutions

16.10.1 Exercise 1

If $x \in S$ and $x \in S^\perp$, then we have in particular that $\langle x, x \rangle = 0$. But then $x = 0$.

16.10.2 Exercise 2

Symmetry and idempotence of M and P can be established using standard rules for matrix algebra. The intuition behind idempotence of M and P is that both are orthogonal projections. After a point is projected into a given subspace, applying the projection again makes no difference. (A point inside the subspace is not shifted by orthogonal projection onto that space because it is already the closest point in the subspace to itself).

16.10.3 Exercise 3

Here's a function that computes the orthonormal vectors using the GS algorithm given in the lecture.

16.10.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

```
In [3]: function gram_schmidt(X)

            U = similar(X, Float64) # for robustness

            function normalized_orthogonal_projection(b, Z)
                # project onto the orthogonal complement of the col span of Z
                orthogonal = I - Z * inv(Z'Z) * Z'
                projection = orthogonal * b
                # normalize
                return projection / norm(projection)
            end

            for col in 1:size(U, 2)
                # set up
                b = X[:,col]       # vector we're going to project
                Z = X[:,1:col - 1] # first i-1 columns of X
                U[:,col] = normalized_orthogonal_projection(b, Z)
            end

            return U
        end
```

```
Out[3]: gram_schmidt (generic function with 1 method)
```

Here are the arrays we'll work with

```
In [4]: y = [1, 3, -3]
        X = [1 0; 0 -6; 2 2];
```

First let's do ordinary projection of y onto the basis spanned by the columns of X.

```
In [5]: Py1 = X * inv(X'X) * X' * y
```

```
Out[5]: 3-element Array{Float64,1}:
         -0.5652173913043479
          3.260869565217391
         -2.217391304347826
```

Now let's orthogonalize first, using Gram–Schmidt:

```
In [6]: U = gram_schmidt(X)
```

```
Out[6]: 3×2 Array{Float64,2}:
         0.447214  -0.131876
         0.0       -0.989071
         0.894427   0.065938
```

Now we can project using the orthonormal basis and see if we get the same thing:

```
In [7]: Py2 = U * U' * y
```

```
Out[7]: 3-element Array{Float64,1}:
         -0.5652173913043477
          3.260869565217391
         -2.2173913043478257
```

The result is the same. To complete the exercise, we get an orthonormal basis by QR decomposition and project once more.

```
In [8]: Q, R = qr(X)
        Q = Matrix(Q)
```

```
Out[8]: 3×2 Array{Float64,2}:
         -0.447214  -0.131876
          0.0       -0.989071
         -0.894427   0.065938
```

```
In [9]: Py3 = Q * Q' * y
```

```
Out[9]: 3-element Array{Float64,1}:
         -0.5652173913043474
          3.2608695652173907
         -2.2173913043478253
```

Again, the result is the same.

Chapter 17

LLN and CLT

17.1 Contents

17.2 Overview

This lecture illustrates two of the most important theorems of probability and statistics: The law of large numbers (LLN) and the central limit theorem (CLT).

These beautiful theorems lie behind many of the most fundamental results in econometrics and quantitative economic modeling.

The lecture is based around simulations that show the LLN and CLT in action.

We also demonstrate how the LLN and CLT break down when the assumptions they are based on do not hold.

In addition, we examine several useful extensions of the classical theorems, such as

- The delta method, for smooth functions of random variables
- The multivariate case

Some of these extensions are presented as exercises.

17.3 Relationships

The CLT refines the LLN.

The LLN gives conditions under which sample moments converge to population moments as sample size increases.

The CLT provides information about the rate at which sample moments converge to population moments as sample size increases.

17.4 LLN

We begin with the law of large numbers, which tells us when sample averages will converge to their population means.

17.4.1 The Classical LLN

The classical law of large numbers concerns independent and identically distributed (IID) random variables.

Here is the strongest version of the classical LLN, known as *Kolmogorov's strong law*.

Let $X_1, \ldots, X_n$ be independent and identically distributed scalar random variables, with common distribution F.

When it exists, let μ denote the common mean of this sample:

$$\mu := \mathbb{E}X = \int x F(dx)$$

In addition, let

$$\bar{X}_n := \frac{1}{n} \sum_{i=1}^{n} X_i$$

Kolmogorov's strong law states that, if $\mathbb{E}|X|$ is finite, then

$$\mathbb{P}\left\{\bar{X}_n \to \mu \text{ as } n \to \infty\right\} = 1 \tag{1}$$

What does this last expression mean?

Let's think about it from a simulation perspective, imagining for a moment that our computer can generate perfect random samples (which of course it can't).

Let's also imagine that we can generate infinite sequences, so that the statement $\bar{X}_n \to \mu$ can be evaluated.

In this setting, (1) should be interpreted as meaning that the probability of the computer producing a sequence where $\bar{X}_n \to \mu$ fails to occur is zero.

17.4.2 Proof

The proof of Kolmogorov's strong law is nontrivial – see, for example, theorem 8.3.5 of [26].

On the other hand, we can prove a weaker version of the LLN very easily and still get most of the intuition.

The version we prove is as follows: If $X_1, \ldots, X_n$ is IID with $\mathbb{E}X_i^2 < \infty$, then, for any $\epsilon > 0$, we have

$$\mathbb{P}\left\{|\bar{X}_n - \mu| \geq \epsilon\right\} \to 0 \quad \text{as} \quad n \to \infty \tag{2}$$

(This version is weaker because we claim only convergence in probability rather than almost sure convergence, and assume a finite second moment)

To see that this is so, fix $\epsilon > 0$, and let σ^2 be the variance of each X_i.

Recall the Chebyshev inequality, which tells us that

$$\mathbb{P}\left\{|\bar{X}_n - \mu| \geq \epsilon\right\} \leq \frac{\mathbb{E}[(\bar{X}_n - \mu)^2]}{\epsilon^2} \tag{3}$$

Now observe that

$$\begin{aligned}
\mathbb{E}[(\bar{X}_n - \mu)^2] &= \mathbb{E}\left\{\left[\frac{1}{n}\sum_{i=1}^{n}(X_i - \mu)\right]^2\right\} \\
&= \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\mathbb{E}(X_i - \mu)(X_j - \mu) \\
&= \frac{1}{n^2}\sum_{i=1}^{n}\mathbb{E}(X_i - \mu)^2 \\
&= \frac{\sigma^2}{n}
\end{aligned}$$

Here the crucial step is at the third equality, which follows from independence.

Independence means that if $i \neq j$, then the covariance term $\mathbb{E}(X_i - \mu)(X_j - \mu)$ drops out.

As a result, $n^2 - n$ terms vanish, leading us to a final expression that goes to zero in n.

Combining our last result with (3), we come to the estimate

$$\mathbb{P}\left\{|\bar{X}_n - \mu| \geq \epsilon\right\} \leq \frac{\sigma^2}{n\epsilon^2} \tag{4}$$

The claim in (2) is now clear.

Of course, if the sequence $X_1, \ldots, X_n$ is correlated, then the cross-product terms $\mathbb{E}(X_i - \mu)(X_j - \mu)$ are not necessarily zero.

While this doesn't mean that the same line of argument is impossible, it does mean that if we want a similar result then the covariances should be "almost zero" for "most" of these terms.

In a long sequence, this would be true if, for example, $\mathbb{E}(X_i - \mu)(X_j - \mu)$ approached zero when the difference between i and j became large.

In other words, the LLN can still work if the sequence $X_1, \ldots, X_n$ has a kind of "asymptotic independence", in the sense that correlation falls to zero as variables become further apart in the sequence.

This idea is very important in time series analysis, and we'll come across it again soon enough.

17.4.3 Illustration

Let's now illustrate the classical IID law of large numbers using simulation.

In particular, we aim to generate some sequences of IID random variables and plot the evolution of $\bar{X}_n$ as n increases.

Below is a figure that does just this (as usual, you can click on it to expand it).

It shows IID observations from three different distributions and plots $\bar{X}_n$ against n in each case.

The dots represent the underlying observations X_i for $i = 1, \ldots, 100$.

In each of the three cases, convergence of $\bar{X}_n$ to μ occurs as predicted.

17.4.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Plots, Distributions, Random, Statistics
        gr(fmt = :png, size = (900, 500))
```

```
Out[2]: Plots.GRBackend()
```

```
In [3]: function ksl(distribution, n = 100)
            title = nameof(typeof(distribution))
            observations = rand(distribution, n)
            sample_means = cumsum(observations) ./ (1:n)
            μ = mean(distribution)
            plot(repeat((1:n)', 2),
                [zeros(1, n); observations'], label = "", color = :grey, alpha = 0.
        5)
            plot!(1:n, observations, color = :grey, markershape = :circle,
                  alpha = 0.5, label = "", linewidth = 0)
            if !isnan(μ)
                hline!([μ], color = :black, linewidth = 1.5, linestyle = :dash,
        grid = false,
                       label = ["Mean"])
            end
            plot!(1:n, sample_means, linewidth = 3, alpha = 0.6, color = :green,
                  label = "Sample mean")
            return plot!(title = title)
        end
```

```
Out[3]: ksl (generic function with 2 methods)
```

```
In [4]: distributions = [TDist(10), Beta(2, 2), Gamma(5, 2), Poisson(4),
        LogNormal(0.5),
                        Exponential(1)]
```

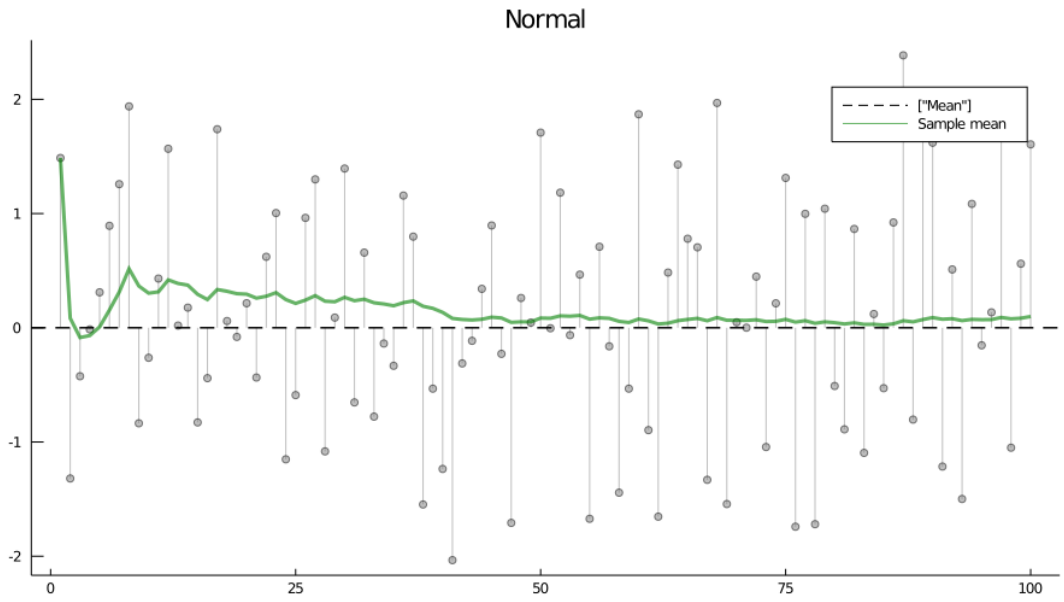
```
Out[4]: 6-element Array{Distribution{Univariate,S} where S<:ValueSupport,1}:
         TDist{Float64}(ν=10.0)
         Beta{Float64}(α=2.0, β=2.0)
         Gamma{Float64}(α=5.0, θ=2.0)
```

```
Poisson{Float64}(λ=4.0)
LogNormal{Float64}(μ=0.5, σ=1.0)
Exponential{Float64}(θ=1.0)
```

Here is in an example for the standard normal distribution

In [5]:
```
ksl(Normal())
```

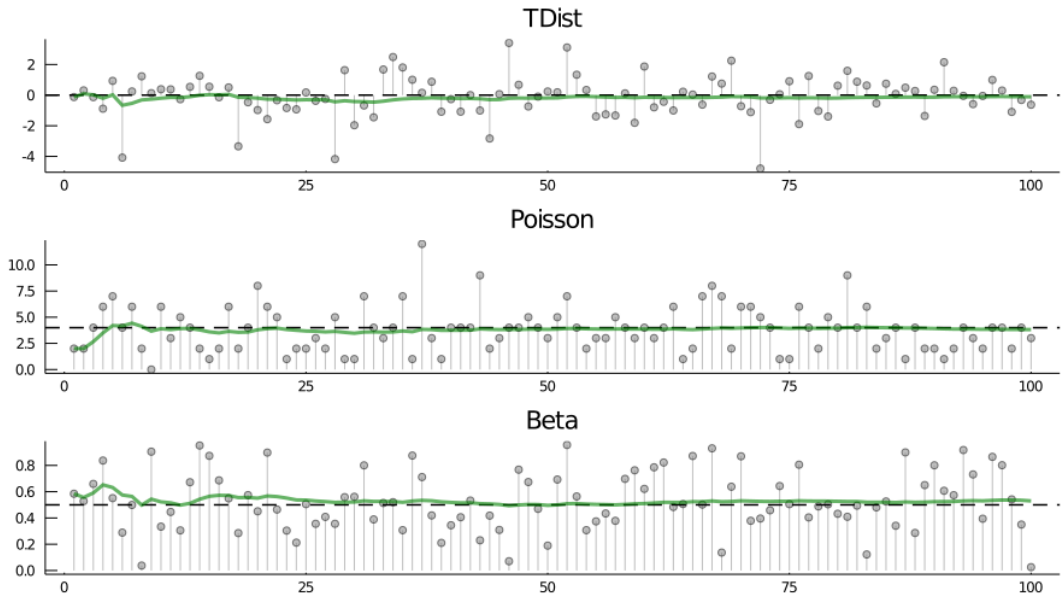
Out[5]:



In [6]:
```
Random.seed!(0); # reproducible results
```

In [7]:
```
plot(ksl.(sample(distributions, 3, replace = false))..., layout = (3, 1),
↪legend =
        false)
```

Out[7]:



The three distributions are chosen at random from distributions.

17.4.5 Infinite Mean

What happens if the condition $\mathbb{E}|X| < \infty$ in the statement of the LLN is not satisfied?

This might be the case if the underlying distribution is heavy tailed — the best known example is the Cauchy distribution, which has density

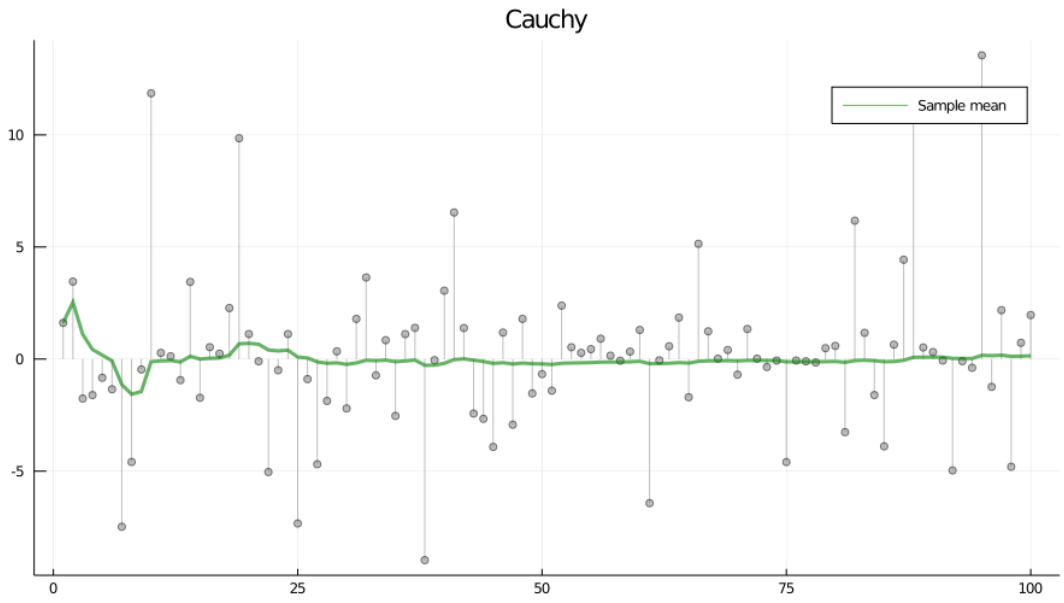
$$f(x) = \frac{1}{\pi(1 + x^2)} \qquad (x \in \mathbb{R})$$

The next figure shows 100 independent draws from this distribution

```
In [8]: Random.seed!(0); # reproducible results
```

```
In [9]: ksl(Cauchy())
```

```
Out[9]:
```



Notice how extreme observations are far more prevalent here than the previous figure.

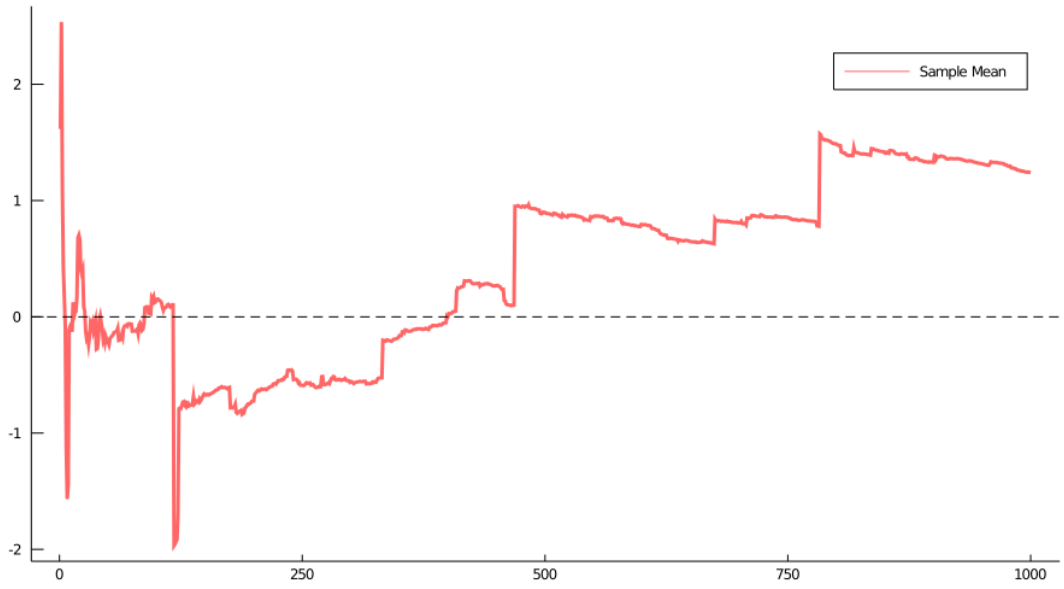
Let's now have a look at the behavior of the sample mean

```
In [10]: Random.seed!(0); # reproducible results
```

```
In [11]: function plot_means(n = 1000)
             sample_mean = cumsum(rand(Cauchy(), n)) ./ (1:n)
             plot(1:n, sample_mean, color = :red, alpha = 0.6, label = "Sample
 ↪Mean", linewidth =
         3)
             return hline!([0], color = :black, linestyle = :dash, label = "",
 ↪grid = false)
```

```
end

plot_means()
```

Out[11]:



Here we've increased n to 1000, but the sequence still shows no sign of converging.

Will convergence become visible if we take n even larger?

The answer is no.

To see this, recall that the characteristic function of the Cauchy distribution is

$$\phi(t) = \mathbb{E}e^{itX} = \int e^{itx} f(x)dx = e^{-|t|} \tag{5}$$

Using independence, the characteristic function of the sample mean becomes

$$\begin{aligned}
\mathbb{E}e^{it\bar{X}_n} &= \mathbb{E}\exp\left\{i\frac{t}{n}\sum_{j=1}^{n} X_j\right\} \\
&= \mathbb{E}\prod_{j=1}^{n}\exp\left\{i\frac{t}{n}X_j\right\} \\
&= \prod_{j=1}^{n}\mathbb{E}\exp\left\{i\frac{t}{n}X_j\right\} = [\phi(t/n)]^n
\end{aligned}$$

In view of (5), this is just $e^{-|t|}$.

Thus, in the case of the Cauchy distribution, the sample mean itself has the very same Cauchy distribution, regardless of n.

In particular, the sequence $\bar{X}_n$ does not converge to a point.

17.5 CLT

Next we turn to the central limit theorem, which tells us about the distribution of the deviation between sample averages and population means.

17.5.1 Statement of the Theorem

The central limit theorem is one of the most remarkable results in all of mathematics.

In the classical IID setting, it tells us the following:

If the sequence $X_1, \ldots, X_n$ is IID, with common mean μ and common variance $\sigma^2 \in (0, \infty)$, then

$$\sqrt{n}(\bar{X}_n - \mu) \xrightarrow{d} N(0, \sigma^2) \quad \text{as} \quad n \to \infty \tag{6}$$

Here $\xrightarrow{d} N(0, \sigma^2)$ indicates convergence in distribution to a centered (i.e, zero mean) normal with standard deviation σ.

17.5.2 Intuition

The striking implication of the CLT is that for **any** distribution with finite second moment, the simple operation of adding independent copies **always** leads to a Gaussian curve.

A relatively simple proof of the central limit theorem can be obtained by working with characteristic functions (see, e.g., theorem 9.5.6 of [26]).

The proof is elegant but almost anticlimactic, and it provides surprisingly little intuition.

In fact all of the proofs of the CLT that we know are similar in this respect.

Why does adding independent copies produce a bell-shaped distribution?

Part of the answer can be obtained by investigating addition of independent Bernoulli random variables.

In particular, let X_i be binary, with $\mathbb{P}\{X_i = 0\} = \mathbb{P}\{X_i = 1\} = 0.5$, and let $X_1, \ldots, X_n$ be independent.

Think of $X_i = 1$ as a "success", so that $Y_n = \sum_{i=1}^n X_i$ is the number of successes in n trials.

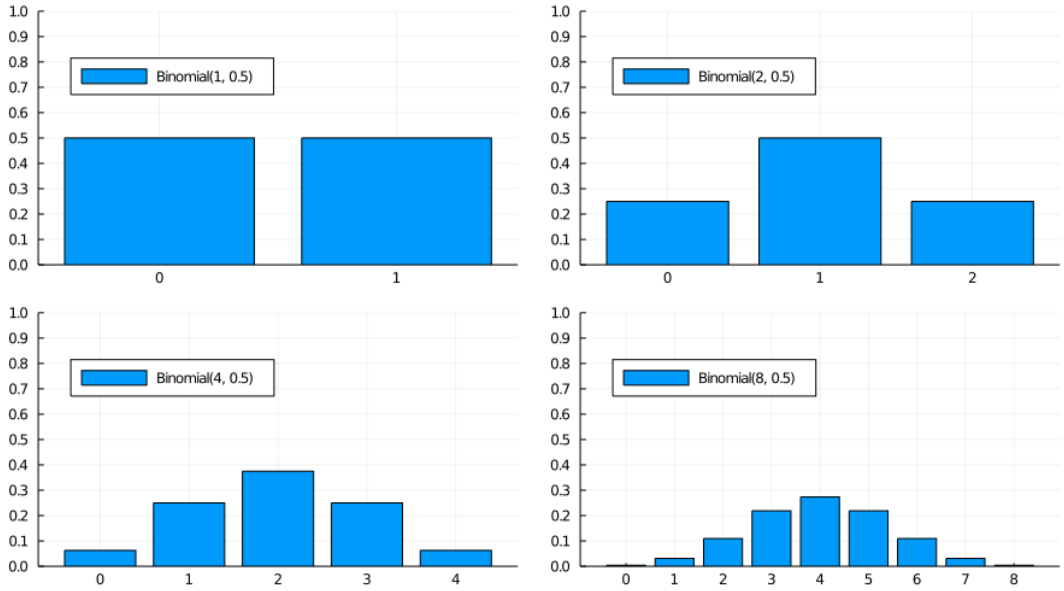
The next figure plots the probability mass function of Y_n for $n = 1, 2, 4, 8$

```
In [12]: binomial_pdf(n) =
             bar(0:n, pdf.(Binomial(n), 0:n),
                 xticks = 0:10, ylim = (0, 1), yticks = 0:0.1:1,
                 label = "Binomial($n, 0.5)", legend = :topleft)
```

```
Out[12]: binomial_pdf (generic function with 1 method)
```

```
In [13]: plot(binomial_pdf.((1,2,4,8))...)
```

```
Out[13]:
```



When $n = 1$, the distribution is flat — one success or no successes have the same probability.

When $n = 2$ we can either have 0, 1 or 2 successes.

Notice the peak in probability mass at the mid-point $k = 1$.

The reason is that there are more ways to get 1 success ("fail then succeed" or "succeed then fail") than to get zero or two successes.

Moreover, the two trials are independent, so the outcomes "fail then succeed" and "succeed then fail" are just as likely as the outcomes "fail then fail" and "succeed then succeed".

(If there was positive correlation, say, then "succeed then fail" would be less likely than "succeed then succeed")

Here, already we have the essence of the CLT: addition under independence leads probability mass to pile up in the middle and thin out at the tails.

For $n = 4$ and $n = 8$ we again get a peak at the "middle" value (halfway between the minimum and the maximum possible value).

The intuition is the same — there are simply more ways to get these middle outcomes.

If we continue, the bell-shaped curve becomes ever more pronounced.

We are witnessing the binomial approximation of the normal distribution.

17.5.3 Simulation 1

Since the CLT seems almost magical, running simulations that verify its implications is one good way to build intuition.

To this end, we now perform the following simulation

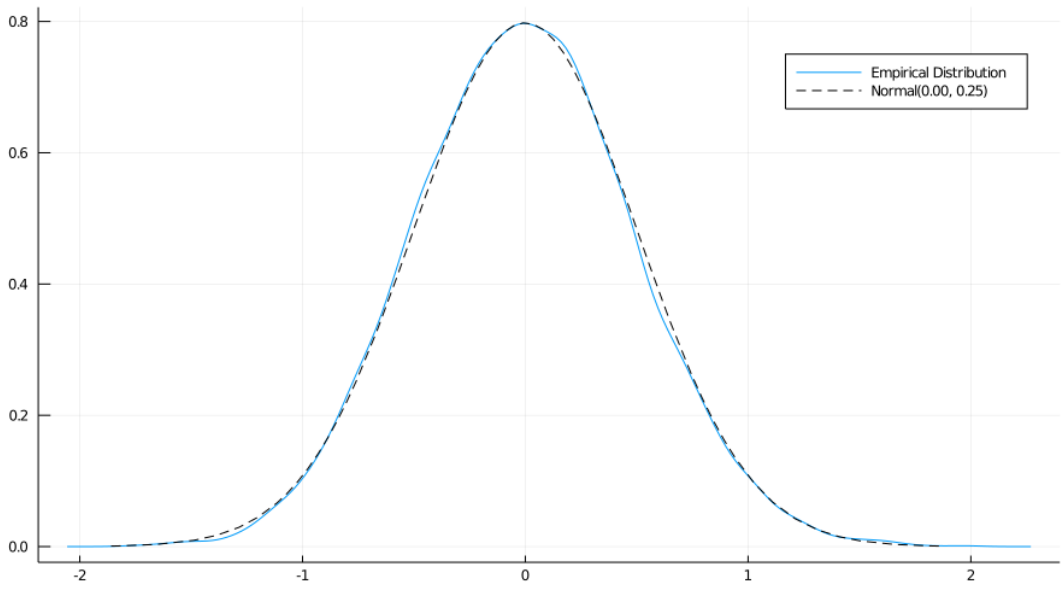
1. Choose an arbitrary distribution F for the underlying observations X_i.
2. Generate independent draws of $Y_n := \sqrt{n}(\bar{X}_n - \mu)$.
3. Use these draws to compute some measure of their distribution — such as a histogram.

4. Compare the latter to $N(0, \sigma^2)$.

Here's some code that does exactly this for the exponential distribution $F(x) = 1 - e^{-\lambda x}$.

(Please experiment with other choices of F, but remember that, to conform with the conditions of the CLT, the distribution must have finite second moment)

```
In [14]: using StatsPlots

         function simulation1(distribution, n = 250, k = 10_000)
             σ = std(distribution)
             y = rand(distribution, n, k)
             y .-= mean(distribution)
             y = mean(y, dims = 1)
             y = √n * vec(y)
             density(y, label = "Empirical Distribution")
             return plot!(Normal(0, σ), linestyle = :dash, color = :black,
                          label = "Normal(0.00, $(σ^2))")
         end

Out[14]: simulation1 (generic function with 3 methods)

In [15]: simulation1(Exponential(0.5))

Out[15]:
```



The fit to the normal density is already tight, and can be further improved by increasing `n`.

You can also experiment with other specifications of F.

17.5.4 Simulation 2

Our next simulation is somewhat like the first, except that we aim to track the distribution of $Y_n := \sqrt{n}(\bar{X}_n - \mu)$ as n increases.

In the simulation we'll be working with random variables having $\mu = 0$.

Thus, when $n = 1$, we have $Y_1 = X_1$, so the first distribution is just the distribution of the underlying random variable.

For $n = 2$, the distribution of Y_2 is that of $(X_1 + X_2)/\sqrt{2}$, and so on.

What we expect is that, regardless of the distribution of the underlying random variable, the distribution of Y_n will smooth out into a bell shaped curve.

The next figure shows this process for $X_i \sim f$, where f was specified as the convex combination of three different beta densities.

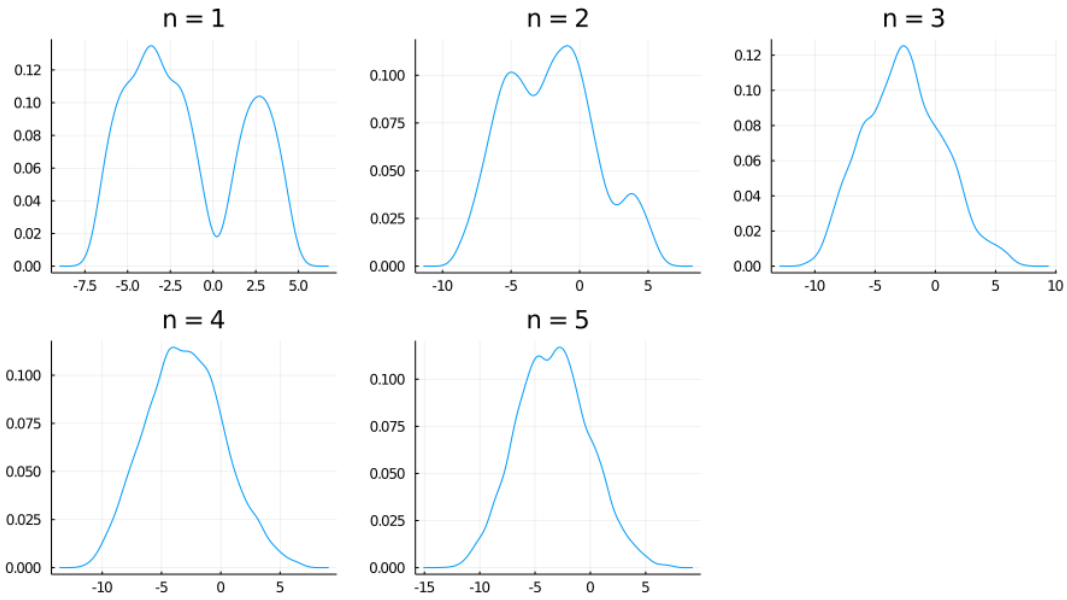
(Taking a convex combination is an easy way to produce an irregular shape for f)

In [16]:
```
function simulation2(distribution = Beta(2, 2), n = 5, k = 10_000)
    y = rand(distribution, k, n)
    for col in 1:n
        y[:,col] += rand([-0.5, 0.6, -1.1], k)
    end
    y = (y .- mean(distribution)) ./ std(distribution)
    y = cumsum(y, dims = 2) ./ sqrt.(1:5)' # return grid of data
end
```

Out[16]:
```
simulation2 (generic function with 4 methods)
```

In [17]:
```
ys = simulation2()
plots = [] # would preallocate in optimized code
for i in 1:size(ys, 2)
    p = density(ys[:, i], linealpha = i, title = "n = $i")
    push!(plots, p)
end

plot(plots..., legend = false)
```

Out[17]:



As expected, the distribution smooths out into a bell curve as n increases.

We leave you to investigate its contents if you wish to know more.

If you run the file from the ordinary Julia or IJulia shell, the figure should pop up in a window that you can rotate with your mouse, giving different views on the density sequence.

17.5.5 The Multivariate Case

The law of large numbers and central limit theorem work just as nicely in multidimensional settings.

To state the results, let's recall some elementary facts about random vectors.

A random vector $\mathbf{X}$ is just a sequence of k random variables $(X_1, \ldots, X_k)$.

Each realization of $\mathbf{X}$ is an element of $\mathbb{R}^k$.

A collection of random vectors $\mathbf{X}_1, \ldots, \mathbf{X}_n$ is called independent if, given any n vectors $\mathbf{x}_1, \ldots, \mathbf{x}_n$ in $\mathbb{R}^k$, we have

$$\mathbb{P}\{\mathbf{X}_1 \leq \mathbf{x}_1, \ldots, \mathbf{X}_n \leq \mathbf{x}_n\} = \mathbb{P}\{\mathbf{X}_1 \leq \mathbf{x}_1\} \times \cdots \times \mathbb{P}\{\mathbf{X}_n \leq \mathbf{x}_n\}$$

(The vector inequality $\mathbf{X} \leq \mathbf{x}$ means that $X_j \leq x_j$ for $j = 1, \ldots, k$)

Let $\mu_j := \mathbb{E}[X_j]$ for all $j = 1, \ldots, k$.

The expectation $\mathbb{E}[\mathbf{X}]$ of $\mathbf{X}$ is defined to be the vector of expectations:

$$\mathbb{E}[\mathbf{X}] := \begin{pmatrix} \mathbb{E}[X_1] \\ \mathbb{E}[X_2] \\ \vdots \\ \mathbb{E}[X_k] \end{pmatrix} = \begin{pmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_k \end{pmatrix} =: \mu$$

The *variance-covariance matrix* of random vector $\mathbf{X}$ is defined as

$$\mathrm{Var}[\mathbf{X}] := \mathbb{E}[(\mathbf{X} - \mu)(\mathbf{X} - \mu)']$$

Expanding this out, we get

$$\mathrm{Var}[\mathbf{X}] = \begin{pmatrix} \mathbb{E}[(X_1 - \mu_1)(X_1 - \mu_1)] & \cdots & \mathbb{E}[(X_1 - \mu_1)(X_k - \mu_k)] \\ \mathbb{E}[(X_2 - \mu_2)(X_1 - \mu_1)] & \cdots & \mathbb{E}[(X_2 - \mu_2)(X_k - \mu_k)] \\ \vdots & \vdots & \vdots \\ \mathbb{E}[(X_k - \mu_k)(X_1 - \mu_1)] & \cdots & \mathbb{E}[(X_k - \mu_k)(X_k - \mu_k)] \end{pmatrix}$$

The j, k-th term is the scalar covariance between X_j and X_k.

With this notation we can proceed to the multivariate LLN and CLT.

Let $\mathbf{X}_1, \ldots, \mathbf{X}_n$ be a sequence of independent and identically distributed random vectors, each one taking values in $\mathbb{R}^k$.

Let μ be the vector $\mathbb{E}[\mathbf{X}_i]$, and let Σ be the variance-covariance matrix of $\mathbf{X}_i$.

Interpreting vector addition and scalar multiplication in the usual way (i.e., pointwise), let

$$\bar{\mathbf{X}}_n := \frac{1}{n} \sum_{i=1}^{n} \mathbf{X}_i$$

In this setting, the LLN tells us that

$$\mathbb{P}\left\{\bar{\mathbf{X}}_n \to \mu \text{ as } n \to \infty\right\} = 1 \tag{7}$$

Here $\bar{\mathbf{X}}_n \to \mu$ means that $\|\bar{\mathbf{X}}_n - \mu\| \to 0$, where $\|\cdot\|$ is the standard Euclidean norm.

The CLT tells us that, provided Σ is finite,

$$\sqrt{n}(\bar{\mathbf{X}}_n - \mu) \xrightarrow{d} N(\mathbf{0}, \Sigma) \quad \text{as} \quad n \to \infty \tag{8}$$

17.6 Exercises

17.6.1 Exercise 1

One very useful consequence of the central limit theorem is as follows.

Assume the conditions of the CLT as stated above.

If $g\colon \mathbb{R} \to \mathbb{R}$ is differentiable at μ and $g'(\mu) \neq 0$, then

$$\sqrt{n}\{g(\bar{X}_n) - g(\mu)\} \xrightarrow{d} N(0, g'(\mu)^2 \sigma^2) \quad \text{as} \quad n \to \infty \tag{9}$$

This theorem is used frequently in statistics to obtain the asymptotic distribution of estimators — many of which can be expressed as functions of sample means.

(These kinds of results are often said to use the "delta method")

The proof is based on a Taylor expansion of g around the point μ.

Taking the result as given, let the distribution F of each X_i be uniform on $[0, \pi/2]$ and let $g(x) = \sin(x)$.

Derive the asymptotic distribution of $\sqrt{n}\{g(\bar{X}_n) - g(\mu)\}$ and illustrate convergence in the same spirit as the program `illustrate_clt.jl` discussed above.

What happens when you replace $[0, \pi/2]$ with $[0, \pi]$?

What is the source of the problem?

17.6.2 Exercise 2

Here's a result that's often used in developing statistical tests, and is connected to the multivariate central limit theorem.

If you study econometric theory, you will see this result used again and again.

Assume the setting of the multivariate CLT discussed above, so that

1. $\mathbf{X}_1, \ldots, \mathbf{X}_n$ is a sequence of IID random vectors, each taking values in $\mathbb{R}^k$

2. $\mu := \mathbb{E}[\mathbf{X}_i]$, and Σ is the variance-covariance matrix of $\mathbf{X}_i$
3. The convergence

$$\sqrt{n}(\bar{\mathbf{X}}_n - \mu) \xrightarrow{d} N(\mathbf{0}, \Sigma) \tag{10}$$

is valid.

In a statistical setting, one often wants the right hand side to be **standard** normal, so that confidence intervals are easily computed.

This normalization can be achieved on the basis of three observations.

First, if $\mathbf{X}$ is a random vector in $\mathbb{R}^k$ and $\mathbf{A}$ is constant and $k \times k$, then

$$\operatorname{Var}[\mathbf{AX}] = \mathbf{A} \operatorname{Var}[\mathbf{X}] \mathbf{A}'$$

Second, by the continuous mapping theorem, if $\mathbf{Z}_n \xrightarrow{d} \mathbf{Z}$ in $\mathbb{R}^k$ and $\mathbf{A}$ is constant and $k \times k$, then

$$\mathbf{AZ}_n \xrightarrow{d} \mathbf{AZ}$$

Third, if $\mathbf{S}$ is a $k \times k$ symmetric positive definite matrix, then there exists a symmetric positive definite matrix $\mathbf{Q}$, called the inverse square root of $\mathbf{S}$, such that

$$\mathbf{QSQ}' = \mathbf{I}$$

Here $\mathbf{I}$ is the $k \times k$ identity matrix.

Putting these things together, your first exercise is to show that if $\mathbf{Q}$ is the inverse square root of , then

$$\mathbf{Z}_n := \sqrt{n}\mathbf{Q}(\bar{\mathbf{X}}_n - \mu) \xrightarrow{d} \mathbf{Z} \sim N(\mathbf{0}, \mathbf{I})$$

Applying the continuous mapping theorem one more time tells us that

$$\|\mathbf{Z}_n\|^2 \xrightarrow{d} \|\mathbf{Z}\|^2$$

Given the distribution of $\mathbf{Z}$, we conclude that

$$n\|\mathbf{Q}(\bar{\mathbf{X}}_n - \mu)\|^2 \xrightarrow{d} \chi^2(k) \tag{11}$$

where $\chi^2(k)$ is the chi-squared distribution with k degrees of freedom.

(Recall that k is the dimension of $\mathbf{X}_i$, the underlying random vectors)

Your second exercise is to illustrate the convergence in (11) with a simulation.

In doing so, let

$$\mathbf{X}_i := \begin{pmatrix} W_i \\ U_i + W_i \end{pmatrix}$$

where

- each W_i is an IID draw from the uniform distribution on $[-1, 1]$
- each U_i is an IID draw from the uniform distribution on $[-2, 2]$
- U_i and W_i are independent of each other

Hints:

1. `sqrt(A::AbstractMatrix{<:Number})` computes the square root of `A`. You still need to invert it.

2. You should be able to work out Σ from the proceeding information.

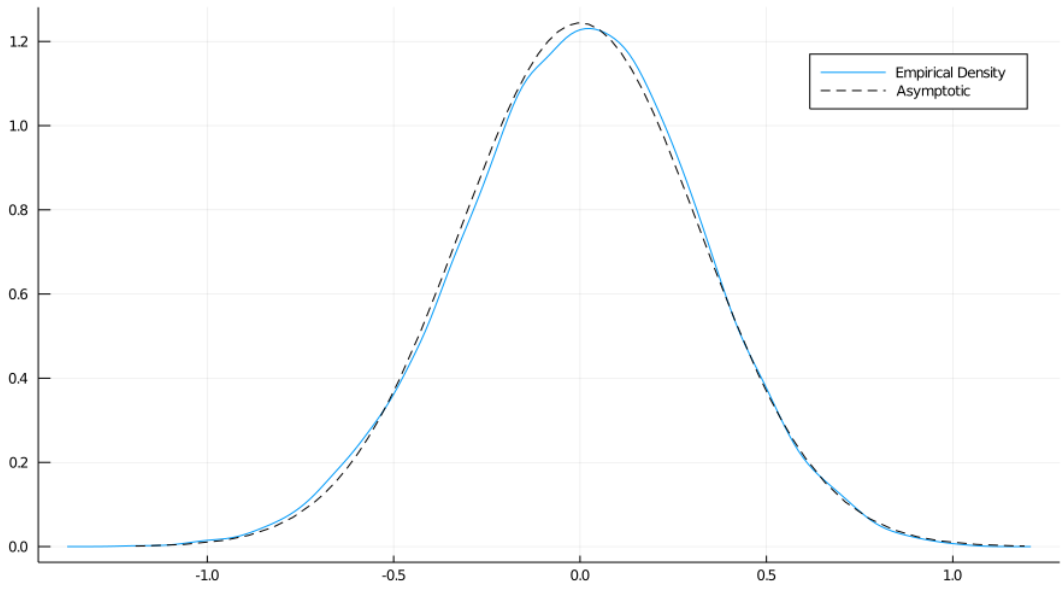
17.7 Solutions

17.7.1 Exercise 1

Here is one solution

```
In [18]: function exercise1(distribution = Uniform(0, π/2); n = 250, k = 10_000, g
  ↪= sin, g' =
          cos)
              μ, σ = mean(distribution), std(distribution)
              y = rand(distribution, n, k)
              y = mean(y, dims = 1)
              y = vec(y)
              error_obs = sqrt(n) .* (g.(y) .- g.(μ))
              density(error_obs, label = "Empirical Density")
              return plot!(Normal(0, g'(μ) .* σ), linestyle = :dash, label =
  ↪"Asymptotic",
                           color = :black)
          end
          exercise1()
```

```
Out[18]:
```



What happens when you replace $[0, \pi/2]$ with $[0, \pi]$?

In this case, the mean μ of this distribution is $\pi/2$, and since $g' = \cos$, we have $g'(\mu) = 0$.

Hence the conditions of the delta theorem are not satisfied.

17.7.2 Exercise 2

First we want to verify the claim that

$$\sqrt{n}\mathbf{Q}(\bar{\mathbf{X}}_n - \mu) \xrightarrow{d} N(\mathbf{0}, \mathbf{I})$$

This is straightforward given the facts presented in the exercise.

Let

$$\mathbf{Y}_n := \sqrt{n}(\bar{\mathbf{X}}_n - \mu) \quad \text{and} \quad \mathbf{Y} \sim N(\mathbf{0}, \Sigma)$$

By the multivariate CLT and the continuous mapping theorem, we have

$$\mathbf{Q}\mathbf{Y}_n \xrightarrow{d} \mathbf{Q}\mathbf{Y}$$

Since linear combinations of normal random variables are normal, the vector $\mathbf{Q}\mathbf{Y}$ is also normal.

Its mean is clearly $\mathbf{0}$, and its variance covariance matrix is

$$\text{Var}[\mathbf{Q}\mathbf{Y}] = \mathbf{Q}\text{Var}[\mathbf{Y}]\mathbf{Q}' = \mathbf{Q}\Sigma\mathbf{Q}' = \mathbf{I}$$

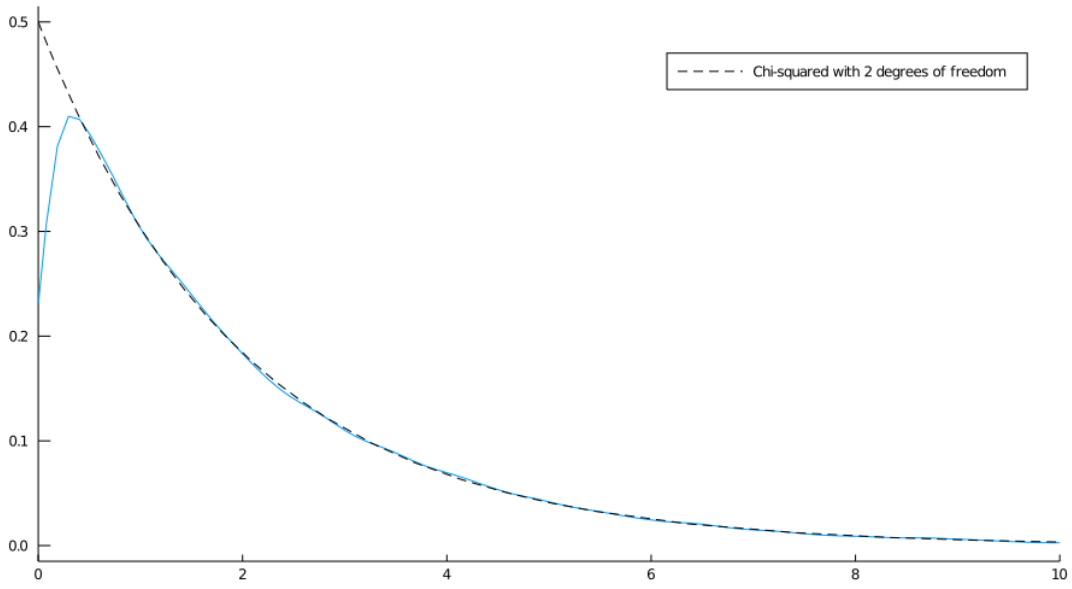
In conclusion, $\mathbf{Q}\mathbf{Y}_n \xrightarrow{d} \mathbf{Q}\mathbf{Y} \sim N(\mathbf{0}, \mathbf{I})$, which is what we aimed to show.

Now we turn to the simulation exercise.

Our solution is as follows

```
In [19]: function exercise2(;n = 250, k = 50_000, dw = Uniform(-1, 1), du =
  ↪Uniform(-2, 2))
             vw = var(dw)
             vu = var(du)
             Σ = [vw    vw
                  vw vw + vu]
             Q = inv(sqrt(Σ))
             function generate_data(dw, du, n)
                 dw = rand(dw, n)
                 X = [dw dw + rand(du, n)]
                 return sqrt(n) * mean(X, dims = 1)
             end
             X = mapreduce(x -> generate_data(dw, du, n), vcat, 1:k)
             X = Q * X'
             X = sum(abs2, X, dims = 1)
             X = vec(X)
             density(X, label = "", xlim = (0, 10))
             return plot!(Chisq(2), color = :black, linestyle = :dash,
                          label = "Chi-squared with 2 degrees of freedom", grid =
  ↪false)
         end
         exercise2()
```

Out[19]:



Chapter 18

Linear State Space Models

18.1 Contents

> "We may regard the present state of the universe as the effect of its past and the cause of its future" – Marquis de Laplace

18.2 Overview

This lecture introduces the **linear state space** dynamic system.

This model is a workhorse that carries a powerful theory of prediction.

Its many applications include:

- representing dynamics of higher-order linear systems
- predicting the position of a system j steps into the future
- predicting a geometric sum of future values of a variable like
  - non financial income
  - dividends on a stock
  - the money supply
  - a government deficit or surplus, etc.
- key ingredient of useful models
  - Friedman's permanent income model of consumption smoothing
  - Barro's model of smoothing total tax collections
  - Rational expectations version of Cagan's model of hyperinflation
  - Sargent and Wallace's "unpleasant monetarist arithmetic," etc.

18.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

18.3 The Linear State Space Model

The objects in play are:

- An $n \times 1$ vector x_t denoting the **state** at time $t = 0, 1, 2, \ldots$.
- An iid sequence of $m \times 1$ random vectors $w_t \sim N(0, I)$.
- A $k \times 1$ vector y_t of **observations** at time $t = 0, 1, 2, \ldots$.
- An $n \times n$ matrix A called the **transition matrix**.
- An $n \times m$ matrix C called the **volatility matrix**.
- A $k \times n$ matrix G sometimes called the **output matrix**.

Here is the linear state-space system

$$\begin{aligned} x_{t+1} &= Ax_t + Cw_{t+1} \\ y_t &= Gx_t \\ x_0 &\sim N(\mu_0, \Sigma_0) \end{aligned} \tag{1}$$

18.3.1 Primitives

The primitives of the model are

1. the matrices A, C, G
2. shock distribution, which we have specialized to $N(0, I)$
3. the distribution of the initial condition x_0, which we have set to $N(\mu_0, \Sigma_0)$

Given A, C, G and draws of x_0 and $w_1, w_2, \ldots$, the model (1) pins down the values of the sequences $\{x_t\}$ and $\{y_t\}$.

Even without these draws, the primitives 1–3 pin down the *probability distributions* of $\{x_t\}$ and $\{y_t\}$.

Later we'll see how to compute these distributions and their moments.

Martingale difference shocks

We've made the common assumption that the shocks are independent standardized normal vectors.

But some of what we say will be valid under the assumption that $\{w_{t+1}\}$ is a **martingale difference sequence**.

A martingale difference sequence is a sequence that is zero mean when conditioned on past information.

In the present case, since $\{x_t\}$ is our state sequence, this means that it satisfies

$$\mathbb{E}[w_{t+1}|x_t, x_{t-1}, ...] = 0$$

This is a weaker condition than that $\{w_t\}$ is iid with $w_{t+1} \sim N(0, I)$.

18.3.2 Examples

By appropriate choice of the primitives, a variety of dynamics can be represented in terms of the linear state space model.

The following examples help to highlight this point.

They also illustrate the wise dictum *finding the state is an art*.

Second-order difference equation

Let $\{y_t\}$ be a deterministic sequence that satisfies

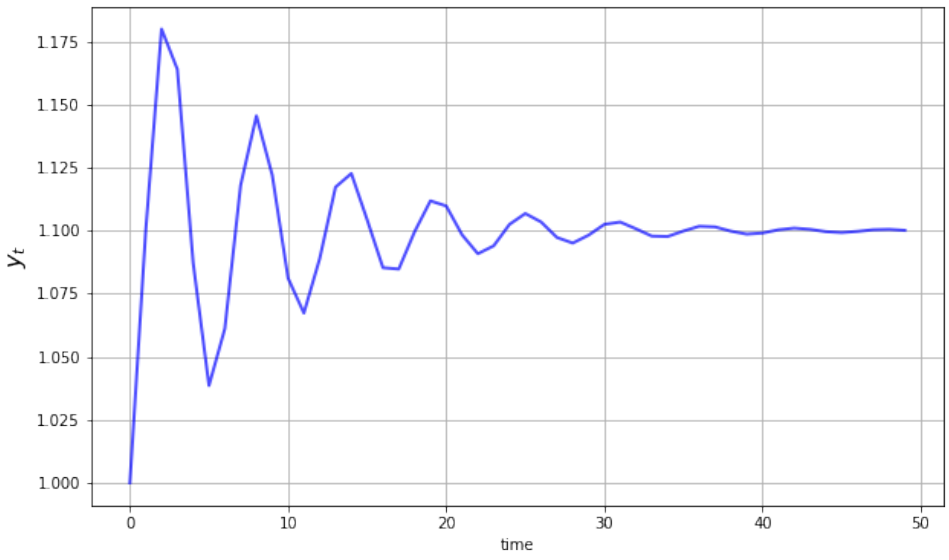
$$y_{t+1} = \phi_0 + \phi_1 y_t + \phi_2 y_{t-1} \quad \text{s.t.} \quad y_0, y_{-1} \text{ given} \tag{2}$$

To map (2) into our state space system (1), we set

$$x_t = \begin{bmatrix} 1 \\ y_t \\ y_{t-1} \end{bmatrix} \qquad A = \begin{bmatrix} 1 & 0 & 0 \\ \phi_0 & \phi_1 & \phi_2 \\ 0 & 1 & 0 \end{bmatrix} \qquad C = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \qquad G = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$$

You can confirm that under these definitions, (1) and (2) agree.

The next figure shows dynamics of this process when $\phi_0 = 1.1, \phi_1 = 0.8, \phi_2 = -0.8, y_0 = y_{-1} = 1$



Later you'll be asked to recreate this figure.

Univariate Autoregressive Processes

We can use (1) to represent the model

$$y_{t+1} = \phi_1 y_t + \phi_2 y_{t-1} + \phi_3 y_{t-2} + \phi_4 y_{t-3} + \sigma w_{t+1} \tag{3}$$

where $\{w_t\}$ is iid and standard normal.

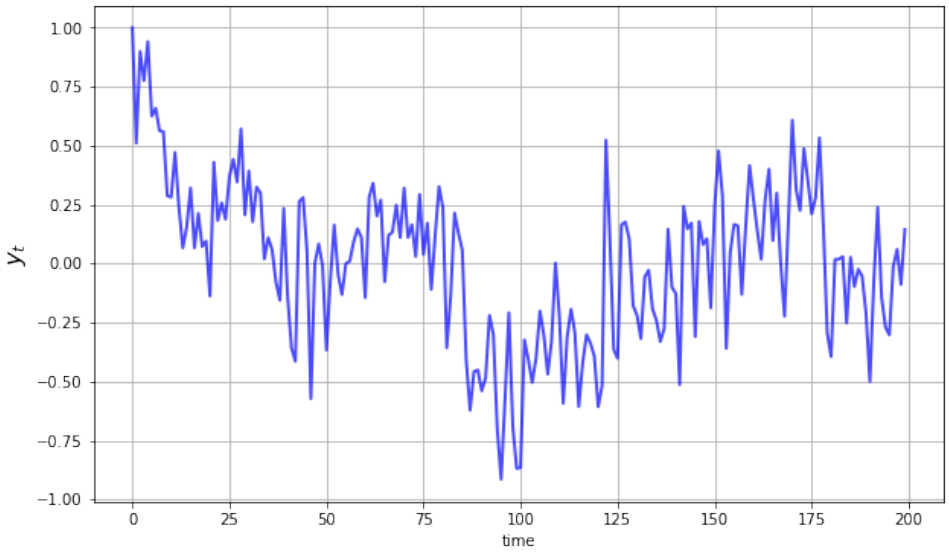
To put this in the linear state space format we take $x_t = \begin{bmatrix} y_t & y_{t-1} & y_{t-2} & y_{t-3} \end{bmatrix}'$ and

$$A = \begin{bmatrix} \phi_1 & \phi_2 & \phi_3 & \phi_4 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad C = \begin{bmatrix} \sigma \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad G = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

The matrix A has the form of the *companion matrix* to the vector $\begin{bmatrix} \phi_1 & \phi_2 & \phi_3 & \phi_4 \end{bmatrix}$.

The next figure shows dynamics of this process when

$$\phi_1 = 0.5, \phi_2 = -0.2, \phi_3 = 0, \phi_4 = 0.5, \sigma = 0.2, y_0 = y_{-1} = y_{-2} = y_{-3} = 1$$



Vector Autoregressions

Now suppose that

- y_t is a $k \times 1$ vector
- ϕ_j is a $k \times k$ matrix and
- w_t is $k \times 1$

Then (3) is termed a *vector autoregression*.

To map this into (1), we set

$$x_t = \begin{bmatrix} y_t \\ y_{t-1} \\ y_{t-2} \\ y_{t-3} \end{bmatrix} \quad A = \begin{bmatrix} \phi_1 & \phi_2 & \phi_3 & \phi_4 \\ I & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \end{bmatrix} \quad C = \begin{bmatrix} \sigma \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad G = \begin{bmatrix} I & 0 & 0 & 0 \end{bmatrix}$$

where I is the $k \times k$ identity matrix and σ is a $k \times k$ matrix.

Seasonals

We can use (1) to represent

1. the *deterministic seasonal* $y_t = y_{t-4}$
2. the *indeterministic seasonal* $y_t = \phi_4 y_{t-4} + w_t$

In fact both are special cases of (3).

With the deterministic seasonal, the transition matrix becomes

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

It is easy to check that $A^4 = I$, which implies that x_t is strictly periodic with period 4:Section **??**

$$x_{t+4} = x_t$$

Such an x_t process can be used to model deterministic seasonals in quarterly time series.

The *indeterministic* seasonal produces recurrent, but aperiodic, seasonal fluctuations.

Time Trends

The model $y_t = at + b$ is known as a *linear time trend*.

We can represent this model in the linear state space form by taking

$$A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \qquad C = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad G = \begin{bmatrix} a & b \end{bmatrix} \tag{4}$$

and starting at initial condition $x_0 = \begin{bmatrix} 0 & 1 \end{bmatrix}'$.

In fact it's possible to use the state-space system to represent polynomial trends of any order.

For instance, let

$$x_0 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad A = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \qquad C = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

It follows that

$$A^t = \begin{bmatrix} 1 & t & t(t-1)/2 \\ 0 & 1 & t \\ 0 & 0 & 1 \end{bmatrix}$$

Then $x_t' = \begin{bmatrix} t(t-1)/2 & t & 1 \end{bmatrix}$, so that x_t contains linear and quadratic time trends.

18.3.3 Moving Average Representations

A nonrecursive expression for x_t as a function of $x_0, w_1, w_2, \ldots, w_t$ can be found by using (1) repeatedly to obtain

$$\begin{aligned} x_t &= Ax_{t-1} + Cw_t \\ &= A^2 x_{t-2} + ACw_{t-1} + Cw_t \\ &\quad \vdots \\ &= \sum_{j=0}^{t-1} A^j C w_{t-j} + A^t x_0 \end{aligned} \tag{5}$$

Representation (5) is a *moving average* representation.

It expresses $\{x_t\}$ as a linear function of

1. current and past values of the process $\{w_t\}$ and
2. the initial condition x_0

As an example of a moving average representation, let the model be

$$A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \qquad C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

You will be able to show that $A^t = \begin{bmatrix} 1 & t \\ 0 & 1 \end{bmatrix}$ and $A^j C = \begin{bmatrix} 1 & 0 \end{bmatrix}'$.

Substituting into the moving average representation (5), we obtain

$$x_{1t} = \sum_{j=0}^{t-1} w_{t-j} + \begin{bmatrix} 1 & t \end{bmatrix} x_0$$

where x_{1t} is the first entry of x_t.

The first term on the right is a cumulated sum of martingale differences, and is therefore a martingale.

The second term is a translated linear function of time.

For this reason, x_{1t} is called a *martingale with drift*.

18.4 Distributions and Moments

18.4.1 Unconditional Moments

Using (1), it's easy to obtain expressions for the (unconditional) means of x_t and y_t.

We'll explain what *unconditional* and *conditional* mean soon.

Letting $\mu_t := \mathbb{E}[x_t]$ and using linearity of expectations, we find that

$$\mu_{t+1} = A\mu_t \quad \text{with} \quad \mu_0 \text{ given} \tag{6}$$

Here μ_0 is a primitive given in (1).

The variance-covariance matrix of x_t is $\Sigma_t := \mathbb{E}[(x_t - \mu_t)(x_t - \mu_t)']$.

Using $x_{t+1} - \mu_{t+1} = A(x_t - \mu_t) + Cw_{t+1}$, we can determine this matrix recursively via

$$\Sigma_{t+1} = A\Sigma_t A' + CC' \quad \text{with} \quad \Sigma_0 \text{ given} \tag{7}$$

As with μ_0, the matrix Σ_0 is a primitive given in (1).

As a matter of terminology, we will sometimes call

- μ_t the *unconditional mean* of x_t
- Σ_t the *unconditional variance-convariance matrix* of x_t

This is to distinguish μ_t and Σ_t from related objects that use conditioning information, to be defined below.

However, you should be aware that these "unconditional" moments do depend on the initial distribution $N(\mu_0, \Sigma_0)$.

Moments of the Observations

Using linearity of expectations again we have

$$\mathbb{E}[y_t] = \mathbb{E}[Gx_t] = G\mu_t \tag{8}$$

The variance-covariance matrix of y_t is easily shown to be

$$\text{Var}[y_t] = \text{Var}[Gx_t] = G\Sigma_t G' \tag{9}$$

18.4.2 Distributions

In general, knowing the mean and variance-covariance matrix of a random vector is not quite as good as knowing the full distribution.

However, there are some situations where these moments alone tell us all we need to know.

These are situations in which the mean vector and covariance matrix are **sufficient statistics** for the population distribution.

(Sufficient statistics form a list of objects that characterize a population distribution)

One such situation is when the vector in question is Gaussian (i.e., normally distributed).

This is the case here, given

1. our Gaussian assumptions on the primitives
2. the fact that normality is preserved under linear operations

In fact, it's well-known that

$$u \sim N(\bar{u}, S) \quad \text{and} \quad v = a + Bu \implies v \sim N(a + B\bar{u}, BSB') \tag{10}$$

In particular, given our Gaussian assumptions on the primitives and the linearity of (1) we can see immediately that both x_t and y_t are Gaussian for all $t \geq 0$ Section **??**.

Since x_t is Gaussian, to find the distribution, all we need to do is find its mean and variance-covariance matrix.

But in fact we've already done this, in (6) and (7).

Letting μ_t and Σ_t be as defined by these equations, we have

$$x_t \sim N(\mu_t, \Sigma_t) \tag{11}$$

By similar reasoning combined with (8) and (9),

$$y_t \sim N(G\mu_t, G\Sigma_t G') \tag{12}$$

18.4.3 Ensemble Interpretations

How should we interpret the distributions defined by (11)–(12)?

Intuitively, the probabilities in a distribution correspond to relative frequencies in a large population drawn from that distribution.

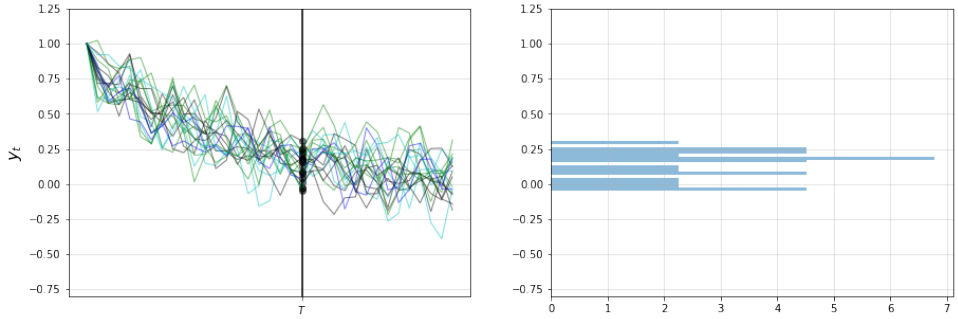
Let's apply this idea to our setting, focusing on the distribution of y_T for fixed T.

We can generate independent draws of y_T by repeatedly simulating the evolution of the system up to time T, using an independent set of shocks each time.

The next figure shows 20 simulations, producing 20 time series for $\{y_t\}$, and hence 20 draws of y_T.

The system in question is the univariate autoregressive model (3).

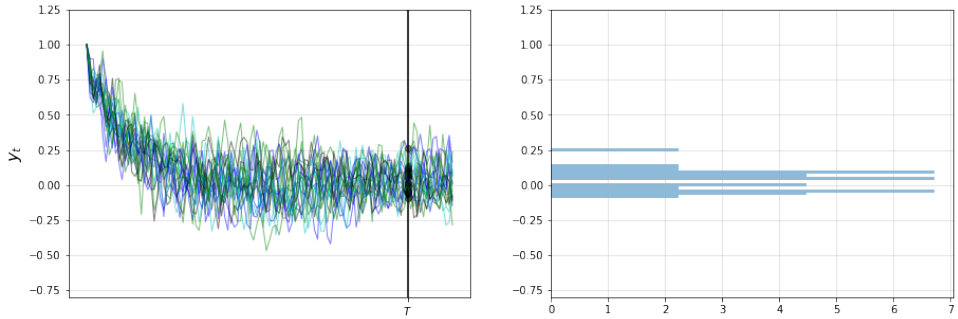
The values of y_T are represented by black dots in the left-hand figure



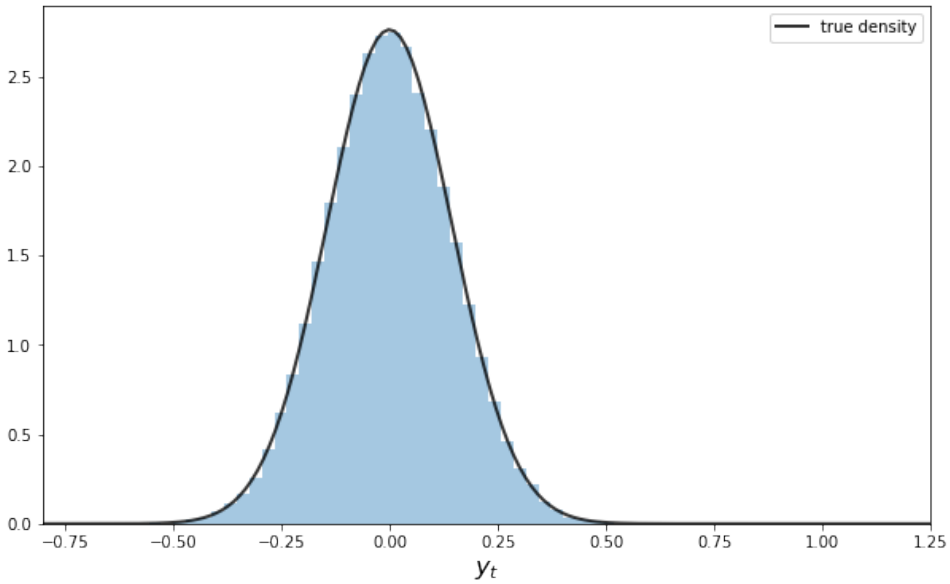
In the right-hand figure, these values are converted into a rotated histogram that shows relative frequencies from our sample of 20 y_T's.

(The parameters and source code for the figures can be found in file linear_models/paths_and_hist.jl)

Here is another figure, this time with 100 observations



Let's now try with 500,000 observations, showing only the histogram (without rotation)



The black line is the population density of y_T calculated from (12).

The histogram and population distribution are close, as expected.

By looking at the figures and experimenting with parameters, you will gain a feel for how the population distribution depends on the model primitives listed above, as intermediated by the distribution's sufficient statistics.

Ensemble means

In the preceding figure we approximated the population distribution of y_T by

1. generating I sample paths (i.e., time series) where I is a large number
2. recording each observation y_T^i
3. histogramming this sample

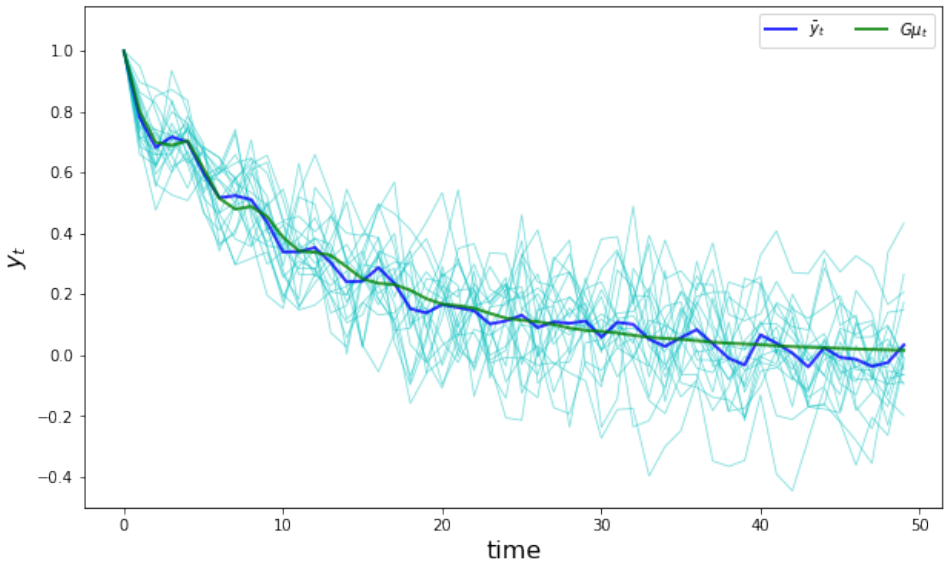
Just as the histogram approximates the population distribution, the *ensemble* or *cross-sectional average*

$$\bar{y}_T := \frac{1}{I} \sum_{i=1}^{I} y_T^i$$

approximates the expectation $\mathbb{E}[y_T] = G\mu_T$ (as implied by the law of large numbers).

Here's a simulation comparing the ensemble averages and population means at time points $t = 0, \ldots, 50$.

The parameters are the same as for the preceding figures, and the sample size is relatively small ($I = 20$).



The ensemble mean for x_t is

$$\bar{x}_T := \frac{1}{I} \sum_{i=1}^{I} x_T^i \to \mu_T \qquad (I \to \infty)$$

The limit μ_T is a "long-run average".

(By *long-run average* we mean the average for an infinite ($I = \infty$) number of sample x_T's)

Another application of the law of large numbers assures us that

$$\frac{1}{I}\sum_{i=1}^{I}(x_T^i - \bar{x}_T)(x_T^i - \bar{x}_T)' \to \Sigma_T \qquad (I \to \infty)$$

18.4.4 Joint Distributions

In the preceding discussion we looked at the distributions of x_t and y_t in isolation.

This gives us useful information, but doesn't allow us to answer questions like

- what's the probability that $x_t \geq 0$ for all t?
- what's the probability that the process $\{y_t\}$ exceeds some value a before falling below b?
- etc., etc.

Such questions concern the *joint distributions* of these sequences.

To compute the joint distribution of $x_0, x_1, \ldots, x_T$, recall that joint and conditional densities are linked by the rule

$$p(x, y) = p(y \,|\, x)p(x) \qquad (\text{joint} \;=\; \text{conditional} \;\times\; \text{marginal})$$

From this rule we get $p(x_0, x_1) = p(x_1 \,|\, x_0)p(x_0)$.

The Markov property $p(x_t \,|\, x_{t-1}, \ldots, x_0) = p(x_t \,|\, x_{t-1})$ and repeated applications of the preceding rule lead us to

$$p(x_0, x_1, \ldots, x_T) = p(x_0)\prod_{t=0}^{T-1} p(x_{t+1} \,|\, x_t)$$

The marginal $p(x_0)$ is just the primitive $N(\mu_0, \Sigma_0)$.

In view of (1), the conditional densities are

$$p(x_{t+1} \,|\, x_t) = N(Ax_t, CC')$$

Autocovariance functions

An important object related to the joint distribution is the *autocovariance function*

$$\Sigma_{t+j,t} := \mathbb{E}[(x_{t+j} - \mu_{t+j})(x_t - \mu_t)'] \tag{13}$$

Elementary calculations show that

$$\Sigma_{t+j,t} = A^j\Sigma_t \tag{14}$$

Notice that $\Sigma_{t+j,t}$ in general depends on both j, the gap between the two dates, and t, the earlier date.

18.5 Stationarity and Ergodicity

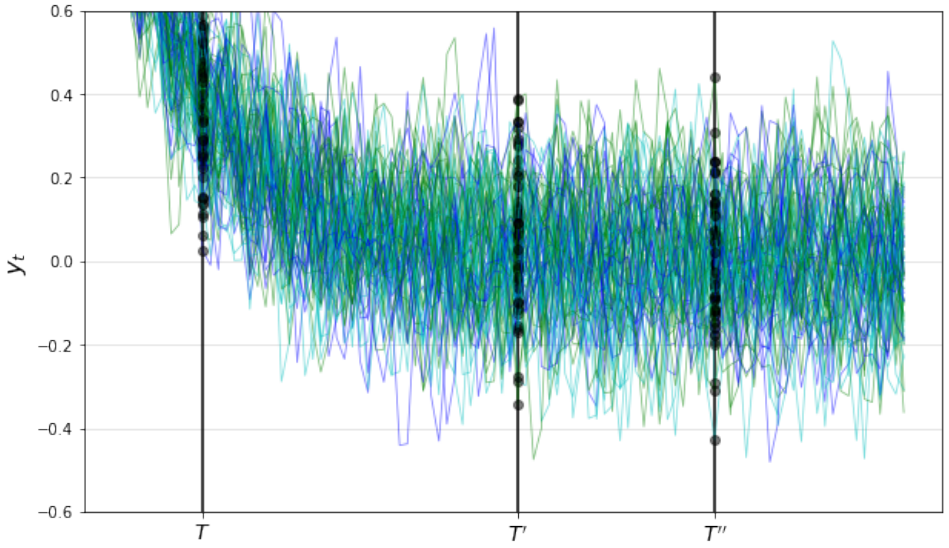
Stationarity and ergodicity are two properties that, when they hold, greatly aid analysis of linear state space models.

Let's start with the intuition.

18.5.1 Visualizing Stability

Let's look at some more time series from the same model that we analyzed above.

This picture shows cross-sectional distributions for y at times T, T', T''



Note how the time series "settle down" in the sense that the distributions at T' and T'' are relatively similar to each other — but unlike the distribution at T.

Apparently, the distributions of y_t converge to a fixed long-run distribution as $t \to \infty$.

When such a distribution exists it is called a *stationary distribution*.

18.5.2 Stationary Distributions

In our setting, a distribution ψ_∞ is said to be *stationary* for x_t if

$$x_t \sim \psi_\infty \quad \text{and} \quad x_{t+1} = Ax_t + Cw_{t+1} \quad \Longrightarrow \quad x_{t+1} \sim \psi_\infty$$

Since

1. in the present case all distributions are Gaussian

2. a Gaussian distribution is pinned down by its mean and variance-covariance matrix

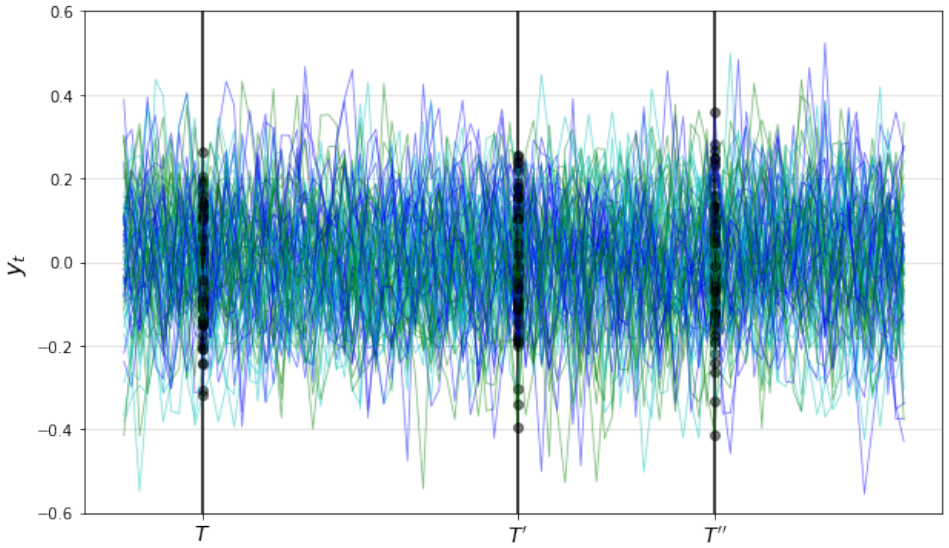
we can restate the definition as follows: ψ_∞ is stationary for x_t if

$$\psi_\infty = N(\mu_\infty, \Sigma_\infty)$$

where μ_∞ and Σ_∞ are fixed points of (6) and (7) respectively.

18.5.3 Covariance Stationary Processes

Let's see what happens to the preceding figure if we start x_0 at the stationary distribution.



Now the differences in the observed distributions at T, T' and T'' come entirely from random fluctuations due to the finite sample size.

By

- our choosing $x_0 \sim N(\mu_\infty, \Sigma_\infty)$
- the definitions of μ_∞ and Σ_∞ as fixed points of (6) and (7) respectively

we've ensured that

$$\mu_t = \mu_\infty \quad \text{and} \quad \Sigma_t = \Sigma_\infty \quad \text{for all } t$$

Moreover, in view of (14), the autocovariance function takes the form $\Sigma_{t+j,t} = A^j \Sigma_\infty$, which depends on j but not on t.

This motivates the following definition.

A process $\{x_t\}$ is said to be *covariance stationary* if

- both μ_t and Σ_t are constant in t
- $\Sigma_{t+j,t}$ depends on the time gap j but not on time t

In our setting, $\{x_t\}$ will be covariance stationary if μ_0, Σ_0, A, C assume values that imply that none of $\mu_t, \Sigma_t, \Sigma_{t+j,t}$ depends on t.

18.5.4 Conditions for Stationarity

The globally stable case

The difference equation $\mu_{t+1} = A\mu_t$ is known to have *unique* fixed point $\mu_\infty = 0$ if all eigenvalues of A have moduli strictly less than unity.

That is, if `all(abs(eigvals(A)) .< 1) == true`.

The difference equation (7) also has a unique fixed point in this case, and, moreover

$$\mu_t \to \mu_\infty = 0 \quad \text{and} \quad \Sigma_t \to \Sigma_\infty \quad \text{as} \quad t \to \infty$$

regardless of the initial conditions μ_0 and Σ_0.

This is the *globally stable case* — see these notes for more a theoretical treatment

However, global stability is more than we need for stationary solutions, and often more than we want.

To illustrate, consider our second order difference equation example.

Here the state is $x_t = \begin{bmatrix} 1 & y_t & y_{t-1} \end{bmatrix}'$.

Because of the constant first component in the state vector, we will never have $\mu_t \to 0$.

How can we find stationary solutions that respect a constant state component?

Processes with a constant state component

To investigate such a process, suppose that A and C take the form

$$A = \begin{bmatrix} A_1 & a \\ 0 & 1 \end{bmatrix} \qquad C = \begin{bmatrix} C_1 \\ 0 \end{bmatrix}$$

where

- A_1 is an $(n-1) \times (n-1)$ matrix
- a is an $(n-1) \times 1$ column vector

Let $x_t = \begin{bmatrix} x_{1t}' & 1 \end{bmatrix}'$ where x_{1t} is $(n-1) \times 1$.

It follows that

$$x_{1,t+1} = A_1 x_{1t} + a + C_1 w_{t+1}$$

Let $\mu_{1t} = \mathbb{E}[x_{1t}]$ and take expectations on both sides of this expression to get

$$\mu_{1,t+1} = A_1 \mu_{1,t} + a \tag{15}$$

Assume now that the moduli of the eigenvalues of A_1 are all strictly less than one.

Then (15) has a unique stationary solution, namely,

$$\mu_{1\infty} = (I - A_1)^{-1} a$$

The stationary value of μ_t itself is then $\mu_\infty := \begin{bmatrix} \mu'_{1\infty} & 1 \end{bmatrix}'$.

The stationary values of Σ_t and $\Sigma_{t+j,t}$ satisfy

$$\begin{aligned} \Sigma_\infty &= A\Sigma_\infty A' + CC' \\ \Sigma_{t+j,t} &= A^j \Sigma_\infty \end{aligned} \tag{16}$$

Notice that here $\Sigma_{t+j,t}$ depends on the time gap j but not on calendar time t.

In conclusion, if

- $x_0 \sim N(\mu_\infty, \Sigma_\infty)$ and
- the moduli of the eigenvalues of A_1 are all strictly less than unity

then the $\{x_t\}$ process is covariance stationary, with constant state component

Note

If the eigenvalues of A_1 are less than unity in modulus, then (a) starting from any initial value, the mean and variance-covariance matrix both converge to their stationary values; and (b) iterations on (7) converge to the fixed point of the *discrete Lyapunov equation* in the first line of (16).

18.5.5 Ergodicity

Let's suppose that we're working with a covariance stationary process.

In this case we know that the ensemble mean will converge to μ_∞ as the sample size I approaches infinity.

Averages over time

Ensemble averages across simulations are interesting theoretically, but in real life we usually observe only a *single* realization $\{x_t, y_t\}_{t=0}^T$.

So now let's take a single realization and form the time series averages

$$\bar{x} := \frac{1}{T}\sum_{t=1}^{T} x_t \quad \text{and} \quad \bar{y} := \frac{1}{T}\sum_{t=1}^{T} y_t$$

Do these time series averages converge to something interpretable in terms of our basic state-space representation?

The answer depends on something called *ergodicity*.

Ergodicity is the property that time series and ensemble averages coincide.

More formally, ergodicity implies that time series sample averages converge to their expectation under the stationary distribution.

In particular,

- $\frac{1}{T}\sum_{t=1}^{T} x_t \to \mu_\infty$
- $\frac{1}{T}\sum_{t=1}^{T} (x_t - \bar{x}_T)(x_t - \bar{x}_T)' \to \Sigma_\infty$
- $\frac{1}{T}\sum_{t=1}^{T} (x_{t+j} - \bar{x}_T)(x_t - \bar{x}_T)' \to A^j \Sigma_\infty$

In our linear Gaussian setting, any covariance stationary process is also ergodic.

18.6 Noisy Observations

In some settings the observation equation $y_t = Gx_t$ is modified to include an error term.

Often this error term represents the idea that the true state can only be observed imperfectly.

To include an error term in the observation we introduce

- An iid sequence of $\ell \times 1$ random vectors $v_t \sim N(0, I)$
- A $k \times \ell$ matrix H

and extend the linear state-space system to

$$\begin{aligned} x_{t+1} &= Ax_t + Cw_{t+1} \\ y_t &= Gx_t + Hv_t \\ x_0 &\sim N(\mu_0, \Sigma_0) \end{aligned} \tag{17}$$

The sequence $\{v_t\}$ is assumed to be independent of $\{w_t\}$.

The process $\{x_t\}$ is not modified by noise in the observation equation and its moments, distributions and stability properties remain the same.

The unconditional moments of y_t from (8) and (9) now become

$$\mathbb{E}[y_t] = \mathbb{E}[Gx_t + Hv_t] = G\mu_t \tag{18}$$

The variance-covariance matrix of y_t is easily shown to be

$$\text{Var}[y_t] = \text{Var}[Gx_t + Hv_t] = G\Sigma_t G' + HH' \tag{19}$$

The distribution of y_t is therefore

$$y_t \sim N(G\mu_t, G\Sigma_t G' + HH')$$

18.7 Prediction

The theory of prediction for linear state space systems is elegant and simple.

18.7.1 Forecasting Formulas – Conditional Means

The natural way to predict variables is to use conditional distributions.

For example, the optimal forecast of x_{t+1} given information known at time t is

$$\mathbb{E}_t[x_{t+1}] := \mathbb{E}[x_{t+1} \mid x_t, x_{t-1}, \ldots, x_0] = Ax_t$$

The right-hand side follows from $x_{t+1} = Ax_t + Cw_{t+1}$ and the fact that w_{t+1} is zero mean and independent of $x_t, x_{t-1}, \ldots, x_0$.

That $\mathbb{E}_t[x_{t+1}] = \mathbb{E}[x_{t+1} \mid x_t]$ is an implication of $\{x_t\}$ having the *Markov property*.

The one-step-ahead forecast error is

$$x_{t+1} - \mathbb{E}_t[x_{t+1}] = Cw_{t+1}$$

The covariance matrix of the forecast error is

$$\mathbb{E}[(x_{t+1} - \mathbb{E}_t[x_{t+1}])(x_{t+1} - \mathbb{E}_t[x_{t+1}])'] = CC'$$

More generally, we'd like to compute the j-step ahead forecasts $\mathbb{E}_t[x_{t+j}]$ and $\mathbb{E}_t[y_{t+j}]$.

With a bit of algebra we obtain

$$x_{t+j} = A^j x_t + A^{j-1} C w_{t+1} + A^{j-2} C w_{t+2} + \cdots + A^0 C w_{t+j}$$

In view of the iid property, current and past state values provide no information about future values of the shock.

Hence $\mathbb{E}_t[w_{t+k}] = \mathbb{E}[w_{t+k}] = 0$.

It now follows from linearity of expectations that the j-step ahead forecast of x is

$$\mathbb{E}_t[x_{t+j}] = A^j x_t$$

The j-step ahead forecast of y is therefore

$$\mathbb{E}_t[y_{t+j}] = \mathbb{E}_t[Gx_{t+j} + Hv_{t+j}] = GA^j x_t$$

18.7.2 Covariance of Prediction Errors

It is useful to obtain the covariance matrix of the vector of j-step-ahead prediction errors

$$x_{t+j} - \mathbb{E}_t[x_{t+j}] = \sum_{s=0}^{j-1} A^s C w_{t-s+j} \tag{20}$$

Evidently,

$$V_j := \mathbb{E}_t[(x_{t+j} - \mathbb{E}_t[x_{t+j}])(x_{t+j} - \mathbb{E}_t[x_{t+j}])'] = \sum_{k=0}^{j-1} A^k CC' A^{k'} \tag{21}$$

V_j defined in (21) can be calculated recursively via $V_1 = CC'$ and

$$V_j = CC' + AV_{j-1}A', \quad j \geq 2 \tag{22}$$

V_j is the *conditional covariance matrix* of the errors in forecasting x_{t+j}, conditioned on time t information x_t.

Under particular conditions, V_j converges to

$$V_\infty = CC' + AV_\infty A' \tag{23}$$

Equation (23) is an example of a *discrete Lyapunov* equation in the covariance matrix V_∞.

A sufficient condition for V_j to converge is that the eigenvalues of A be strictly less than one in modulus.

Weaker sufficient conditions for convergence associate eigenvalues equaling or exceeding one in modulus with elements of C that equal 0.

18.7.3 Forecasts of Geometric Sums

In several contexts, we want to compute forecasts of geometric sums of future random variables governed by the linear state-space system (1).

We want the following objects

- Forecast of a geometric sum of future x's, or $\mathbb{E}_t\left[\sum_{j=0}^{\infty}\beta^j x_{t+j}\right]$.
- Forecast of a geometric sum of future y's, or $\mathbb{E}_t\left[\sum_{j=0}^{\infty}\beta^j y_{t+j}\right]$.

These objects are important components of some famous and interesting dynamic models.

For example,

- if $\{y_t\}$ is a stream of dividends, then $\mathbb{E}\left[\sum_{j=0}^{\infty}\beta^j y_{t+j}|x_t\right]$ is a model of a stock price
- if $\{y_t\}$ is the money supply, then $\mathbb{E}\left[\sum_{j=0}^{\infty}\beta^j y_{t+j}|x_t\right]$ is a model of the price level

Formulas

Fortunately, it is easy to use a little matrix algebra to compute these objects.

Suppose that every eigenvalue of A has modulus strictly less than $\frac{1}{\beta}$.

It then follows that $I + \beta A + \beta^2 A^2 + \cdots = [I - \beta A]^{-1}$.

This leads to our formulas:

- Forecast of a geometric sum of future x's

$$\mathbb{E}_t\left[\sum_{j=0}^{\infty}\beta^j x_{t+j}\right] = [I + \beta A + \beta^2 A^2 + \cdots]x_t = [I - \beta A]^{-1}x_t$$

- Forecast of a geometric sum of future y's

$$\mathbb{E}_t\left[\sum_{j=0}^{\infty}\beta^j y_{t+j}\right] = G[I + \beta A + \beta^2 A^2 + \cdots]x_t = G[I - \beta A]^{-1}x_t$$

18.8 Code

Our preceding simulations and calculations are based on code in the file lss.jl from the QuantEcon.jl package.

The code implements a type which the linear state space models can act on directly through specific methods (for simulations, calculating moments, etc.).

Examples of usage are given in the solutions to the exercises.

18.9 Exercises

18.9.1 Exercise 1

Replicate this figure using the `LSS` type from `lss.jl`.

18.9.2 Exercise 2

Replicate this figure modulo randomness using the same type.

18.9.3 Exercise 3

Replicate this figure modulo randomness using the same type.

The state space model and parameters are the same as for the preceding exercise.

18.9.4 Exercise 4

Replicate this figure modulo randomness using the same type.

The state space model and parameters are the same as for the preceding exercise, except that the initial condition is the stationary distribution.

Hint: You can use the `stationary_distributions` method to get the initial conditions.

The number of sample paths is 80, and the time horizon in the figure is 100.

Producing the vertical bars and dots is optional, but if you wish to try, the bars are at dates 10, 50 and 75.

18.10 Solutions

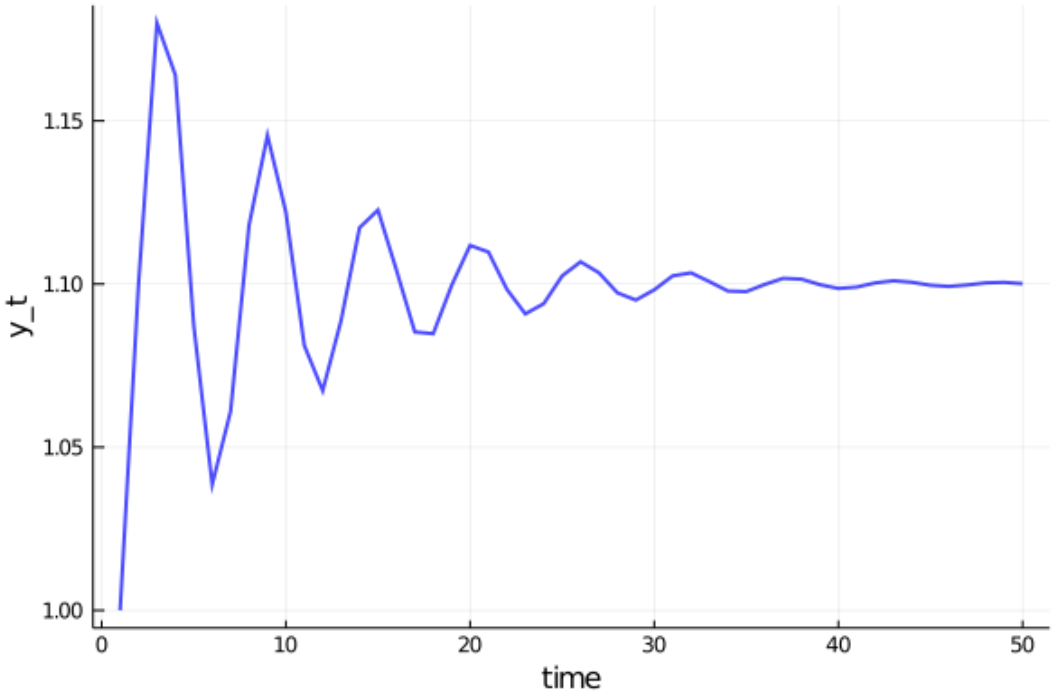
In [3]:
```
using QuantEcon, Plots
gr(fmt=:png);
```

18.10.1 Exercise 1

In [4]:
```
ϕ0, ϕ1, ϕ2 = 1.1, 0.8, -0.8

A = [1.0   0.0   0
       ϕ0    ϕ1    ϕ2
     0.0   1.0   0.0]
C = zeros(3, 1)
G = [0.0 1.0 0.0]
μ_0 = ones(3)
```

```
lss = LSS(A, C, G; mu_0=μ_0)

x, y = simulate(lss, 50)
plot(dropdims(y, dims = 1), color = :blue, linewidth = 2, alpha = 0.7)
plot!(xlabel="time", ylabel = "y_t", legend = :none)
```

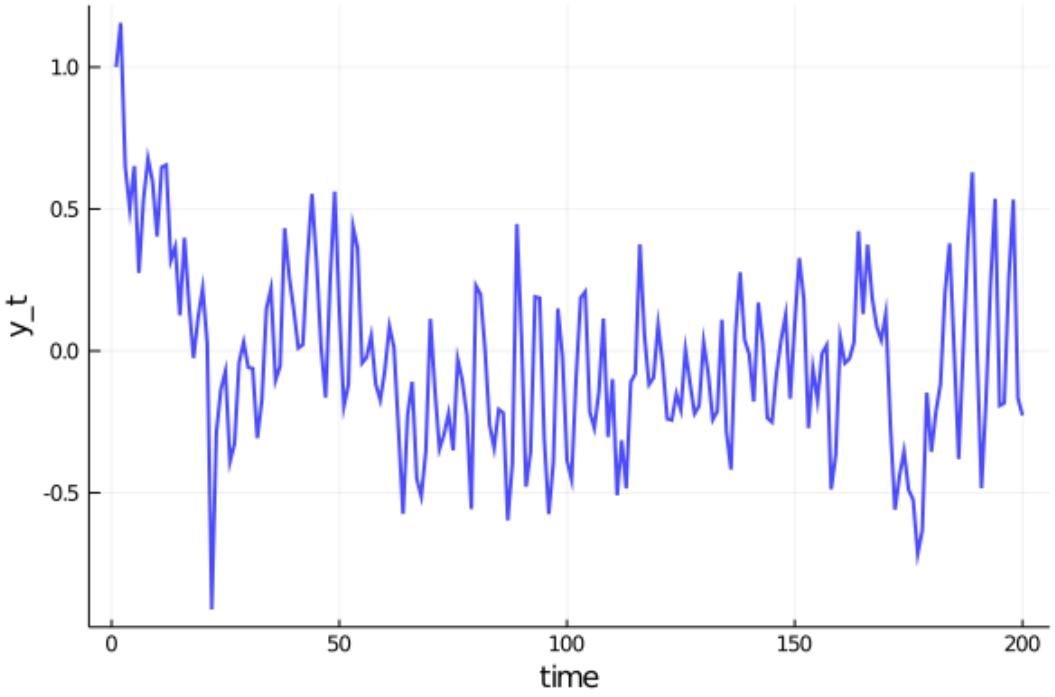
Out[4]:



18.10.2 Exercise 2

In [5]:
```
using Random
Random.seed!(42) # For deterministic results.

ϕ1, ϕ2, ϕ3, ϕ4 = 0.5, -0.2, 0, 0.5
σ = 0.2

A = [ϕ1     ϕ2    ϕ3    ϕ4
        1.0   0.0   0.0   0.0
        0.0   1.0   0.0   0.0
        0.0   0.0   1.0   0.0]
C = [σ
        0.0
        0.0
        0.0]''
G = [1.0 0.0 0.0 0.0]

ar = LSS(A, C, G; mu_0 = ones(4))
x, y = simulate(ar, 200)

plot(dropdims(y, dims = 1), color = :blue, linewidth = 2, alpha = 0.7)
plot!(xlabel="time", ylabel = "y_t", legend = :none)
```

Out[5]:

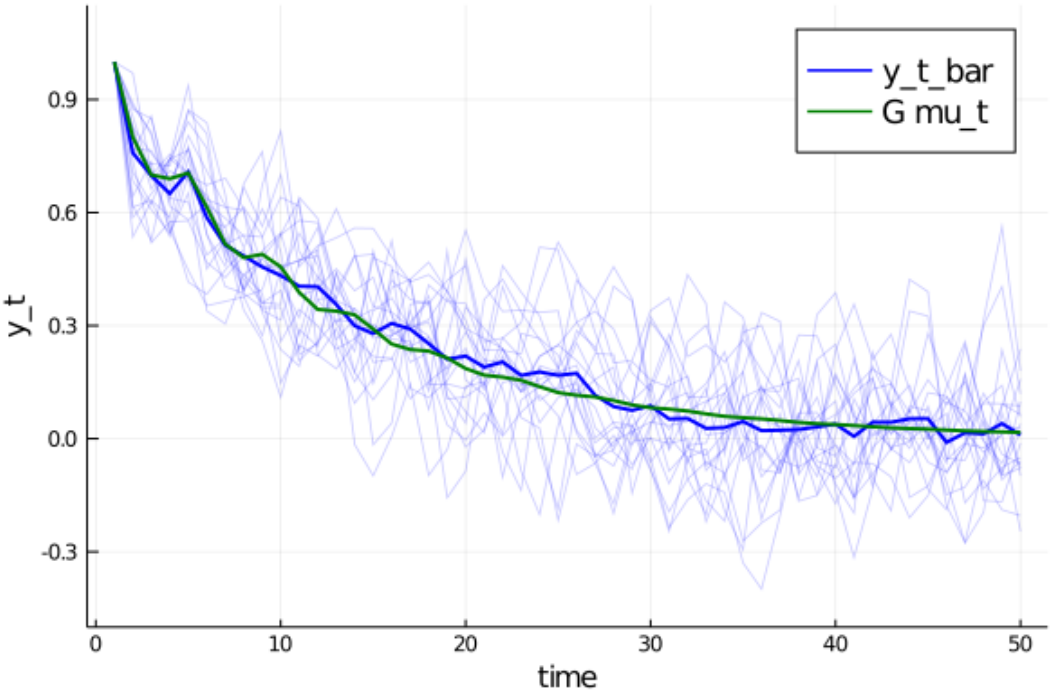


18.10.3 Exercise 3

In [6]:
```
ϕ1, ϕ2, ϕ3, ϕ4 = 0.5, -0.2, 0, 0.5
σ = 0.1

A = [ ϕ1    ϕ2    ϕ3    ϕ4
        1.0   0.0   0.0   0.0
        0.0   1.0   0.0   0.0
        0.0   0.0   1.0   0.0]
C = [σ
        0.0
        0.0
        0.0]
G = [1.0 0.0 0.0 0.0]
I = 20
T = 50
ar = LSS(A, C, G; mu_0 = ones(4))
ymin, ymax = -0.5, 1.15

ensemble_mean = zeros(T)
ys = []
for i  1:I
    x, y = simulate(ar, T)
    y = dropdims(y, dims = 1)
    push!(ys, y)
    ensemble_mean .+= y
end

ensemble_mean = ensemble_mean ./ I
plot(ys, color = :blue, alpha = 0.2, linewidth = 0.8, label = "")
plot!(ensemble_mean, color = :blue, linewidth = 2, label = "y_t_bar")
m = moment_sequence(ar)
pop_means = zeros(0)
```

```
    for (i, t)  enumerate(m)
        (μ_x, μ_y, Σ_x, Σ_y) = t
        push!(pop_means, μ_y[1])
        i == 50 && break
    end
    plot!(pop_means, color = :green, linewidth = 2, label = "G mu_t")
    plot!(ylims=(ymin, ymax), xlabel = "time", ylabel = "y_t", legendfont =
↪font(12))
```

Out[6]:

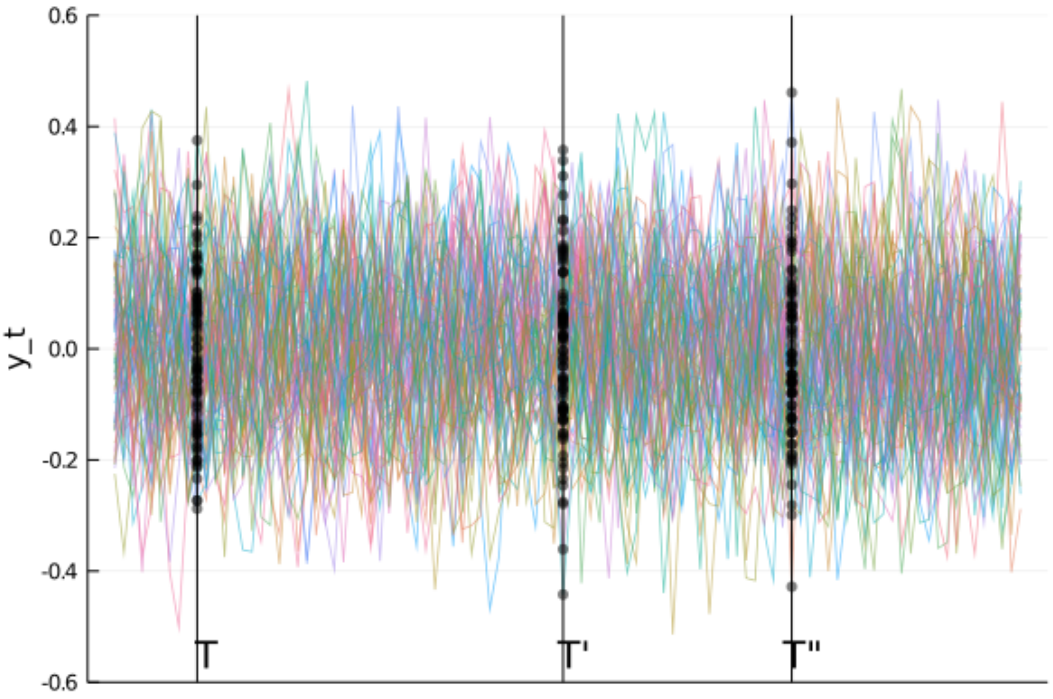


18.10.4 Exercise 4

In [7]:
```
ϕ1, ϕ2, ϕ3, ϕ4 = 0.5, -0.2, 0, 0.5
σ = 0.1

A = [ϕ1     ϕ2    ϕ3    ϕ4
        1.0   0.0   0.0   0.0
        0.0   1.0   0.0   0.0
        0.0   0.0   1.0   0.0]
C = [σ
        0.0
        0.0
        0.0]''
G = [1.0 0.0 0.0 0.0]

T0 = 10
T1 = 50
T2 = 75
T4 = 100

ar = LSS(A, C, G; mu_0 = ones(4))
```

```
ymin, ymax = -0.6, 0.6

μ_x, μ_y, Σ_x, Σ_y = stationary_distributions(ar)
ar = LSS(A, C, G; mu_0=μ_x, Sigma_0=Σ_x)
colors = ["c", "g", "b"]

ys = []
x_scatter = []
y_scatter = []
for i  1:80
    rcolor = colors[rand(1:3)]
    x, y = simulate(ar, T4)
    y = dropdims(y, dims = 1)
    push!(ys, y)
    x_scatter = [x_scatter; T0; T1; T2]
    y_scatter = [y_scatter; y[T0]; y[T1]; y[T2]]
end

plot(ys, linewidth = 0.8, alpha = 0.5)
plot!([T0 T1 T2; T0 T1 T2], [-1 -1 -1; 1 1 1], color = :black, legend = :
↪none)
scatter!(x_scatter, y_scatter, color = :black, alpha = 0.5)
plot!(ylims=(ymin, ymax), ylabel = "y_t", xticks =[], yticks = ymin:0.2:
↪ymax)
plot!(annotations = [(T0+1, -0.55, "T");(T1+1, -0.55, "T'");(T2+1, -0.55,
↪"T''")])
```

Out[7]:



Footnotes

[1] The eigenvalues of A are $(1, -1, i, -i)$.

[2] The correct way to argue this is by induction. Suppose that x_t is Gaussian. Then (1) and (10) imply that x_{t+1} is Gaussian. Since x_0 is assumed to be Gaussian, it follows that every x_t is Gaussian. Evidently this implies that each y_t is Gaussian.

Chapter 19

Finite Markov Chains

19.1 Contents

19.2 Overview

Markov chains are one of the most useful classes of stochastic processes, being

- simple, flexible and supported by many elegant theoretical results
- valuable for building intuition about random dynamic models
- central to quantitative modeling in their own right

You will find them in many of the workhorse models of economics and finance.

In this lecture we review some of the theory of Markov chains.

We will also introduce some of the high quality routines for working with Markov chains available in QuantEcon.jl.

Prerequisite knowledge is basic probability and linear algebra.

19.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Plots, Printf, QuantEcon, Random
        gr(fmt = :png);
```

19.3 Definitions

The following concepts are fundamental.

19.3.1 Stochastic Matrices

A **stochastic matrix** (or **Markov matrix**) is an $n \times n$ square matrix P such that

1. each element of P is nonnegative, and
2. each row of P sums to one

Each row of P can be regarded as a probability mass function over n possible outcomes.

It is too not difficult to check Section **??** that if P is a stochastic matrix, then so is the k-th power P^k for all $k \in \mathbb{N}$.

19.3.2 Markov Chains

There is a close connection between stochastic matrices and Markov chains.

To begin, let S be a finite set with n elements $\{x_1, \ldots, x_n\}$.

The set S is called the **state space** and $x_1, \ldots, x_n$ are the **state values**.

A **Markov chain** $\{X_t\}$ on S is a sequence of random variables on S that have the **Markov property**.

This means that, for any date t and any state $y \in S$,

$$\mathbb{P}\{X_{t+1} = y \,|\, X_t\} = \mathbb{P}\{X_{t+1} = y \,|\, X_t, X_{t-1}, \ldots\} \tag{1}$$

In other words, knowing the current state is enough to know probabilities for future states.

In particular, the dynamics of a Markov chain are fully determined by the set of values

$$P(x, y) := \mathbb{P}\{X_{t+1} = y \,|\, X_t = x\} \qquad (x, y \in S) \tag{2}$$

By construction,

- $P(x, y)$ is the probability of going from x to y in one unit of time (one step)
- $P(x, \cdot)$ is the conditional distribution of X_{t+1} given $X_t = x$

We can view P as a stochastic matrix where

$$P_{ij} = P(x_i, x_j) \qquad 1 \leq i, j \leq n$$

Going the other way, if we take a stochastic matrix P, we can generate a Markov chain $\{X_t\}$ as follows:

- draw X_0 from some specified distribution
- for each $t = 0, 1, ...$, draw X_{t+1} from $P(X_t, \cdot)$

By construction, the resulting process satisfies (2).

19.3.3 Example 1

Consider a worker who, at any given time t, is either unemployed (state 1) or employed (state 2).

Suppose that, over a one month period,

1. An unemployed worker finds a job with probability $\alpha \in (0, 1)$.
2. An employed worker loses her job and becomes unemployed with probability $\beta \in (0, 1)$.

In terms of a Markov model, we have

- $S = \{1, 2\}$
- $P(1, 2) = \alpha$ and $P(2, 1) = \beta$

We can write out the transition probabilities in matrix form as

$$P = \begin{pmatrix} 1 - \alpha & \alpha \\ \beta & 1 - \beta \end{pmatrix}$$

Once we have the values α and β, we can address a range of questions, such as

- What is the average duration of unemployment?
- Over the long-run, what fraction of time does a worker find herself unemployed?
- Conditional on employment, what is the probability of becoming unemployed at least once over the next 12 months?

We'll cover such applications below.

19.3.4 Example 2

Using US unemployment data, Hamilton [38] estimated the stochastic matrix

$$P = \begin{pmatrix} 0.971 & 0.029 & 0 \\ 0.145 & 0.778 & 0.077 \\ 0 & 0.508 & 0.492 \end{pmatrix}$$

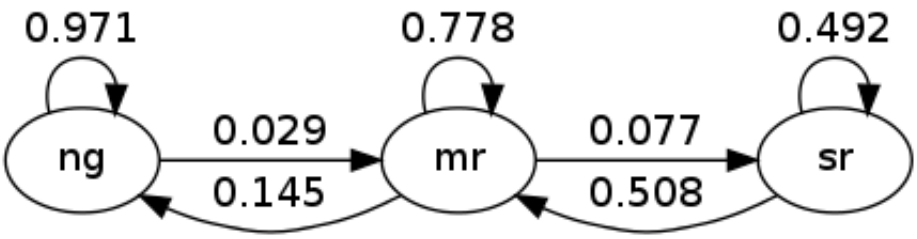
where

- the frequency is monthly
- the first state represents "normal growth"
- the second state represents "mild recession"
- the third state represents "severe recession"

For example, the matrix tells us that when the state is normal growth, the state will again be normal growth next month with probability 0.97.

In general, large values on the main diagonal indicate persistence in the process $\{X_t\}$.

This Markov process can also be represented as a directed graph, with edges labeled by transition probabilities



Here "ng" is normal growth, "mr" is mild recession, etc.

19.4 Simulation

One natural way to answer questions about Markov chains is to simulate them.

(To approximate the probability of event E, we can simulate many times and count the fraction of times that E occurs)

Nice functionality for simulating Markov chains exists in QuantEcon.jl.

- Efficient, bundled with lots of other useful routines for handling Markov chains.

However, it's also a good exercise to roll our own routines — let's do that first and then come back to the methods in QuantEcon.jl.

In these exercises we'll take the state space to be $S = 1, \ldots, n$.

19.4.1 Rolling our own

To simulate a Markov chain, we need its stochastic matrix P and either an initial state or a probability distribution ψ for initial state to be drawn from.

The Markov chain is then constructed as discussed above. To repeat:

1. At time $t = 0$, the X_0 is set to some fixed state or chosen from ψ.
2. At each subsequent time t, the new state X_{t+1} is drawn from $P(X_t, \cdot)$.

In order to implement this simulation procedure, we need a method for generating draws from a discrete distributions.

For this task we'll use a Categorical random variable (i.e. a discrete random variable with assigned probabilities)

```
In [3]: d = Categorical([0.5, 0.3, 0.2]) # 3 discrete states
        @show rand(d, 5)
        @show supertype(typeof(d))
        @show pdf(d, 1) # the probability to be in state 1
        @show support(d)
        @show pdf.(d, support(d)); # broadcast the pdf over the whole support
```

```
    rand(d, 5) = [1, 1, 2, 3, 2]
supertype(typeof(d)) = Distribution{Univariate,Discrete}
pdf(d, 1) = 0.5
support(d) = Base.OneTo(3)
pdf.(d, support(d)) = [0.5, 0.3, 0.2]
```

We'll write our code as a function that takes the following three arguments

- A stochastic matrix `P`
- An initial state `init`
- A positive integer `sample_size` representing the length of the time series the function should return

```
In [4]: function mc_sample_path(P; init = 1, sample_size = 1000)
            @assert size(P)[1] == size(P)[2] # square required
            N = size(P)[1] # should be square

            # create vector of discrete RVs for each row
            dists = [Categorical(P[i, :]) for i in 1:N]

            # setup the simulation
           X = fill(0, sample_size) # allocate memory, or zeros(Int64, sample_size)
            X[1] = init # set the initial state

            for t in 2:sample_size
               dist = dists[X[t-1]] # get discrete RV from last state's transition
 ↪distribution
                X[t] = rand(dist) # draw new value
            end
            return X
        end
```

```
Out[4]: mc_sample_path (generic function with 1 method)
```

Let's see how it works using the small matrix

$$P := \begin{pmatrix} 0.4 & 0.6 \\ 0.2 & 0.8 \end{pmatrix} \tag{3}$$

As we'll see later, for a long series drawn from `P`, the fraction of the sample that takes value 1 will be about 0.25.

If you run the following code you should get roughly that answer

```
In [5]: P = [0.4 0.6; 0.2 0.8]
        X = mc_sample_path(P, sample_size = 100_000); # note 100_000 = 100000
        μ_1 = count(X .== 1)/length(X) # .== broadcasts test for equality. Could
 ↪use mean(X .==
        1)
```

```
Out[5]: 0.25014
```

19.4.2 Using QuantEcon's Routines

As discussed above, QuantEcon.jl has routines for handling Markov chains, including simulation.

Here's an illustration using the same P as the preceding example

```
In [6]: P = [0.4 0.6; 0.2 0.8];
        mc = MarkovChain(P)
        X = simulate(mc, 100_000);
        μ_2 = count(X .== 1)/length(X) # or mean(x -> x == 1, X)
```

```
Out[6]: 0.25053
```

Adding state values and initial conditions

If we wish to, we can provide a specification of state values to `MarkovChain`.

These state values can be integers, floats, or even strings.

The following code illustrates

```
In [7]: mc = MarkovChain(P, ["unemployed", "employed"])
        simulate(mc, 4, init = 1) # start at state 1
```

```
Out[7]: 4-element Array{String,1}:
         "unemployed"
         "unemployed"
         "employed"
         "employed"
```

```
In [8]: simulate(mc, 4, init = 2) # start at state 2
```

```
Out[8]: 4-element Array{String,1}:
         "employed"
         "employed"
         "employed"
         "employed"
```

```
In [9]: simulate(mc, 4) # start with randomly chosen initial condition
```

```
Out[9]: 4-element Array{String,1}:
         "employed"
         "unemployed"
         "unemployed"
         "unemployed"
```

```
In [10]: simulate_indices(mc, 4)
```

```
Out[10]: 4-element Array{Int64,1}:
          2
          2
          2
          2
```

19.5 Marginal Distributions

Suppose that

1. $\{X_t\}$ is a Markov chain with stochastic matrix P
2. the distribution of X_t is known to be ψ_t

What then is the distribution of X_{t+1}, or, more generally, of X_{t+m}?

19.5.1 Solution

Let ψ_t be the distribution of X_t for $t = 0, 1, 2, ...$

Our first aim is to find ψ_{t+1} given ψ_t and P.

To begin, pick any $y \in S$.

Using the law of total probability, we can decompose the probability that $X_{t+1} = y$ as follows:

$$\mathbb{P}\{X_{t+1} = y\} = \sum_{x \in S} \mathbb{P}\{X_{t+1} = y \,|\, X_t = x\} \cdot \mathbb{P}\{X_t = x\}$$

In words, to get the probability of being at y tomorrow, we account for all ways this can happen and sum their probabilities.

Rewriting this statement in terms of marginal and conditional probabilities gives.

$$\psi_{t+1}(y) = \sum_{x \in S} P(x, y)\psi_t(x)$$

There are n such equations, one for each $y \in S$.

If we think of ψ_{t+1} and ψ_t as *row vectors* (as is traditional in this literature), these n equations are summarized by the matrix expression.

$$\psi_{t+1} = \psi_t P \tag{4}$$

In other words, to move the distribution forward one unit of time, we postmultiply by P.

By repeating this m times we move forward m steps into the future.

Hence, iterating on (4), the expression $\psi_{t+m} = \psi_t P^m$ is also valid — here P^m is the m-th power of P.

As a special case, we see that if ψ_0 is the initial distribution from which X_0 is drawn, then $\psi_0 P^m$ is the distribution of X_m.

This is very important, so let's repeat it

$$X_0 \sim \psi_0 \quad \implies \quad X_m \sim \psi_0 P^m \tag{5}$$

and, more generally,

$$X_t \sim \psi_t \quad \implies \quad X_{t+m} \sim \psi_t P^m \tag{6}$$

19.5.2 Multiple Step Transition Probabilities

We know that the probability of transitioning from x to y in one step is $P(x, y)$.

It turns out that the probability of transitioning from x to y in m steps is $P^m(x, y)$, the (x, y)-th element of the m-th power of P.

To see why, consider again (6), but now with ψ_t putting all probability on state x.

- 1 in the x-th position and zero elsewhere.

Inserting this into (6), we see that, conditional on $X_t = x$, the distribution of X_{t+m} is the x-th row of P^m.

In particular

$$\mathbb{P}\{X_{t+m} = y\} = P^m(x, y) = (x, y)\text{-th element of } P^m$$

19.5.3 Example: Probability of Recession

Recall the stochastic matrix P for recession and growth considered above.

Suppose that the current state is unknown — perhaps statistics are available only at the *end* of the current month.

We estimate the probability that the economy is in state x to be $\psi(x)$.

The probability of being in recession (either mild or severe) in 6 months time is given by the inner product

$$\psi P^6 \cdot \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}$$

19.5.4 Example 2: Cross-Sectional Distributions

The marginal distributions we have been studying can be viewed either as probabilities or as cross-sectional frequencies in large samples.

To illustrate, recall our model of employment / unemployment dynamics for a given worker discussed above.

Consider a large (i.e., tending to infinite) population of workers, each of whose lifetime experiences are described by the specified dynamics, independently of one another.

Let ψ be the current *cross-sectional* distribution over $\{1, 2\}$.

- For example, $\psi(1)$ is the unemployment rate.

The cross-sectional distribution records the fractions of workers employed and unemployed at a given moment.

The same distribution also describes the fractions of a particular worker's career spent being employed and unemployed, respectively.

19.6 Irreducibility and Aperiodicity

Irreducibility and aperiodicity are central concepts of modern Markov chain theory.

Let's see what they're about.

19.6.1 Irreducibility

Let P be a fixed stochastic matrix.

Two states x and y are said to **communicate** with each other if there exist positive integers j and k such that

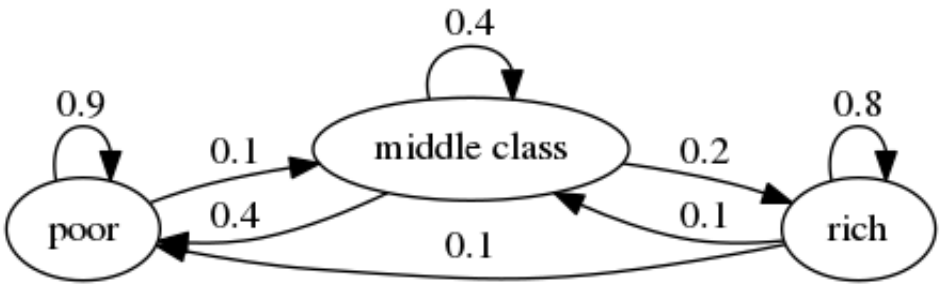
$$P^j(x, y) > 0 \quad \text{and} \quad P^k(y, x) > 0$$

In view of our discussion above, this means precisely that

- state x can be reached eventually from state y, and
- state y can be reached eventually from state x

The stochastic matrix P is called **irreducible** if all states communicate; that is, if x and y communicate for all (x, y) in $S \times S$.

For example, consider the following transition probabilities for wealth of a fictitious set of households



We can translate this into a stochastic matrix, putting zeros where there's no edge between nodes

$$P := \begin{pmatrix} 0.9 & 0.1 & 0 \\ 0.4 & 0.4 & 0.2 \\ 0.1 & 0.1 & 0.8 \end{pmatrix}$$

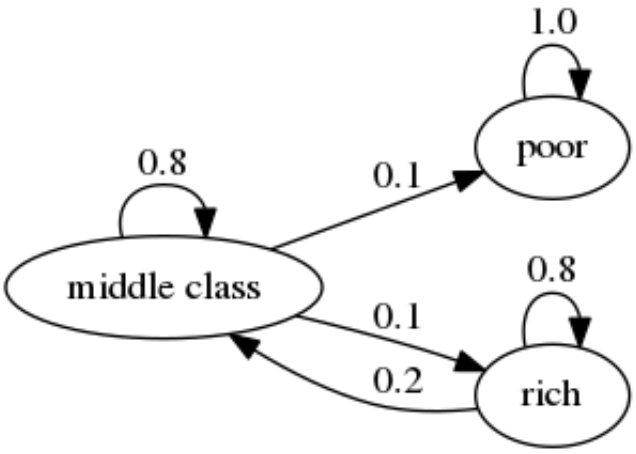
It's clear from the graph that this stochastic matrix is irreducible: we can reach any state from any other state eventually.

We can also test this using QuantEcon.jl's MarkovChain class

```
In [11]: P = [0.9 0.1 0.0; 0.4 0.4 0.2; 0.1 0.1 0.8];
         mc = MarkovChain(P)
         is_irreducible(mc)
```

```
Out[11]: true
```

Here's a more pessimistic scenario, where the poor are poor forever



This stochastic matrix is not irreducible, since, for example, rich is not accessible from poor.

Let's confirm this

```
In [12]: P = [1.0 0.0 0.0; 0.1 0.8 0.1; 0.0 0.2 0.8];
         mc = MarkovChain(P);
         is_irreducible(mc)
```

```
Out[12]: false
```

We can also determine the "communication classes," or the sets of communicating states (where communication refers to a nonzero probability of moving in each direction).

```
In [13]: communication_classes(mc)
```

```
Out[13]: 2-element Array{Array{Int64,1},1}:
          [1]
          [2, 3]
```

It might be clear to you already that irreducibility is going to be important in terms of long run outcomes.

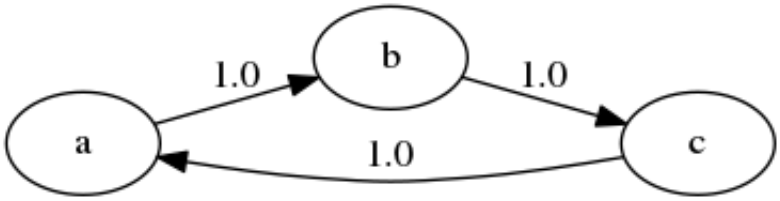
For example, poverty is a life sentence in the second graph but not the first.

We'll come back to this a bit later.

19.6.2 Aperiodicity

Loosely speaking, a Markov chain is called periodic if it cycles in a predictible way, and aperiodic otherwise.

Here's a trivial example with three states



The chain cycles with period 3:

```
In [14]: P = [0 1 0; 0 0 1; 1 0 0];
         mc = MarkovChain(P);
         period(mc)
```

```
Out[14]: 3
```

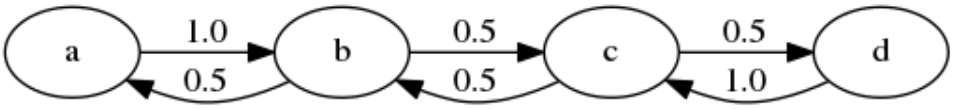
More formally, the **period** of a state x is the greatest common divisor of the set of integers

$$D(x) := \{j \geq 1 : P^j(x, x) > 0\}$$

In the last example, $D(x) = \{3, 6, 9, ...\}$ for every state x, so the period is 3.

A stochastic matrix is called **aperiodic** if the period of every state is 1, and **periodic** otherwise.

For example, the stochastic matrix associated with the transition probabilities below is periodic because, for example, state a has period 2



We can confirm that the stochastic matrix is periodic as follows

```
In [15]: P = zeros(4, 4);
         P[1, 2] = 1;
         P[2, 1] = P[2, 3] = 0.5;
         P[3, 2] = P[3, 4] = 0.5;
         P[4, 3] = 1;
         mc = MarkovChain(P);
         period(mc)
```

```
Out[15]: 2
```

```
In [16]: is_aperiodic(mc)
```

```
Out[16]: false
```

19.7 Stationary Distributions

As seen in (4), we can shift probabilities forward one unit of time via postmultiplication by P.

Some distributions are invariant under this updating process — for example,

```
In [17]: P = [.4 .6; .2 .8];
         ψ = [0.25, 0.75];
         ψ' * P
```

```
Out[17]: 1×2 Adjoint{Float64,Array{Float64,1}}:
          0.25  0.75
```

Such distributions are called **stationary**, or **invariant**.

Formally, a distribution ψ^* on S is called **stationary** for P if $\psi^* = \psi^* P$.

From this equality we immediately get $\psi^* = \psi^* P^t$ for all t.

This tells us an important fact: If the distribution of X_0 is a stationary distribution, then X_t will have this same distribution for all t.

Hence stationary distributions have a natural interpretation as stochastic steady states — we'll discuss this more in just a moment.

Mathematically, a stationary distribution is a fixed point of P when P is thought of as the map $\psi \mapsto \psi P$ from (row) vectors to (row) vectors.

Theorem. Every stochastic matrix P has at least one stationary distribution.

(We are assuming here that the state space S is finite; if not more assumptions are required)

For a proof of this result you can apply Brouwer's fixed point theorem, or see EDTC, theorem 4.3.5.

There may in fact be many stationary distributions corresponding to a given stochastic matrix P.

- For example, if P is the identity matrix, then all distributions are stationary.

Since stationary distributions are long run equilibria, to get uniqueness we require that initial conditions are not infinitely persistent.

Infinite persistence of initial conditions occurs if certain regions of the state space cannot be accessed from other regions, which is the opposite of irreducibility.

This gives some intuition for the following fundamental theorem.

Theorem. If P is both aperiodic and irreducible, then

1. P has exactly one stationary distribution ψ^*.
2. For any initial distribution ψ_0, we have $\|\psi_0 P^t - \psi^*\| \to 0$ as $t \to \infty$.

For a proof, see, for example, theorem 5.2 of [35].

(Note that part 1 of the theorem requires only irreducibility, whereas part 2 requires both irreducibility and aperiodicity)

A stochastic matrix satisfying the conditions of the theorem is sometimes called **uniformly ergodic**.

One easy sufficient condition for aperiodicity and irreducibility is that every element of P is strictly positive

- Try to convince yourself of this

19.7.1 Example

Recall our model of employment / unemployment dynamics for a given worker discussed above.

Assuming $\alpha \in (0,1)$ and $\beta \in (0,1)$, the uniform ergodicity condition is satisfied.

Let $\psi^* = (p, 1-p)$ be the stationary distribution, so that p corresponds to unemployment (state 1).

Using $\psi^* = \psi^* P$ and a bit of algebra yields

$$p = \frac{\beta}{\alpha + \beta}$$

This is, in some sense, a steady state probability of unemployment — more on interpretation below.

Not surprisingly it tends to zero as $\beta \to 0$, and to one as $\alpha \to 0$.

19.7.2 Calculating Stationary Distributions

As discussed above, a given Markov matrix P can have many stationary distributions.

That is, there can be many row vectors ψ such that $\psi = \psi P$.

In fact if P has two distinct stationary distributions ψ_1, ψ_2 then it has infinitely many, since in this case, as you can verify,

$$\psi_3 := \lambda \psi_1 + (1-\lambda)\psi_2$$

is a stationary distribution for P for any $\lambda \in [0,1]$.

If we restrict attention to the case where only one stationary distribution exists, one option for finding it is to try to solve the linear system $\psi(I_n - P) = 0$ for ψ, where I_n is the $n \times n$ identity.

But the zero vector solves this equation.

Hence we need to impose the restriction that the solution must be a probability distribution.

A suitable algorithm is implemented in QuantEcon.jl — the next code block illustrates

```
In [18]: P = [.4 .6; .2 .8];
         mc = MarkovChain(P);
         stationary_distributions(mc)
```

```
Out[18]: 1-element Array{Array{Float64,1},1}:
          [0.25, 0.7499999999999999]
```

The stationary distribution is unique.

19.7.3 Convergence to Stationarity

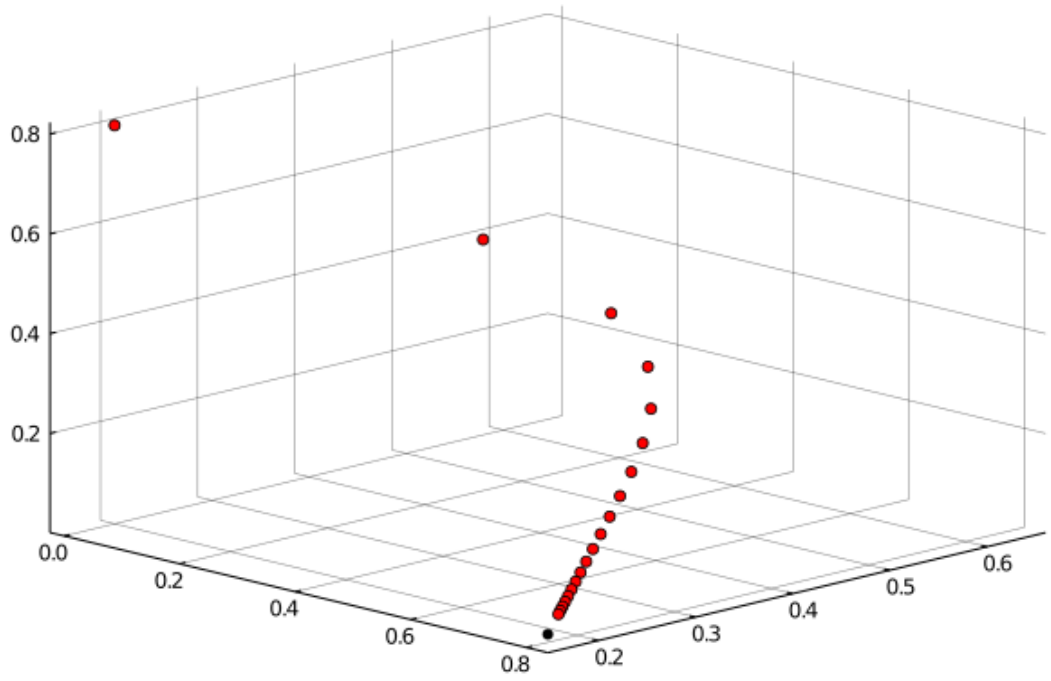
Part 2 of the Markov chain convergence theorem stated above tells us that the distribution of X_t converges to the stationary distribution regardless of where we start off.

This adds considerable weight to our interpretation of ψ^* as a stochastic steady state.

The convergence in the theorem is illustrated in the next figure

```
In [19]: P = [0.971 0.029 0.000
              0.145 0.778 0.077
              0.000 0.508 0.492] # stochastic matrix

         ψ = [0.0 0.2 0.8] # initial distribution

         t = 20 # path length
         x_vals = zeros(t)
         y_vals = similar(x_vals)
         z_vals = similar(x_vals)
         colors = [repeat([:red], 20); :black] # for plotting

         for i in 1:t
             x_vals[i] = ψ[1]
             y_vals[i] = ψ[2]
             z_vals[i] = ψ[3]
             ψ = ψ * P # update distribution
         end

         mc = MarkovChain(P)
         ψ_star = stationary_distributions(mc)[1]
         x_star, y_star, z_star = ψ_star # unpack the stationary dist
        plt = scatter([x_vals; x_star], [y_vals; y_star], [z_vals; z_star], color
  ↪= colors,
                       gridalpha = 0.5, legend = :none)
         plot!(plt, camera = (45,45))
```

Out[19]:



Here

- P is the stochastic matrix for recession and growth considered above
- The highest red dot is an arbitrarily chosen initial probability distribution ψ, represented as a vector in $\mathbb{R}^3$
- The other red dots are the distributions ψP^t for $t = 1, 2, ...$
- The black dot is ψ^*

The code for the figure can be found here — you might like to try experimenting with different initial conditions.

19.8 Ergodicity

Under irreducibility, yet another important result obtains: For all $x \in S$,

$$\frac{1}{m} \sum_{t=1}^{m} \mathbf{1}\{X_t = x\} \to \psi^*(x) \quad \text{as } m \to \infty \tag{7}$$

Here

- $\mathbf{1}\{X_t = x\} = 1$ if $X_t = x$ and zero otherwise
- convergence is with probability one
- the result does not depend on the distribution (or value) of X_0

The result tells us that the fraction of time the chain spends at state x converges to $\psi^*(x)$ as time goes to infinity.

This gives us another way to interpret the stationary distribution — provided that the convergence result in (7) is valid.

The convergence in (7) is a special case of a law of large numbers result for Markov chains — see EDTC, section 4.3.4 for some additional information.

19.8.1 Example

Recall our cross-sectional interpretation of the employment / unemployment model discussed above.

Assume that $\alpha \in (0,1)$ and $\beta \in (0,1)$, so that irreducibility and aperiodicity both hold.

We saw that the stationary distribution is $(p, 1-p)$, where

$$p = \frac{\beta}{\alpha + \beta}$$

In the cross-sectional interpretation, this is the fraction of people unemployed.

In view of our latest (ergodicity) result, it is also the fraction of time that a worker can expect to spend unemployed.

Thus, in the long-run, cross-sectional averages for a population and time-series averages for a given person coincide.

This is one interpretation of the notion of ergodicity.

19.9 Computing Expectations

We are interested in computing expectations of the form

$$\mathbb{E}[h(X_t)] \tag{8}$$

and conditional expectations such as

$$\mathbb{E}[h(X_{t+k}) \mid X_t = x] \tag{9}$$

where

- $\{X_t\}$ is a Markov chain generated by $n \times n$ stochastic matrix P
- h is a given function, which, in expressions involving matrix algebra, we'll think of as the column vector

$$h = \begin{pmatrix} h(x_1) \\ \vdots \\ h(x_n) \end{pmatrix}$$

The unconditional expectation (8) is easy: We just sum over the distribution of X_t to get

$$\mathbb{E}[h(X_t)] = \sum_{x \in S} (\psi P^t)(x) h(x)$$

Here ψ is the distribution of X_0.

Since ψ and hence ψP^t are row vectors, we can also write this as

$$\mathbb{E}[h(X_t)] = \psi P^t h$$

For the conditional expectation (9), we need to sum over the conditional distribution of X_{t+k} given $X_t = x$.

We already know that this is $P^k(x, \cdot)$, so

$$\mathbb{E}[h(X_{t+k}) \mid X_t = x] = (P^k h)(x) \tag{10}$$

The vector $P^k h$ stores the conditional expectation $\mathbb{E}[h(X_{t+k}) \mid X_t = x]$ over all x.

19.9.1 Expectations of Geometric Sums

Sometimes we also want to compute expectations of a geometric sum, such as $\sum_t \beta^t h(X_t)$.

In view of the preceding discussion, this is

$$\mathbb{E}\left[\sum_{j=0}^{\infty} \beta^j h(X_{t+j}) \mid X_t = x\right] = [(I - \beta P)^{-1} h](x)$$

where

$$(I - \beta P)^{-1} = I + \beta P + \beta^2 P^2 + \cdots$$

Premultiplication by $(I - \beta P)^{-1}$ amounts to "applying the **resolvent operator**".

19.10 Exercises

19.10.1 Exercise 1

According to the discussion above, if a worker's employment dynamics obey the stochastic matrix

$$P = \begin{pmatrix} 1 - \alpha & \alpha \\ \beta & 1 - \beta \end{pmatrix}$$

with $\alpha \in (0, 1)$ and $\beta \in (0, 1)$, then, in the long-run, the fraction of time spent unemployed will be

$$p := \frac{\beta}{\alpha + \beta}$$

In other words, if $\{X_t\}$ represents the Markov chain for employment, then $\bar{X}_m \to p$ as $m \to \infty$, where

$$\bar{X}_m := \frac{1}{m} \sum_{t=1}^{m} \mathbf{1}\{X_t = 1\}$$

Your exercise is to illustrate this convergence.

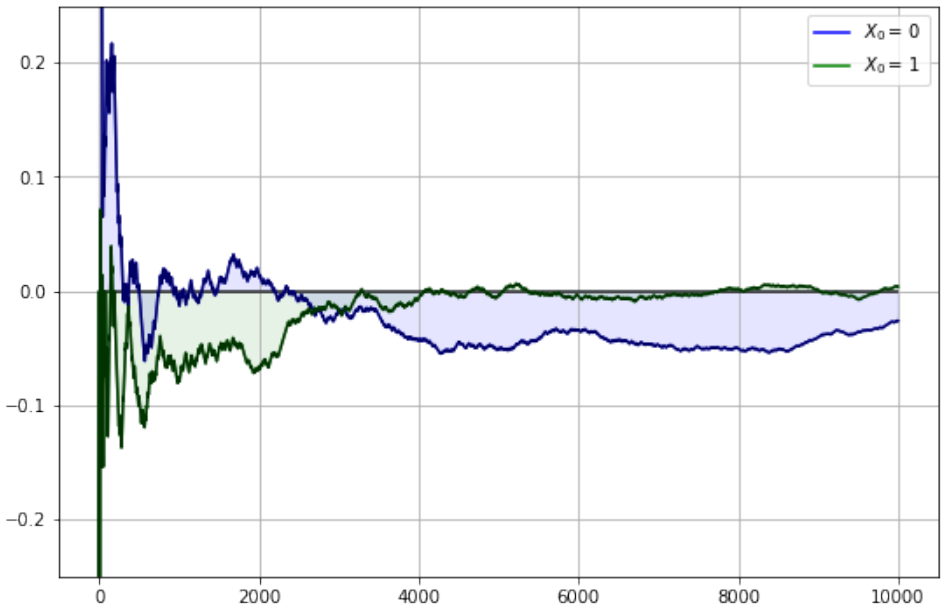
First,

- generate one simulated time series $\{X_t\}$ of length 10,000, starting at $X_0 = 1$
- plot $\bar{X}_m - p$ against m, where p is as defined above

Second, repeat the first step, but this time taking $X_0 = 2$.

In both cases, set $\alpha = \beta = 0.1$.

The result should look something like the following — modulo randomness, of course



(You don't need to add the fancy touches to the graph — see the solution if you're interested)

19.10.2 Exercise 2

A topic of interest for economics and many other disciplines is *ranking*.

Let's now consider one of the most practical and important ranking problems — the rank assigned to web pages by search engines.

(Although the problem is motivated from outside of economics, there is in fact a deep connection between search ranking systems and prices in certain competitive equilibria — see [25])

To understand the issue, consider the set of results returned by a query to a web search engine.

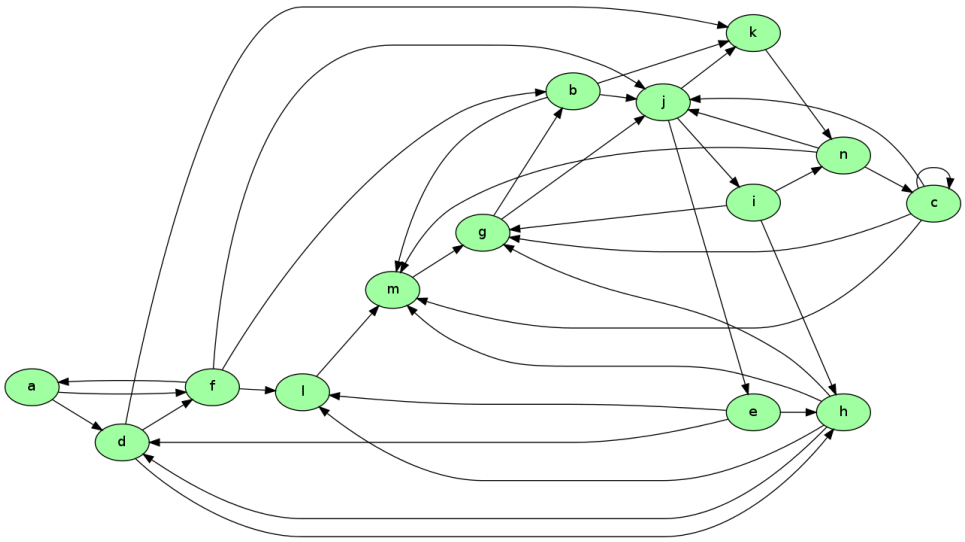
For the user, it is desirable to

1. receive a large set of accurate matches
2. have the matches returned in order, where the order corresponds to some measure of "importance"

Ranking according to a measure of importance is the problem we now consider.

The methodology developed to solve this problem by Google founders Larry Page and Sergey Brin is known as PageRank.

To illustrate the idea, consider the following diagram



Imagine that this is a miniature version of the WWW, with

- each node representing a web page
- each arrow representing the existence of a link from one page to another

Now let's think about which pages are likely to be important, in the sense of being valuable to a search engine user.

One possible criterion for importance of a page is the number of inbound links — an indication of popularity.

By this measure, `m` and `j` are the most important pages, with 5 inbound links each.

However, what if the pages linking to `m`, say, are not themselves important?

Thinking this way, it seems appropriate to weight the inbound nodes by relative importance.

The PageRank algorithm does precisely this.

A slightly simplified presentation that captures the basic idea is as follows.

Letting j be (the integer index of) a typical page and r_j be its ranking, we set

$$r_j = \sum_{i \in L_j} \frac{r_i}{\ell_i}$$

where

- ℓ_i is the total number of outbound links from i
- L_j is the set of all pages i such that i has a link to j

This is a measure of the number of inbound links, weighted by their own ranking (and normalized by $1/\ell_i$).

There is, however, another interpretation, and it brings us back to Markov chains.

Let P be the matrix given by $P(i, j) = \mathbf{1}\{i \to j\}/\ell_i$ where $\mathbf{1}\{i \to j\} = 1$ if i has a link to j and zero otherwise.

The matrix P is a stochastic matrix provided that each page has at least one link.

With this definition of P we have

$$r_j = \sum_{i \in L_j} \frac{r_i}{\ell_i} = \sum_{\text{all } i} \mathbf{1}\{i \to j\} \frac{r_i}{\ell_i} = \sum_{\text{all } i} P(i,j) r_i$$

Writing r for the row vector of rankings, this becomes $r = rP$.

Hence r is the stationary distribution of the stochastic matrix P.

Let's think of $P(i,j)$ as the probability of "moving" from page i to page j.

The value $P(i,j)$ has the interpretation

- $P(i,j) = 1/k$ if i has k outbound links, and j is one of them
- $P(i,j) = 0$ if i has no direct link to j

Thus, motion from page to page is that of a web surfer who moves from one page to another by randomly clicking on one of the links on that page.

Here "random" means that each link is selected with equal probability.

Since r is the stationary distribution of P, assuming that the uniform ergodicity condition is valid, we can interpret r_j as the fraction of time that a (very persistent) random surfer spends at page j.

Your exercise is to apply this ranking algorithm to the graph pictured above, and return the list of pages ordered by rank.

When you solve for the ranking, you will find that the highest ranked node is in fact `g`, while the lowest is `a`.

19.10.3 Exercise 3

In numerical work it is sometimes convenient to replace a continuous model with a discrete one.

In particular, Markov chains are routinely generated as discrete approximations to AR(1) processes of the form

$$y_{t+1} = \rho y_t + u_{t+1}$$

Here u_t is assumed to be i.i.d. and $N(0, \sigma_u^2)$.

The variance of the stationary probability distribution of $\{y_t\}$ is

$$\sigma_y^2 := \frac{\sigma_u^2}{1 - \rho^2}$$

Tauchen's method [104] is the most common method for approximating this continuous state process with a finite state Markov chain.

A routine for this already exists in QuantEcon.jl but let's write our own version as an exercise.

As a first step we choose

- n, the number of states for the discrete approximation

- m, an integer that parameterizes the width of the state space

Next we create a state space $\{x_0, \ldots, x_{n-1}\} \subset \mathbb{R}$ and a stochastic $n \times n$ matrix P such that

- $x_0 = -m\,\sigma_y$
- $x_{n-1} = m\,\sigma_y$
- $x_{i+1} = x_i + s$ where $s = (x_{n-1} - x_0)/(n-1)$

Let F be the cumulative distribution function of the normal distribution $N(0, \sigma_u^2)$.

The values $P(x_i, x_j)$ are computed to approximate the AR(1) process — omitting the derivation, the rules are as follows:

1. If $j = 0$, then set

$$P(x_i, x_j) = P(x_i, x_0) = F(x_0 - \rho x_i + s/2)$$

1. If $j = n - 1$, then set

$$P(x_i, x_j) = P(x_i, x_{n-1}) = 1 - F(x_{n-1} - \rho x_i - s/2)$$

1. Otherwise, set

$$P(x_i, x_j) = F(x_j - \rho x_i + s/2) - F(x_j - \rho x_i - s/2)$$

The exercise is to write a function `approx_markov(rho, sigma_u, m = 3, n = 7)` that returns $\{x_0, \ldots, x_{n-1}\} \subset \mathbb{R}$ and $n \times n$ matrix P as described above.

- Even better, write a function that returns an instance of QuantEcon.jl's MarkovChain type.

19.11 Solutions

19.11.1 Exercise 1

Compute the fraction of time that the worker spends unemployed, and compare it to the stationary probability.

```
In [20]: α = 0.1 # probability of getting hired
         β = 0.1 # probability of getting fired
         N = 10_000
         p = β / (α + β) # steady-state probabilities
         P = [1 - α   α
              β   1 - β] # stochastic matrix
         mc = MarkovChain(P)
         labels = ["start unemployed", "start employed"]
         y_vals = Array{Vector}(undef, 2) # sample paths holder
```

```
    for x0 in 1:2
        X = simulate_indices(mc, N; init = x0) # generate the sample path
        X = cumsum(X .== 1) ./ (1:N) # compute state fraction. ./ required for
↪precedence
        y_vals[x0] = X .- p # plot divergence from steady state
    end

    plot(y_vals, color = [:blue :green], fillrange = 0, fillalpha = 0.1,
         ylims = (-0.25, 0.25), label = reshape(labels, 1, length(labels)))
```

Out[20]:

19.11.2 Exercise 2

```
In [21]: web_graph_data = sort(Dict('a' => ['d', 'f'],
                                    'b' => ['j', 'k', 'm'],
                                    'c' => ['c', 'g', 'j', 'm'],
                                    'd' => ['f', 'h', 'k'],
                                    'e' => ['d', 'h', 'l'],
                                    'f' => ['a', 'b', 'j', 'l'],
                                    'g' => ['b', 'j'],
                                    'h' => ['d', 'g', 'l', 'm'],
                                    'i' => ['g', 'h', 'n'],
                                    'j' => ['e', 'i', 'k'],
                                    'k' => ['n'],
                                    'l' => ['m'],
                                    'm' => ['g'],
                                    'n' => ['c', 'j', 'm']))
```

```
┌ Warning: `sort(d::Dict; args…)` is deprecated, use `sort!(OrderedDict(d);
args…)` instead.
```

```
│   caller = top-level scope at In[21]:1
└ @ Core In[21]:1
```

Out[21]:
```
OrderedCollections.OrderedDict{Char,Array{Char,1}} with 14 entries:
  'a' => ['d', 'f']
  'b' => ['j', 'k', 'm']
  'c' => ['c', 'g', 'j', 'm']
  'd' => ['f', 'h', 'k']
  'e' => ['d', 'h', 'l']
  'f' => ['a', 'b', 'j', 'l']
  'g' => ['b', 'j']
  'h' => ['d', 'g', 'l', 'm']
  'i' => ['g', 'h', 'n']
  'j' => ['e', 'i', 'k']
  'k' => ['n']
  'l' => ['m']
  'm' => ['g']
  'n' => ['c', 'j', 'm']
```

In [22]:
```
nodes = keys(web_graph_data)
n = length(nodes)
# create adjacency matrix of links (Q[i, j] = true for link, false
↪otherwise)
Q = fill(false, n, n)
for (node, edges) in enumerate(values(web_graph_data))
    Q[node, nodes .∈ Ref(edges)] .= true
end

# create the corresponding stochastic matrix
P = Q ./ sum(Q, dims = 2)

mc = MarkovChain(P)
r = stationary_distributions(mc)[1] # stationary distribution
ranked_pages = Dict(zip(keys(web_graph_data), r)) # results holder

# print solution
println("Rankings\n ***")
sort(collect(ranked_pages), by = x -> x[2], rev = true) # print sorted
```

```
  Rankings
 ***
```

Out[22]:
```
14-element Array{Pair{Char,Float64},1}:
 'g' => 0.16070778858515053
 'j' => 0.15936158342833578
 'm' => 0.119515123584059
 'n' => 0.10876973827831275
 'k' => 0.0910628956751643
 'b' => 0.0832646081451476
 'e' => 0.05312052780944526
 'i' => 0.05312052780944526
 'c' => 0.04834210590147233
 'h' => 0.04560118369030004
 'l' => 0.032017852378295776
 'd' => 0.030562495452009602
```

```
'f' => 0.011642855410289372
'a' => 0.002910713852572343
```

19.11.3 Exercise 3

A solution from QuantEcon.jl can be found here.

Footnotes

[1] Hint: First show that if P and Q are stochastic matrices then so is their product — to check the row sums, try postmultiplying by a column vector of ones. Finally, argue that P^n is a stochastic matrix using induction.

Chapter 20

Continuous State Markov Chains

20.1 Contents

20.2 Overview

In a previous lecture we learned about finite Markov chains, a relatively elementary class of stochastic dynamic models.

The present lecture extends this analysis to continuous (i.e., uncountable) state Markov chains.

Most stochastic dynamic models studied by economists either fit directly into this class or can be represented as continuous state Markov chains after minor modifications.

In this lecture, our focus will be on continuous Markov models that

- evolve in discrete time
- are often nonlinear

The fact that we accommodate nonlinear models here is significant, because linear stochastic models have their own highly developed tool set, as we'll see later on.

The question that interests us most is: Given a particular stochastic dynamic model, how will the state of the system evolve over time?

In particular,

- What happens to the distribution of the state variables?
- Is there anything we can say about the "average behavior" of these variables?
- Is there a notion of "steady state" or "long run equilibrium" that's applicable to the model?
  - If so, how can we compute it?

Answering these questions will lead us to revisit many of the topics that occupied us in the finite state case, such as simulation, distribution dynamics, stability, ergodicity, etc.

Note

For some people, the term "Markov chain" always refers to a process with a finite or discrete state space. We follow the mainstream mathematical literature (e.g., [77]) in using the term to refer to any discrete **time** Markov process.

20.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using KernelDensity, Distributions, Plots, QuantEcon, Random
```

20.3 The Density Case

You are probably aware that some distributions can be represented by densities and some cannot.

(For example, distributions on the real numbers $\mathbb{R}$ that put positive probability on individual points have no density representation)

We are going to start our analysis by looking at Markov chains where the one step transition probabilities have density representations.

The benefit is that the density case offers a very direct parallel to the finite case in terms of notation and intuition.

Once we've built some intuition we'll cover the general case.

20.3.1 Definitions and Basic Properties

In our lecture on finite Markov chains, we studied discrete time Markov chains that evolve on a finite state space S.

In this setting, the dynamics of the model are described by a stochastic matrix — a nonnegative square matrix $P = P[i, j]$ such that each row $P[i, \cdot]$ sums to one.

The interpretation of P is that $P[i, j]$ represents the probability of transitioning from state i to state j in one unit of time.

In symbols,

$$\mathbb{P}\{X_{t+1} = j \,|\, X_t = i\} = P[i, j]$$

Equivalently,

- P can be thought of as a family of distributions $P[i, \cdot]$, one for each $i \in S$

- $P[i, \cdot]$ is the distribution of X_{t+1} given $X_t = i$

(As you probably recall, when using Julia arrays, $P[i, \cdot]$ is expressed as `P[i,:]`)

In this section, we'll allow S to be a subset of $\mathbb{R}$, such as

- $\mathbb{R}$ itself
- the positive reals $(0, \infty)$
- a bounded interval (a, b)

The family of discrete distributions $P[i, \cdot]$ will be replaced by a family of densities $p(x, \cdot)$, one for each $x \in S$.

Analogous to the finite state case, $p(x, \cdot)$ is to be understood as the distribution (density) of X_{t+1} given $X_t = x$.

More formally, a *stochastic kernel on* S is a function $p \colon S \times S \to \mathbb{R}$ with the property that

1. $p(x, y) \geq 0$ for all $x, y \in S$
2. $\int p(x, y) dy = 1$ for all $x \in S$

(Integrals are over the whole space unless otherwise specified)

For example, let $S = \mathbb{R}$ and consider the particular stochastic kernel p_w defined by

$$p_w(x, y) := \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{(y - x)^2}{2}\right\} \tag{1}$$

What kind of model does p_w represent?

The answer is, the (normally distributed) random walk

$$X_{t+1} = X_t + \xi_{t+1} \quad \text{where} \quad \{\xi_t\} \overset{\text{IID}}{\sim} N(0, 1) \tag{2}$$

To see this, let's find the stochastic kernel p corresponding to (2).

Recall that $p(x, \cdot)$ represents the distribution of X_{t+1} given $X_t = x$.

Letting $X_t = x$ in (2) and considering the distribution of X_{t+1}, we see that $p(x, \cdot) = N(x, 1)$.

In other words, p is exactly p_w, as defined in (1).

20.3.2 Connection to Stochastic Difference Equations

In the previous section, we made the connection between stochastic difference equation (2) and stochastic kernel (1).

In economics and time series analysis we meet stochastic difference equations of all different shapes and sizes.

It will be useful for us if we have some systematic methods for converting stochastic difference equations into stochastic kernels.

To this end, consider the generic (scalar) stochastic difference equation given by

$$X_{t+1} = \mu(X_t) + \sigma(X_t)\, \xi_{t+1} \tag{3}$$

Here we assume that

- $\{\xi_t\} \overset{\text{IID}}{\sim} \phi$, where ϕ is a given density on $\mathbb{R}$
- μ and σ are given functions on S, with $\sigma(x) > 0$ for all x

Example 1: The random walk (2) is a special case of (3), with $\mu(x) = x$ and $\sigma(x) = 1$.

Example 2: Consider the ARCH model

$$X_{t+1} = \alpha X_t + \sigma_t \, \xi_{t+1}, \qquad \sigma_t^2 = \beta + \gamma X_t^2, \qquad \beta, \gamma > 0$$

Alternatively, we can write the model as

$$X_{t+1} = \alpha X_t + (\beta + \gamma X_t^2)^{1/2} \xi_{t+1} \tag{4}$$

This is a special case of (3) with $\mu(x) = \alpha x$ and $\sigma(x) = (\beta + \gamma x^2)^{1/2}$.

Example 3: With stochastic production and a constant savings rate, the one-sector neoclassical growth model leads to a law of motion for capital per worker such as

$$k_{t+1} = s A_{t+1} f(k_t) + (1 - \delta) k_t \tag{5}$$

Here

- s is the rate of savings
- A_{t+1} is a production shock
  - The $t+1$ subscript indicates that A_{t+1} is not visible at time t
- δ is a depreciation rate
- $f \colon \mathbb{R}_+ \to \mathbb{R}_+$ is a production function satisfying $f(k) > 0$ whenever $k > 0$

(The fixed savings rate can be rationalized as the optimal policy for a particular set of technologies and preferences (see [68], section 3.1.2), although we omit the details here)

Equation (5) is a special case of (3) with $\mu(x) = (1 - \delta)x$ and $\sigma(x) = s f(x)$.

Now let's obtain the stochastic kernel corresponding to the generic model (3).

To find it, note first that if U is a random variable with density f_U, and $V = a + bU$ for some constants a, b with $b > 0$, then the density of V is given by

$$f_V(v) = \frac{1}{b} f_U \left(\frac{v - a}{b} \right) \tag{6}$$

(The proof is below. For a multidimensional version see EDTC, theorem 8.1.3)

Taking (6) as given for the moment, we can obtain the stochastic kernel p for (3) by recalling that $p(x, \cdot)$ is the conditional density of X_{t+1} given $X_t = x$.

In the present case, this is equivalent to stating that $p(x, \cdot)$ is the density of $Y := \mu(x) + \sigma(x) \, \xi_{t+1}$ when $\xi_{t+1} \sim \phi$.

Hence, by (6),

$$p(x, y) = \frac{1}{\sigma(x)} \phi \left(\frac{y - \mu(x)}{\sigma(x)} \right) \tag{7}$$

For example, the growth model in (5) has stochastic kernel

$$p(x, y) = \frac{1}{sf(x)} \phi \left(\frac{y - (1 - \delta)x}{sf(x)} \right) \tag{8}$$

where ϕ is the density of A_{t+1}.

(Regarding the state space S for this model, a natural choice is $(0, \infty)$ — in which case $\sigma(x) = sf(x)$ is strictly positive for all s as required)

20.3.3 Distribution Dynamics

In this section of our lecture on **finite** Markov chains, we asked the following question: If

1. $\{X_t\}$ is a Markov chain with stochastic matrix P
2. the distribution of X_t is known to be ψ_t

then what is the distribution of X_{t+1}?

Letting ψ_{t+1} denote the distribution of X_{t+1}, the answer we gave was that

$$\psi_{t+1}[j] = \sum_{i \in S} P[i, j] \psi_t[i]$$

This intuitive equality states that the probability of being at j tomorrow is the probability of visiting i today and then going on to j, summed over all possible i.

In the density case, we just replace the sum with an integral and probability mass functions with densities, yielding

$$\psi_{t+1}(y) = \int p(x, y) \psi_t(x) \, dx, \qquad \forall y \in S \tag{9}$$

It is convenient to think of this updating process in terms of an operator.

(An operator is just a function, but the term is usually reserved for a function that sends functions into functions)

Let $\mathcal{D}$ be the set of all densities on S, and let P be the operator from $\mathcal{D}$ to itself that takes density ψ and sends it into new density ψP, where the latter is defined by

$$(\psi P)(y) = \int p(x, y) \psi(x) dx \tag{10}$$

This operator is usually called the *Markov operator* corresponding to p

> **Note**
>
> Unlike most operators, we write P to the right of its argument, instead of to the left (i.e., ψP instead of $P\psi$). This is a common convention, with the intention being to maintain the parallel with the finite case — see here.

With this notation, we can write (9) more succinctly as $\psi_{t+1}(y) = (\psi_t P)(y)$ for all y, or, dropping the y and letting "=" indicate equality of functions,

$$\psi_{t+1} = \psi_t P \tag{11}$$

Equation (11) tells us that if we specify a distribution for ψ_0, then the entire sequence of future distributions can be obtained by iterating with P.

It's interesting to note that (11) is a deterministic difference equation.

Thus, by converting a stochastic difference equation such as (3) into a stochastic kernel p and hence an operator P, we convert a stochastic difference equation into a deterministic one (albeit in a much higher dimensional space).

Note

Some people might be aware that discrete Markov chains are in fact a special case of the continuous Markov chains we have just described. The reason is that probability mass functions are densities with respect to the counting measure.

20.3.4 Computation

To learn about the dynamics of a given process, it's useful to compute and study the sequences of densities generated by the model.

One way to do this is to try to implement the iteration described by (10) and (11) using numerical integration.

However, to produce ψP from ψ via (10), you would need to integrate at every y, and there is a continuum of such y.

Another possibility is to discretize the model, but this introduces errors of unknown size.

A nicer alternative in the present setting is to combine simulation with an elegant estimator called the *look ahead* estimator.

Let's go over the ideas with reference to the growth model discussed above, the dynamics of which we repeat here for convenience:

$$k_{t+1} = sA_{t+1}f(k_t) + (1-\delta)k_t \tag{12}$$

Our aim is to compute the sequence $\{\psi_t\}$ associated with this model and fixed initial condition ψ_0.

To approximate ψ_t by simulation, recall that, by definition, ψ_t is the density of k_t given $k_0 \sim \psi_0$.

If we wish to generate observations of this random variable, all we need to do is

1. draw k_0 from the specified initial condition ψ_0
2. draw the shocks $A_1, \ldots, A_t$ from their specified density ϕ
3. compute k_t iteratively via (12)

If we repeat this n times, we get n independent observations $k_t^1, \ldots, k_t^n$.

With these draws in hand, the next step is to generate some kind of representation of their distribution ψ_t.

A naive approach would be to use a histogram, or perhaps a smoothed histogram using the `kde` function from KernelDensity.jl.

However, in the present setting there is a much better way to do this, based on the look-ahead estimator.

With this estimator, to construct an estimate of ψ_t, we actually generate n observations of k_{t-1}, rather than k_t.

Now we take these n observations $k_{t-1}^1, \ldots, k_{t-1}^n$ and form the estimate

$$\psi_t^n(y) = \frac{1}{n} \sum_{i=1}^n p(k_{t-1}^i, y) \tag{13}$$

where p is the growth model stochastic kernel in (8).

What is the justification for this slightly surprising estimator?

The idea is that, by the strong law of large numbers,

$$\frac{1}{n} \sum_{i=1}^n p(k_{t-1}^i, y) \to \mathbb{E} p(k_{t-1}^i, y) = \int p(x, y) \psi_{t-1}(x) \, dx = \psi_t(y)$$

with probability one as $n \to \infty$.

Here the first equality is by the definition of ψ_{t-1}, and the second is by (9).

We have just shown that our estimator $\psi_t^n(y)$ in (13) converges almost surely to $\psi_t(y)$, which is just what we want to compute.

In fact much stronger convergence results are true (see, for example, this paper).

20.3.5 Implementation

A function which calls an `LAE` type for estimating densities by this technique can be found in lae.jl.

This function returns the right-hand side of (13) using

- an object of type `LAE` that stores the stochastic kernel and the observations
- the value y as its second argument

The function is vectorized, in the sense that if `psi` is such an instance and `y` is an array, then the call `psi(y)` acts elementwise.

(This is the reason that we reshaped `X` and `y` inside the type — to make vectorization work)

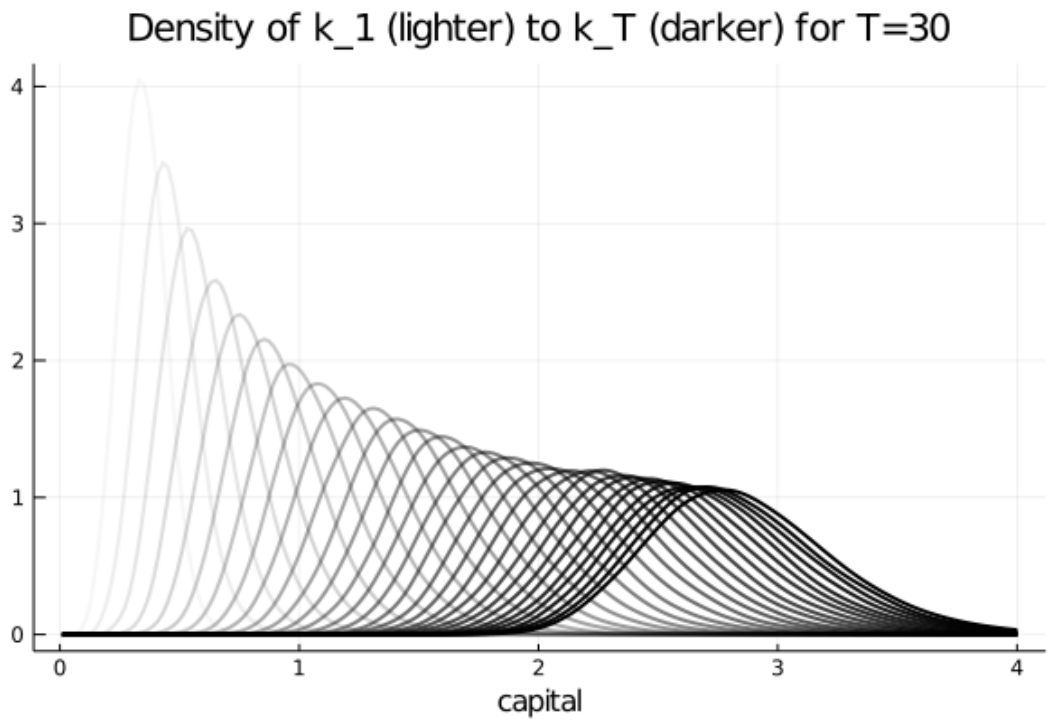
20.3.6 Example

The following code is example of usage for the stochastic growth model described above

```
In [3]: using Distributions, StatsPlots, Plots, QuantEcon, Random
        gr(fmt = :png)
        Random.seed!(42) # For deterministic results.

        s = 0.2
```

```
δ = 0.1
a_σ = 0.4                    # A = exp(B) where B ~ N(0, a_σ)
α = 0.4                      # We set f(k) = k**α
ψ_0 = Beta(5.0, 5.0)         # Initial distribution
ϕ = LogNormal(0.0, a_σ)

function p(x, y)
    # Stochastic kernel for the growth model with Cobb-Douglas production.
    # Both x and y must be strictly positive.

    d = s * x.^α

    pdf_arg = clamp.((y .- (1-δ) .* x) ./ d, eps(), Inf)
    return pdf.(ϕ, pdf_arg) ./ d
end

n = 10000  # Number of observations at each date t
T = 30     # Compute density of k_t at 1,...,T+1

# Generate matrix s.t. t-th column is n observations of k_t
k = zeros(n, T)
A = rand!(ϕ, zeros(n, T))

# Draw first column from initial distribution
k[:, 1] = rand(ψ_0, n) ./ 2  # divide by 2 to match scale = 0.5 in py version
for t in 1:T-1
    k[:, t+1] = s*A[:, t] .* k[:, t].^α + (1-δ) .* k[:, t]
end

# Generate T instances of LAE using this data, one for each date t
laes = [LAE(p, k[:, t]) for t in T:-1:1]

# Plot
ygrid = range(0.01, 4, length = 200)
laes_plot = []
colors = []
for i in 1:T
    ψ = laes[i]
    push!(laes_plot, lae_est(ψ , ygrid))
    push!(colors,  RGBA(0, 0, 0, 1 - (i - 1)/T))
end
plot(ygrid, laes_plot, color = reshape(colors, 1, length(colors)), lw = 2,
     xlabel = "capital", legend = :none)
t = "Density of k_1 (lighter) to k_T (darker) for T=$T"
plot!(title = t)
```

Out[3]:



The figure shows part of the density sequence $\{\psi_t\}$, with each density computed via the look ahead estimator.

Notice that the sequence of densities shown in the figure seems to be converging — more on this in just a moment.

Another quick comment is that each of these distributions could be interpreted as a cross sectional distribution (recall this discussion).

20.4 Beyond Densities

Up until now, we have focused exclusively on continuous state Markov chains where all conditional distributions $p(x, \cdot)$ are densities.

As discussed above, not all distributions can be represented as densities.

If the conditional distribution of X_{t+1} given $X_t = x$ **cannot** be represented as a density for some $x \in S$, then we need a slightly different theory.

The ultimate option is to switch from densities to probability measures, but not all readers will be familiar with measure theory.

We can, however, construct a fairly general theory using distribution functions.

20.4.1 Example and Definitions

To illustrate the issues, recall that Hopenhayn and Rogerson [55] study a model of firm dynamics where individual firm productivity follows the exogenous process

$$X_{t+1} = a + \rho X_t + \xi_{t+1}, \quad \text{where} \quad \{\xi_t\} \overset{\text{IID}}{\sim} N(0, \sigma^2)$$

As is, this fits into the density case we treated above.

However, the authors wanted this process to take values in $[0, 1]$, so they added boundaries at the end points 0 and 1.

One way to write this is

$$X_{t+1} = h(a + \rho X_t + \xi_{t+1}) \quad \text{where} \quad h(x) := x \, \mathbf{1}\{0 \leq x \leq 1\} + \mathbf{1}\{x > 1\}$$

If you think about it, you will see that for any given $x \in [0, 1]$, the conditional distribution of X_{t+1} given $X_t = x$ puts positive probability mass on 0 and 1.

Hence it cannot be represented as a density.

What we can do instead is use cumulative distribution functions (cdfs).

To this end, set

$$G(x, y) := \mathbb{P}\{h(a + \rho x + \xi_{t+1}) \leq y\} \qquad (0 \leq x, y \leq 1)$$

This family of cdfs $G(x, \cdot)$ plays a role analogous to the stochastic kernel in the density case.

The distribution dynamics in (9) are then replaced by

$$F_{t+1}(y) = \int G(x, y) F_t(dx) \tag{14}$$

Here F_t and F_{t+1} are cdfs representing the distribution of the current state and next period state.

The intuition behind (14) is essentially the same as for (9).

20.4.2 Computation

If you wish to compute these cdfs, you cannot use the look-ahead estimator as before.

Indeed, you should not use any density estimator, since the objects you are estimating/computing are not densities.

One good option is simulation as before, combined with the empirical distribution function.

20.5 Stability

In our lecture on finite Markov chains we also studied stationarity, stability and ergodicity.

Here we will cover the same topics for the continuous case.

We will, however, treat only the density case (as in this section), where the stochastic kernel is a family of densities.

The general case is relatively similar — references are given below.

20.5.1 Theoretical Results

Analogous to the finite case, given a stochastic kernel p and corresponding Markov operator as defined in (10), a density ψ^* on S is called *stationary* for P if it is a fixed point of the operator P.

In other words,

$$\psi^*(y) = \int p(x, y)\psi^*(x)\, dx, \qquad \forall y \in S \tag{15}$$

As with the finite case, if ψ^* is stationary for P, and the distribution of X_0 is ψ^*, then, in view of (11), X_t will have this same distribution for all t.

Hence ψ^* is the stochastic equivalent of a steady state.

In the finite case, we learned that at least one stationary distribution exists, although there may be many.

When the state space is infinite, the situation is more complicated.

Even existence can fail very easily.

For example, the random walk model has no stationary density (see, e.g., EDTC, p. 210).

However, there are well-known conditions under which a stationary density ψ^* exists.

With additional conditions, we can also get a unique stationary density ($\psi \in \mathcal{D}$ and $\psi = \psi P \implies \psi = \psi^*$), and also global convergence in the sense that

$$\forall\, \psi \in \mathcal{D}, \quad \psi P^t \to \psi^* \quad \text{as} \quad t \to \infty \tag{16}$$

This combination of existence, uniqueness and global convergence in the sense of (16) is often referred to as *global stability*.

Under very similar conditions, we get *ergodicity*, which means that

$$\frac{1}{n} \sum_{t=1}^{n} h(X_t) \to \int h(x)\psi^*(x)dx \quad \text{as } n \to \infty \tag{17}$$

for any (measurable) function $h \colon S \to \mathbb{R}$ such that the right-hand side is finite.

Note that the convergence in (17) does not depend on the distribution (or value) of X_0.

This is actually very important for simulation — it means we can learn about ψ^* (i.e., approximate the right hand side of (17) via the left hand side) without requiring any special knowledge about what to do with X_0.

So what are these conditions we require to get global stability and ergodicity?

In essence, it must be the case that

1. Probability mass does not drift off to the "edges" of the state space
2. Sufficient "mixing" obtains

For one such set of conditions see theorem 8.2.14 of EDTC.

In addition

- [100] contains a classic (but slightly outdated) treatment of these topics.
- From the mathematical literature, [64] and [77] give outstanding in depth treatments.
- Section 8.1.2 of EDTC provides detailed intuition, and section 8.3 gives additional references.
- EDTC, section 11.3.4 provides a specific treatment for the growth model we considered in this lecture.

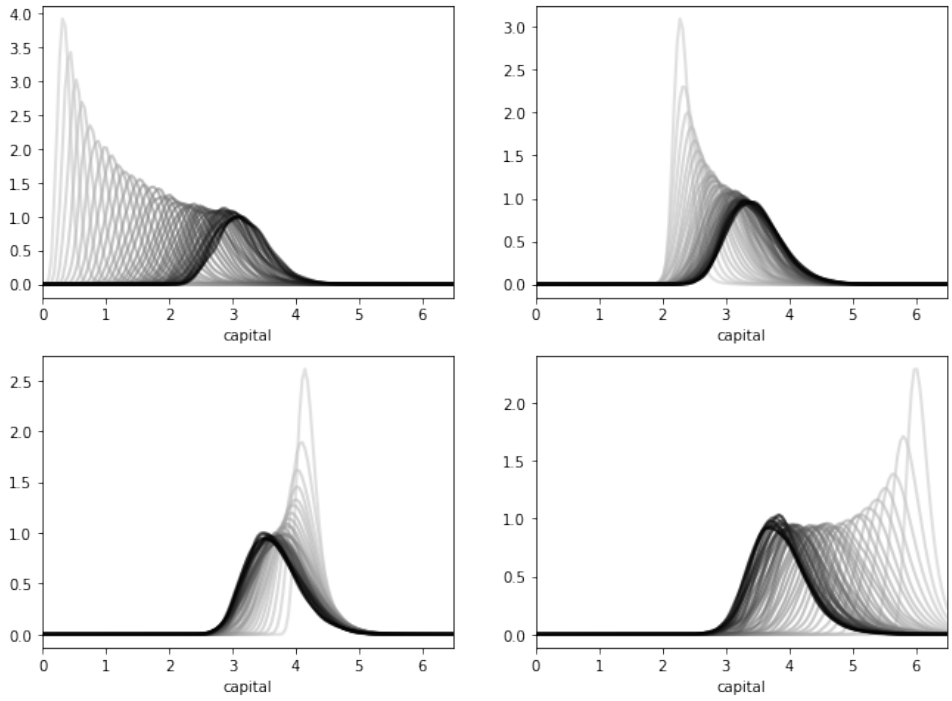
20.5.2 An Example of Stability

As stated above, the growth model treated here is stable under mild conditions on the primitives.

- See EDTC, section 11.3.4 for more details.

We can see this stability in action — in particular, the convergence in (16) — by simulating the path of densities from various initial conditions.

Here is such a figure



All sequences are converging towards the same limit, regardless of their initial condition.

The details regarding initial conditions and so on are given in this exercise, where you are asked to replicate the figure.

20.5.3 Computing Stationary Densities

In the preceding figure, each sequence of densities is converging towards the unique stationary density ψ^*.

Even from this figure we can get a fair idea what ψ^* looks like, and where its mass is located.

However, there is a much more direct way to estimate the stationary density, and it involves only a slight modification of the look ahead estimator.

Let's say that we have a model of the form (3) that is stable and ergodic.

Let p be the corresponding stochastic kernel, as given in (7).

To approximate the stationary density ψ^*, we can simply generate a long time series $X_0, X_1, \ldots, X_n$ and estimate ψ^* via

$$\psi_n^*(y) = \frac{1}{n} \sum_{t=1}^{n} p(X_t, y) \tag{18}$$

This is essentially the same as the look ahead estimator (13), except that now the observations we generate are a single time series, rather than a cross section.

The justification for (18) is that, with probability one as $n \to \infty$,

$$\frac{1}{n} \sum_{t=1}^{n} p(X_t, y) \to \int p(x, y) \psi^*(x) \, dx = \psi^*(y)$$

where the convergence is by (17) and the equality on the right is by (15).

The right hand side is exactly what we want to compute.

On top of this asymptotic result, it turns out that the rate of convergence for the look ahead estimator is very good.

The first exercise helps illustrate this point.

20.6 Exercises

20.6.1 Exercise 1

Consider the simple threshold autoregressive model

$$X_{t+1} = \theta |X_t| + (1 - \theta^2)^{1/2} \xi_{t+1} \qquad \text{where} \quad \{\xi_t\} \overset{\text{IID}}{\sim} N(0, 1) \tag{19}$$

This is one of those rare nonlinear stochastic models where an analytical expression for the stationary density is available.

In particular, provided that $|\theta| < 1$, there is a unique stationary density ψ^* given by

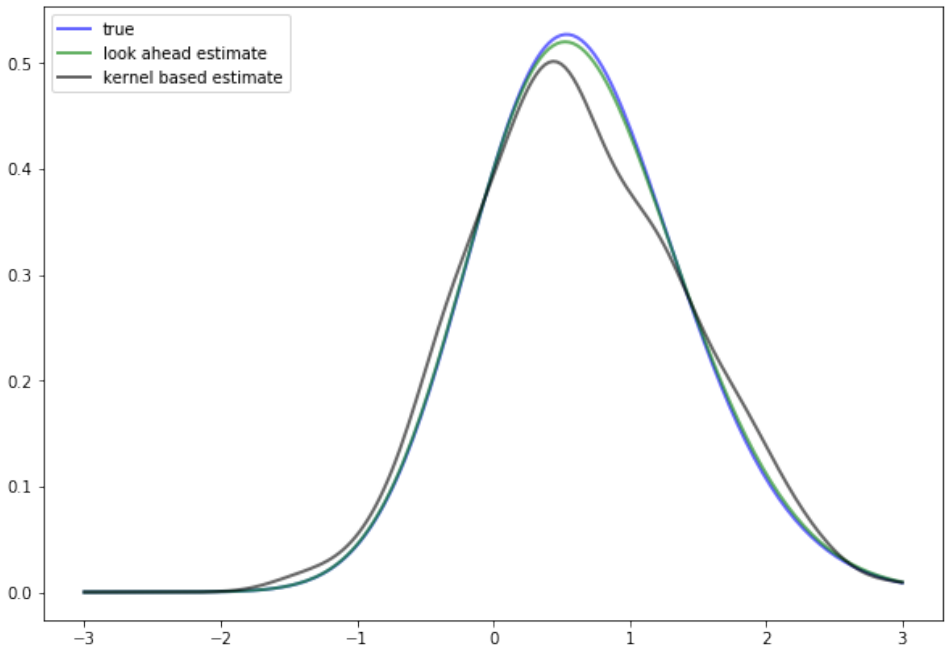
$$\psi^*(y) = 2 \, \phi(y) \, \Phi \left[\frac{\theta y}{(1 - \theta^2)^{1/2}} \right] \tag{20}$$

Here ϕ is the standard normal density and Φ is the standard normal cdf.

As an exercise, compute the look ahead estimate of ψ^*, as defined in (18), and compare it with ψ^* in (20) to see whether they are indeed close for large n.

In doing so, set $\theta = 0.8$ and $n = 500$.

The next figure shows the result of such a computation



The additional density (black line) is a nonparametric kernel density estimate, added to the solution for illustration.

(You can try to replicate it before looking at the solution if you want to)

As you can see, the look ahead estimator is a much tighter fit than the kernel density estimator.

If you repeat the simulation you will see that this is consistently the case.

20.6.2 Exercise 2

Replicate the figure on global convergence shown above.

The densities come from the stochastic growth model treated at the start of the lecture.

Begin with the code found in stochasticgrowth.py.

Use the same parameters.

For the four initial distributions, use the beta distribution and shift the random draws as shown below

```
ψ_0 = Beta(5.0, 5.0)  # Initial distribution
n = 1000
# .... more setup

for i in 1:4
    # .... some code
    rand_draws = (rand(ψ_0, n) .+ 2.5i) ./ 2
```

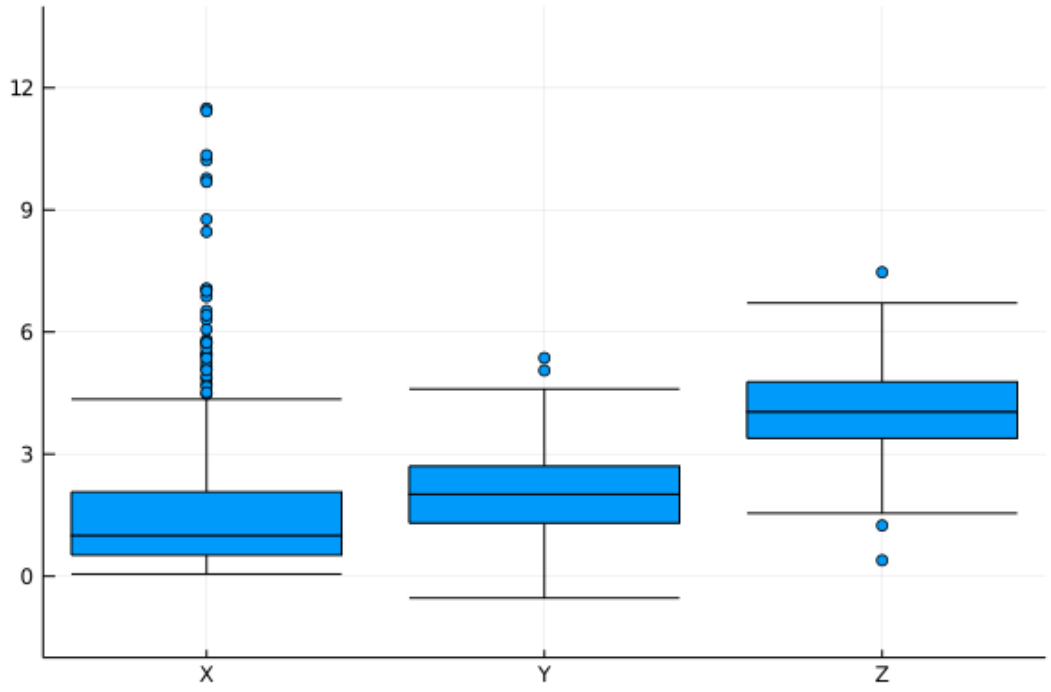
20.6.3 Exercise 3

A common way to compare distributions visually is with boxplots.

To illustrate, let's generate three artificial data sets and compare them with a boxplot

In [4]:
```
n = 500
x = randn(n)          # N(0, 1)
x = exp.(x)           # Map x to lognormal
y = randn(n) .+ 2.0   # N(2, 1)
z = randn(n) .+ 4.0   # N(4, 1)
data = vcat(x, y, z)
l = ["X" "Y" "Z"]
xlabels = reshape(repeat(l, n), 3n, 1)

boxplot(xlabels, data, label = "", ylims = (-2, 14))
```

Out[4]:



The three data sets are

$$\{X_1, \ldots, X_n\} \sim LN(0,1), \quad \{Y_1, \ldots, Y_n\} \sim N(2,1), \quad \text{and} \quad \{Z_1, \ldots, Z_n\} \sim N(4,1),$$

The figure looks as follows.

Each data set is represented by a box, where the top and bottom of the box are the third and first quartiles of the data, and the red line in the center is the median.

The boxes give some indication as to

- the location of probability mass for each sample
- whether the distribution is right-skewed (as is the lognormal distribution), etc

Now let's put these ideas to use in a simulation.

Consider the threshold autoregressive model in (19).

We know that the distribution of X_t will converge to (20) whenever $|\theta| < 1$.

Let's observe this convergence from different initial conditions using boxplots.

In particular, the exercise is to generate J boxplot figures, one for each initial condition X_0 in

```
initial_conditions = range(8, 0, length = J)
```

For each X_0 in this set,

1. Generate k time series of length n, each starting at X_0 and obeying (19).
2. Create a boxplot representing n distributions, where the t-th distribution shows the k observations of X_t.

Use $\theta = 0.9, n = 20, k = 5000, J = 8$.

20.7 Solutions

```
In [5]: using KernelDensity
```

20.7.1 Exercise 1

Look ahead estimation of a TAR stationary density, where the TAR model is

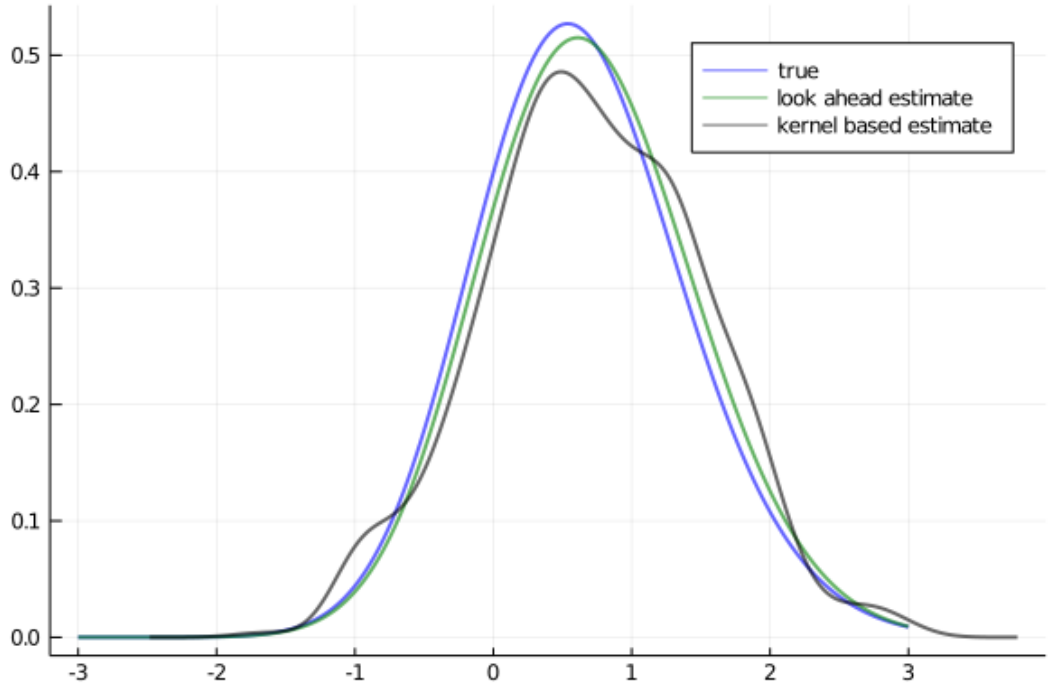
$$X_{t+1} = \theta|X_t| + (1 - \theta^2)^{1/2}\xi_{t+1}$$

and $\xi_t \sim N(0, 1)$. Try running at n = 10, 100, 1000, 10000 to get an idea of the speed of convergence.

```
In [6]: ϕ = Normal()
        n = 500
        θ = 0.8
        d = sqrt(1.0 - θ^2)
        δ = θ / d

        # true density of TAR model
        ψ_star(y) = 2 .* pdf.(ϕ, y) .* cdf.(ϕ, δ * y)

        # Stochastic kernel for the TAR model.
        p_TAR(x, y) = pdf.(ϕ, (y .- θ .* abs.(x)) ./ d) ./ d

        Z = rand(ϕ, n)
        X = zeros(n)
        for t in 1:n-1
            X[t+1] = θ * abs(X[t]) + d * Z[t]
        end
```

```
ψ_est(a) = lae_est(LAE(p_TAR, X), a)
k_est = kde(X)

ys = range(-3, 3, length = 200)
plot(ys, ψ_star(ys), color=:blue, lw = 2, alpha = 0.6, label = "true")
plot!(ys, ψ_est(ys), color=:green, lw = 2, alpha = 0.6, label = "look
↪ahead estimate")
plot!(k_est.x, k_est.density, color = :black, lw = 2, alpha = 0.6,
      label = "kernel based estimate")
```

Out[6]:



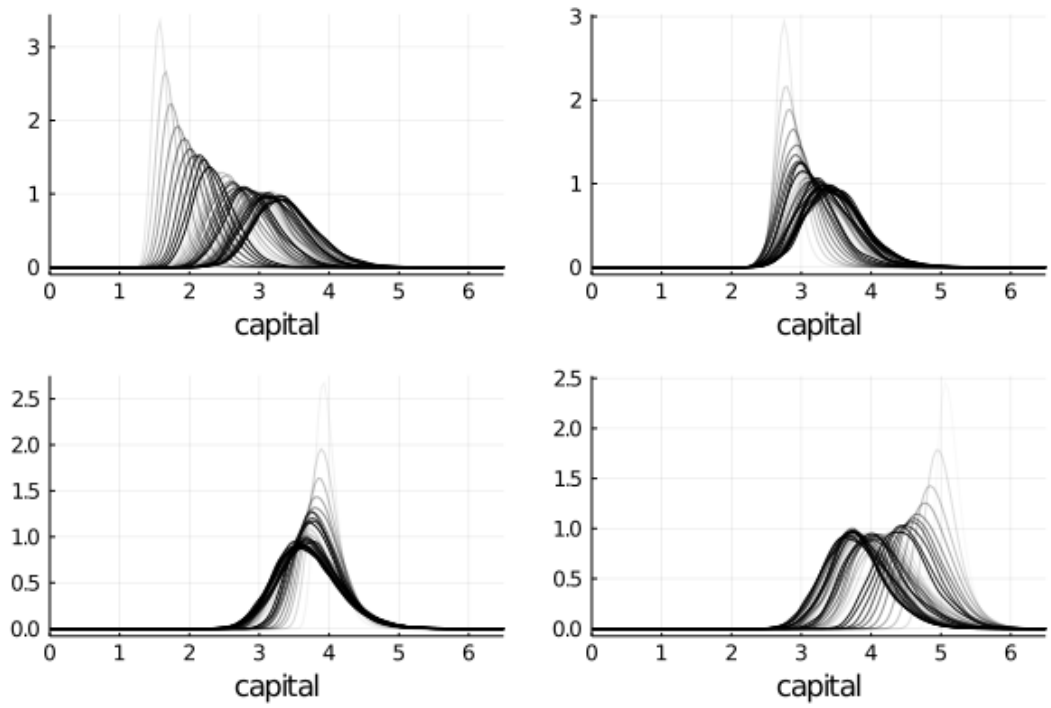
20.7.2 Exercise 2

Here's one program that does the job.

In [7]:
```
s = 0.2
δ = 0.1
a_σ = 0.4  # A = exp(B) where B ~ N(0, a_σ)
α = 0.4    # We set f(k) = k**α
ψ_0 = Beta(5.0, 5.0)  # Initial distribution
ϕ = LogNormal(0.0, a_σ)

function p_growth(x, y)
    # Stochastic kernel for the growth model with Cobb-Douglas production.
    # Both x and y must be strictly positive.

        d = s * x.^α

    pdf_arg = clamp.((y .- (1-δ) .* x) ./ d, eps(), Inf)
    return pdf.(ϕ, pdf_arg) ./ d
```

```
end

n = 1000  # Number of observations at each date t
T = 40    # Compute density of k_t at 1,...,T+1

xmax = 6.5
ygrid = range(0.01, xmax, length = 150)
laes_plot = zeros(length(ygrid), 4T)
colors = []
for i in 1:4
    k = zeros(n, T)
    A = rand!(ϕ, zeros(n, T))

    # Draw first column from initial distribution
    # match scale = 0.5 and loc = 2i in julia version
    k[:, 1] = (rand(ψ_0, n) .+ 2.5i) ./ 2
    for t in 1:T-1
        k[:, t+1] = s * A[:, t] .* k[:, t].^α + (1 - δ) .* k[:, t]
    end

    # Generate T instances of LAE using this data, one for each date t
    laes = [LAE(p_growth, k[:, t]) for t in T:-1:1]
    ind = i
    for j in 1:T
        ψ = laes[j]
        laes_plot[:, ind] = lae_est(ψ, ygrid)
        ind = ind + 4
        push!(colors,  RGBA(0, 0, 0, 1 - (j - 1) / T))
    end
end

#colors = reshape(reshape(colors, T, 4)', 4*T, 1)
colors = reshape(colors, 1, length(colors))
plot(ygrid, laes_plot, layout = (2,2), color = colors,
     legend = :none, xlabel = "capital", xlims = (0, xmax))
```

Out[7]:



20.7.3 Exercise 3

Here's a possible solution.

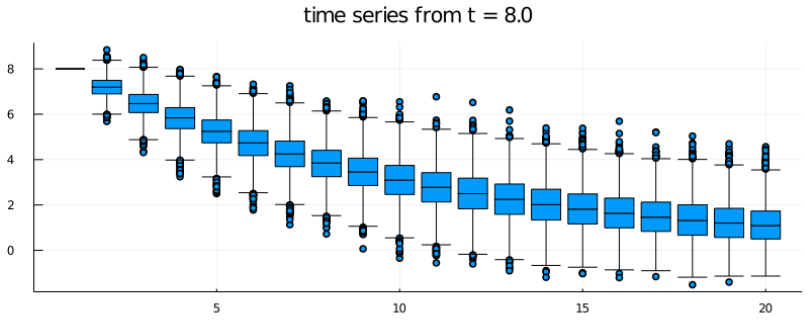
Note the way we use vectorized code to simulate the k time series for one boxplot all at once.

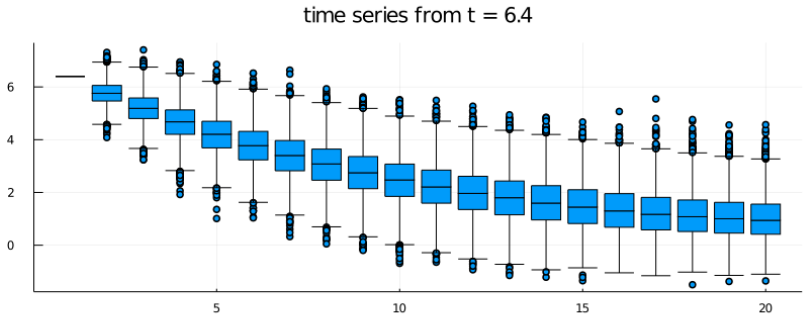
```
In [8]: n = 20
        k = 5000
        J = 6

        θ = 0.9
        d = sqrt(1 - θ^2)
        δ = θ / d

        initial_conditions = range(8, 0, length = J)

        Z = randn(k, n, J)
        titles = []
        data = []
        x_labels = []
        for j in 1:J
            title = "time series from t = $(initial_conditions[j])"
            push!(titles, title)

            X = zeros(k, n)
            X[:, 1] .= initial_conditions[j]
            labels = []
            labels = vcat(labels, ones(k, 1))
            for t in 2:n
                X[:, t] = θ .* abs.(X[:, t-1]) .+ d .* Z[:, t, j]
                labels = vcat(labels, t*ones(k, 1))
            end
            X = reshape(X, n*k, 1)
```

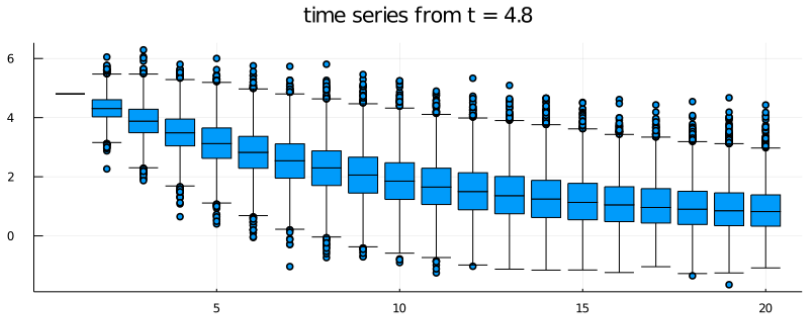
```
        push!(data, X)
        push!(x_labels, labels)
    end
```

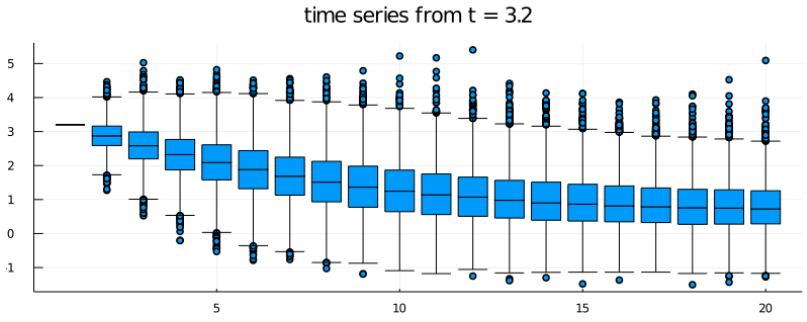
In [9]:
```
plots = []
for i in 1:J
   push!(plots, boxplot(vec(x_labels[i]), vec(data[i]), title = titles[i]))
end
plot(plots..., layout = (J, 1), legend = :none, size = (800, 2000))
```

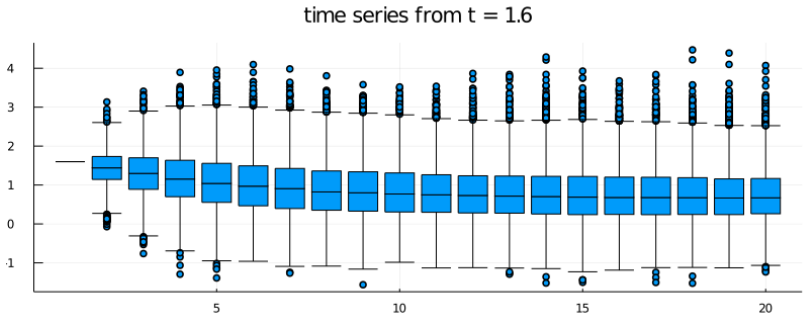
Out[9]:

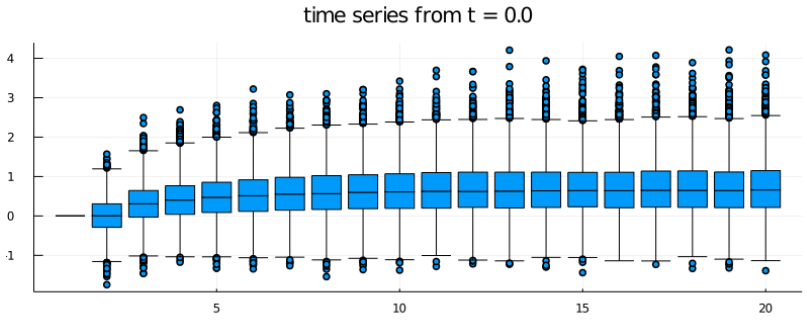

time series from t = 8.0


time series from t = 6.4


time series from t = 4.8


time series from t = 3.2


time series from t = 1.6


time series from t = 0.0

20.8 Appendix

Here's the proof of (6).

Let F_U and F_V be the cumulative distributions of U and V respectively.

By the definition of V, we have $F_V(v) = \mathbb{P}\{a + bU \leq v\} = \mathbb{P}\{U \leq (v-a)/b\}$.

In other words, $F_V(v) = F_U((v-a)/b)$.

Differentiating with respect to v yields (6).

Chapter 21

A First Look at the Kalman Filter

21.1 Contents

21.2 Overview

This lecture provides a simple and intuitive introduction to the Kalman filter, for those who either

- have heard of the Kalman filter but don't know how it works, or
- know the Kalman filter equations, but don't know where they come from

For additional (more advanced) reading on the Kalman filter, see

- [68], section 2.7.
- [3]

The second reference presents a comprehensive treatment of the Kalman filter.

Required knowledge: Familiarity with matrix manipulations, multivariate normal distributions, covariance matrices, etc.

21.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

21.3 The Basic Idea

The Kalman filter has many applications in economics, but for now let's pretend that we are rocket scientists.

A missile has been launched from country Y and our mission is to track it.

Let $x \in \mathbb{R}^2$ denote the current location of the missile—a pair indicating latitude-longitude coordinates on a map.

At the present moment in time, the precise location x is unknown, but we do have some beliefs about x.

One way to summarize our knowledge is a point prediction $\hat{x}$

- But what if the President wants to know the probability that the missile is currently over the Sea of Japan?
- Then it is better to summarize our initial beliefs with a bivariate probability density p.
  - $\int_E p(x)dx$ indicates the probability that we attach to the missile being in region E

The density p is called our *prior* for the random variable x.

To keep things tractable in our example, we assume that our prior is Gaussian. In particular, we take

$$p = N(\hat{x}, \Sigma) \tag{1}$$

where $\hat{x}$ is the mean of the distribution and Σ is a 2×2 covariance matrix. In our simulations, we will suppose that

$$\hat{x} = \begin{pmatrix} 0.2 \\ -0.2 \end{pmatrix}, \qquad \Sigma = \begin{pmatrix} 0.4 & 0.3 \\ 0.3 & 0.45 \end{pmatrix} \tag{2}$$

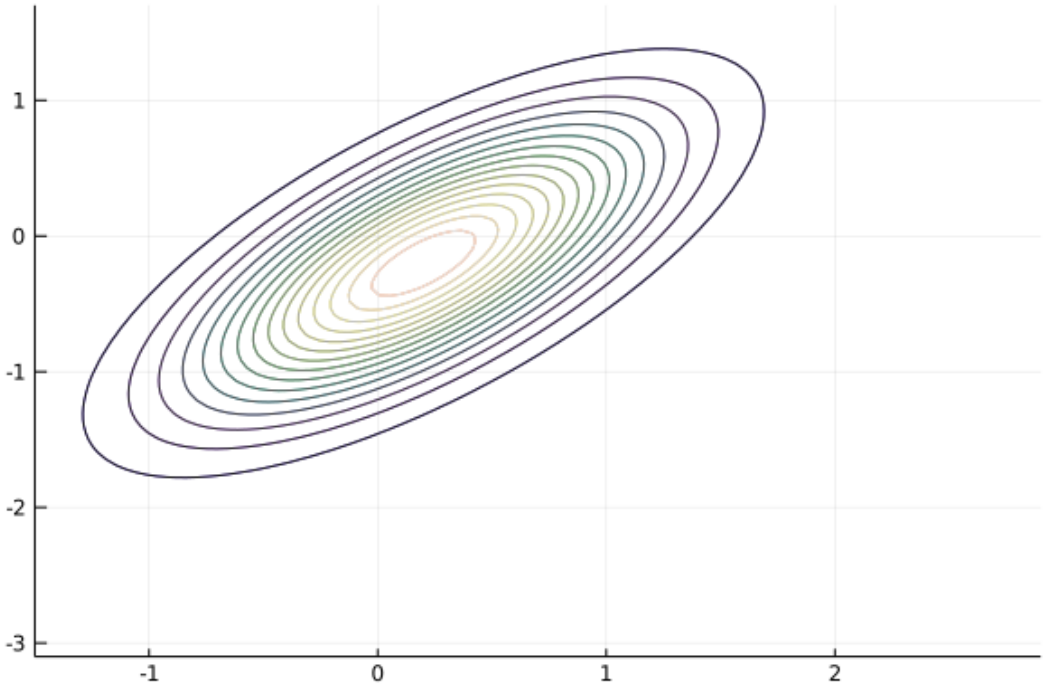
This density $p(x)$ is shown below as a contour map, with the center of the red ellipse being equal to $\hat{x}$

```
In [3]: using Plots, Distributions
        gr(fmt = :png); # plots setup
```

```
In [4]: # set up prior objects
        Σ = [0.4  0.3
             0.3  0.45]
        x̂ = [0.2, -0.2]

        # define G and R from the equation y = Gx + N(0, R)
        G = I # this is a generic identity object that conforms to the right
      ↪dimensions
        R = 0.5 .* Σ

        # define A and Q
        A = [1.2  0
             0   -0.2]
        Q = 0.3Σ

        y = [2.3, -1.9]
```

```
        # plotting objects
        x_grid = range(-1.5, 2.9, length = 100)
        y_grid = range(-3.1, 1.7, length = 100)

        # generate distribution
        dist = MvNormal(x̄, Σ)
        two_args_to_pdf(dist) = (x, y) -> pdf(dist, [x, y]) # returns a function
↪to be plotted

        # plot
        contour(x_grid, y_grid, two_args_to_pdf(dist), fill = false,
                color = :lighttest, cbar = false)
        contour!(x_grid, y_grid, two_args_to_pdf(dist), fill = false, lw=1,
                 color = :grays, cbar = false)
```

Out[4]:



21.3.1 The Filtering Step

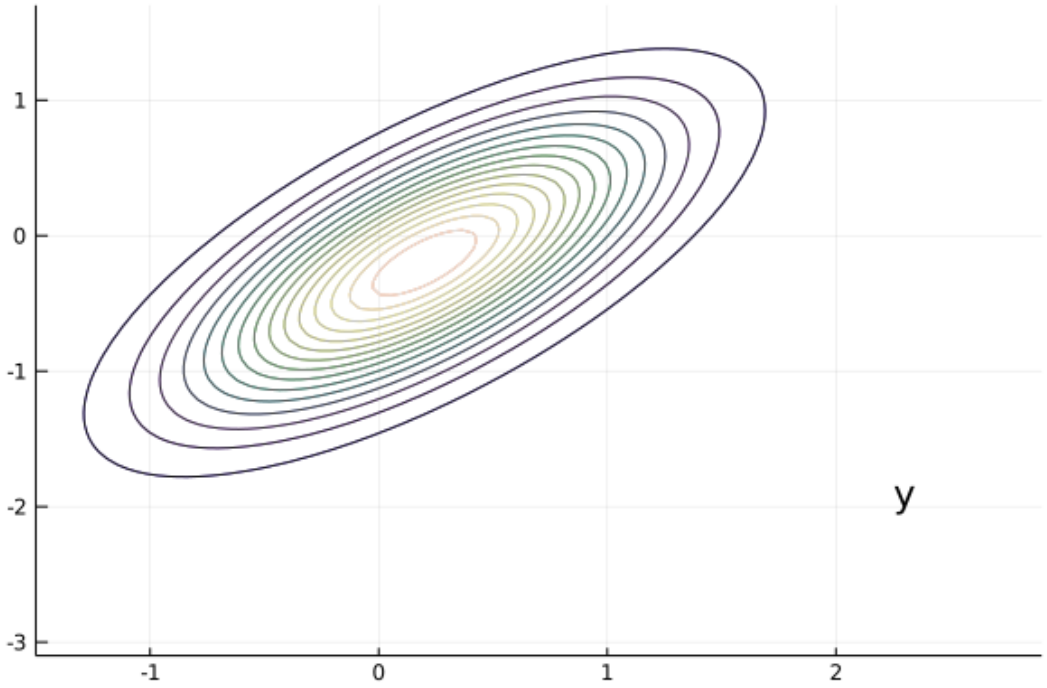
We are now presented with some good news and some bad news.

The good news is that the missile has been located by our sensors, which report that the current location is $y = (2.3, -1.9)$.

The next figure shows the original prior $p(x)$ and the new reported location y

In [5]:
```
        # plot the figure
        annotate!(y[1], y[2], "y", color = :black)
```

Out[5]:



The bad news is that our sensors are imprecise.

In particular, we should interpret the output of our sensor not as $y = x$, but rather as

$$y = Gx + v, \quad \text{where} \quad v \sim N(0, R) \tag{3}$$

Here G and R are 2×2 matrices with R positive definite. Both are assumed known, and the noise term v is assumed to be independent of x.

How then should we combine our prior $p(x) = N(\hat{x}, \Sigma)$ and this new information y to improve our understanding of the location of the missile?

As you may have guessed, the answer is to use Bayes' theorem, which tells us to update our prior $p(x)$ to $p(x \,|\, y)$ via

$$p(x \,|\, y) = \frac{p(y \,|\, x)\, p(x)}{p(y)}$$

where $p(y) = \int p(y \,|\, x)\, p(x) dx$.

In solving for $p(x \,|\, y)$, we observe that

- $p(x) = N(\hat{x}, \Sigma)$
- In view of (3), the conditional density $p(y \,|\, x)$ is $N(Gx, R)$
- $p(y)$ does not depend on x, and enters into the calculations only as a normalizing constant

Because we are in a linear and Gaussian framework, the updated density can be computed by calculating population linear regressions.

In particular, the solution is known Section **??** to be

$$p(x \,|\, y) = N(\hat{x}^F, \Sigma^F)$$

where

$$\hat{x}^F := \hat{x} + \Sigma G'(G\Sigma G' + R)^{-1}(y - G\hat{x}) \quad \text{and} \quad \Sigma^F := \Sigma - \Sigma G'(G\Sigma G' + R)^{-1}G\Sigma \tag{4}$$

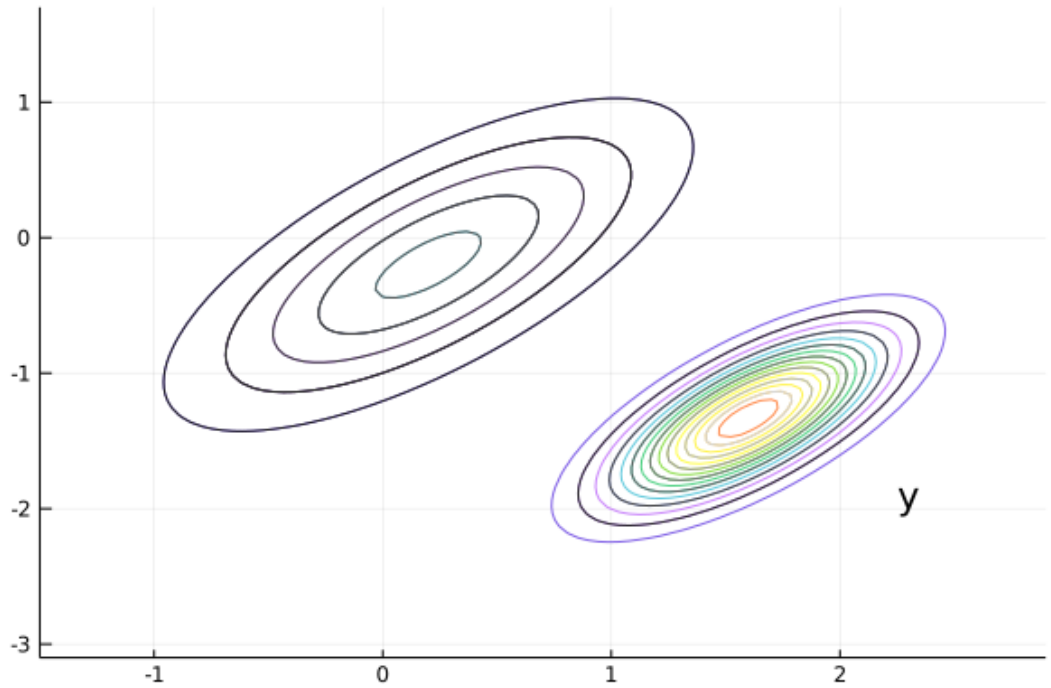
Here $\Sigma G'(G\Sigma G' + R)^{-1}$ is the matrix of population regression coefficients of the hidden object $x - \hat{x}$ on the surprise $y - G\hat{x}$.

This new density $p(x \mid y) = N(\hat{x}^F, \Sigma^F)$ is shown in the next figure via contour lines and the color map.

The original density is left in as contour lines for comparison

In [6]:
```
# define posterior objects
M = Σ * G' * inv(G * Σ * G' + R)
x̂_F = x̂ + M * (y - G * x̂)
Σ_F = Σ - M * G * Σ

# plot the new density on the old plot
newdist = MvNormal(x̂_F, Symmetric(Σ_F)) # because Σ_F
contour!(x_grid, y_grid, two_args_to_pdf(newdist), fill = false,
         color = :lighttest, cbar = false)
contour!(x_grid, y_grid, two_args_to_pdf(newdist), fill = false, levels = 7,
         color = :grays, cbar = false)
contour!(x_grid, y_grid, two_args_to_pdf(dist), fill = false, levels = 7,
↪lw=1,
         color = :grays, cbar = false)
```

Out[6]:



Our new density twists the prior $p(x)$ in a direction determined by the new information $y - G\hat{x}$.

In generating the figure, we set G to the identity matrix and $R = 0.5\Sigma$ for Σ defined in (2).

21.3.2 The Forecast Step

What have we achieved so far?

We have obtained probabilities for the current location of the state (missile) given prior and current information.

This is called "filtering" rather than forecasting, because we are filtering out noise rather than looking into the future

- $p(x \mid y) = N(\hat{x}^F, \Sigma^F)$ is called the *filtering distribution*

But now let's suppose that we are given another task: to predict the location of the missile after one unit of time (whatever that may be) has elapsed.

To do this we need a model of how the state evolves.

Let's suppose that we have one, and that it's linear and Gaussian. In particular,

$$x_{t+1} = Ax_t + w_{t+1}, \quad \text{where} \quad w_t \sim N(0, Q) \tag{5}$$

Our aim is to combine this law of motion and our current distribution $p(x \mid y) = N(\hat{x}^F, \Sigma^F)$ to come up with a new *predictive* distribution for the location in one unit of time.

In view of (5), all we have to do is introduce a random vector $x^F \sim N(\hat{x}^F, \Sigma^F)$ and work out the distribution of $Ax^F + w$ where w is independent of x^F and has distribution $N(0, Q)$.

Since linear combinations of Gaussians are Gaussian, $Ax^F + w$ is Gaussian.

Elementary calculations and the expressions in (4) tell us that

$$\mathbb{E}[Ax^F + w] = A\mathbb{E}x^F + \mathbb{E}w = A\hat{x}^F = A\hat{x} + A\Sigma G'(G\Sigma G' + R)^{-1}(y - G\hat{x})$$

and

$$\operatorname{Var}[Ax^F + w] = A \operatorname{Var}[x^F]A' + Q = A\Sigma^F A' + Q = A\Sigma A' - A\Sigma G'(G\Sigma G' + R)^{-1}G\Sigma A' + Q$$

The matrix $A\Sigma G'(G\Sigma G' + R)^{-1}$ is often written as K_Σ and called the *Kalman gain*.

- The subscript Σ has been added to remind us that K_Σ depends on Σ, but not y or $\hat{x}$.

Using this notation, we can summarize our results as follows.

Our updated prediction is the density $N(\hat{x}_{new}, \Sigma_{new})$ where

$$\begin{aligned} \hat{x}_{new} &:= A\hat{x} + K_\Sigma(y - G\hat{x}) \\ \Sigma_{new} &:= A\Sigma A' - K_\Sigma G\Sigma A' + Q \end{aligned} \tag{6}$$

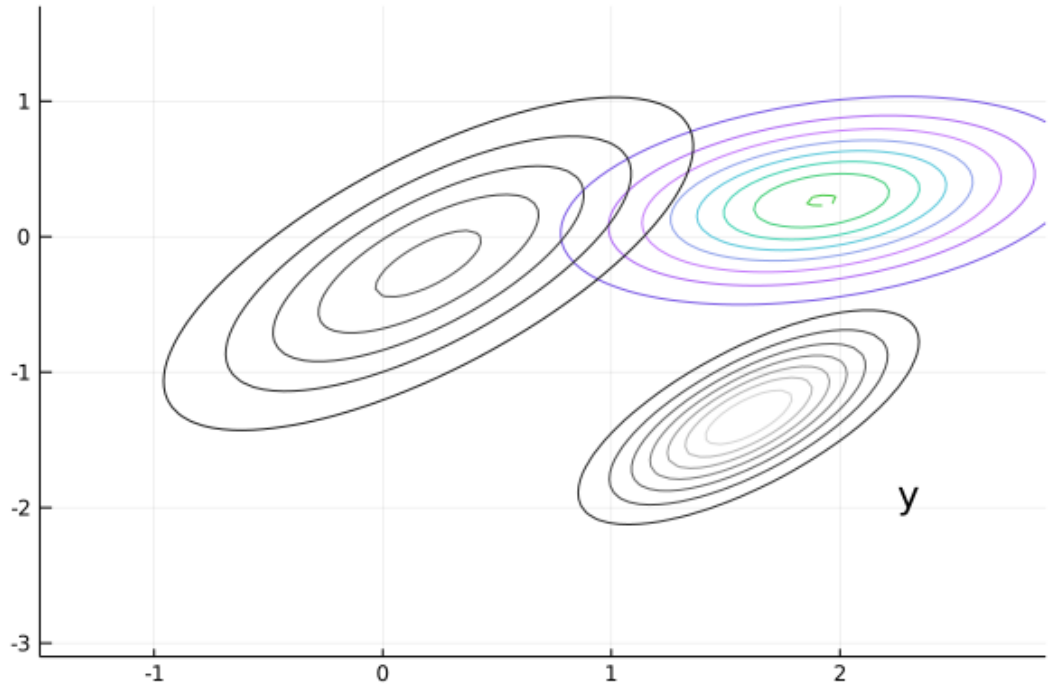
- The density $p_{new}(x) = N(\hat{x}_{new}, \Sigma_{new})$ is called the *predictive distribution*.

The predictive distribution is the new density shown in the following figure, where the update has used parameters

$$A = \begin{pmatrix} 1.2 & 0.0 \\ 0.0 & -0.2 \end{pmatrix}, \qquad Q = 0.3 * \Sigma$$

In [7]:
```
# get the predictive distribution
new_x = A * x_F
new_Σ = A * Σ_F * A' + Q
predictdist = MvNormal(new_x, Symmetric(new_Σ))

# plot Density 3
contour(x_grid, y_grid, two_args_to_pdf(predictdist), fill = false, lw = 1,
        color = :lighttest, cbar = false)
contour!(x_grid, y_grid, two_args_to_pdf(dist),
         color = :grays, cbar = false)
contour!(x_grid, y_grid, two_args_to_pdf(newdist), fill = false, levels = 7,
         color = :grays, cbar = false)
annotate!(y[1], y[2], "y", color = :black)
```

Out[7]:



21.3.3 The Recursive Procedure

Let's look back at what we've done.

We started the current period with a prior $p(x)$ for the location x of the missile.

We then used the current measurement y to update to $p(x \mid y)$.

Finally, we used the law of motion (5) for $\{x_t\}$ to update to $p_{new}(x)$.

If we now step into the next period, we are ready to go round again, taking $p_{new}(x)$ as the current prior.

Swapping notation $p_t(x)$ for $p(x)$ and $p_{t+1}(x)$ for $p_{new}(x)$, the full recursive procedure is:

1. Start the current period with prior $p_t(x) = N(\hat{x}_t, \Sigma_t)$.
2. Observe current measurement y_t.
3. Compute the filtering distribution $p_t(x \mid y) = N(\hat{x}_t^F, \Sigma_t^F)$ from $p_t(x)$ and y_t, applying Bayes rule and the conditional distribution (3).
4. Compute the predictive distribution $p_{t+1}(x) = N(\hat{x}_{t+1}, \Sigma_{t+1})$ from the filtering distribution and (5).
5. Increment t by one and go to step 1.

Repeating (6), the dynamics for $\hat{x}_t$ and Σ_t are as follows

$$\begin{aligned} \hat{x}_{t+1} &= A\hat{x}_t + K_{\Sigma_t}(y_t - G\hat{x}_t) \\ \Sigma_{t+1} &= A\Sigma_t A' - K_{\Sigma_t} G\Sigma_t A' + Q \end{aligned} \tag{7}$$

These are the standard dynamic equations for the Kalman filter (see, for example, [68], page 58).

21.4 Convergence

The matrix Σ_t is a measure of the uncertainty of our prediction $\hat{x}_t$ of x_t.

Apart from special cases, this uncertainty will never be fully resolved, regardless of how much time elapses.

One reason is that our prediction $\hat{x}_t$ is made based on information available at $t-1$, not t.

Even if we know the precise value of x_{t-1} (which we don't), the transition equation (5) implies that $x_t = Ax_{t-1} + w_t$.

Since the shock w_t is not observable at $t-1$, any time $t-1$ prediction of x_t will incur some error (unless w_t is degenerate).

However, it is certainly possible that Σ_t converges to a constant matrix as $t \to \infty$.

To study this topic, let's expand the second equation in (7):

$$\Sigma_{t+1} = A\Sigma_t A' - A\Sigma_t G'(G\Sigma_t G' + R)^{-1} G\Sigma_t A' + Q \tag{8}$$

This is a nonlinear difference equation in Σ_t.

A fixed point of (8) is a constant matrix Σ such that

$$\Sigma = A\Sigma A' - A\Sigma G'(G\Sigma G' + R)^{-1} G\Sigma A' + Q \tag{9}$$

Equation (8) is known as a discrete time Riccati difference equation.

Equation (9) is known as a discrete time algebraic Riccati equation.

Conditions under which a fixed point exists and the sequence $\{\Sigma_t\}$ converges to it are discussed in [4] and [3], chapter 4.

A sufficient (but not necessary) condition is that all the eigenvalues λ_i of A satisfy $|\lambda_i| < 1$ (cf. e.g., [3], p. 77).

(This strong condition assures that the unconditional distribution of x_t converges as $t \to +\infty$)

In this case, for any initial choice of Σ_0 that is both nonnegative and symmetric, the sequence $\{\Sigma_t\}$ in (8) converges to a nonnegative symmetric matrix Σ that solves (9).

21.5 Implementation

The QuantEcon.jl package is able to implement the Kalman filter by using methods for the type `Kalman`

- Instance data consists of:
  - The parameters A, G, Q, R of a given model
  - the moments $(\hat{x}_t, \Sigma_t)$ of the current prior
- The type `Kalman` from the QuantEcon.jl package has a number of methods, some that we will wait to use until we study more advanced applications in subsequent lectures.
- Methods pertinent for this lecture are:
  - `prior_to_filtered`, which updates $(\hat{x}_t, \Sigma_t)$ to $(\hat{x}_t^F, \Sigma_t^F)$
  - `filtered_to_forecast`, which updates the filtering distribution to the predictive distribution – which becomes the new prior $(\hat{x}_{t+1}, \Sigma_{t+1})$
  - `update`, which combines the last two methods
  - a `stationary_values`, which computes the solution to (9) and the corresponding (stationary) Kalman gain

You can view the program on GitHub.

21.6 Exercises

21.6.1 Exercise 1

Consider the following simple application of the Kalman filter, loosely based on [68], section 2.9.2.

Suppose that

- all variables are scalars
- the hidden state $\{x_t\}$ is in fact constant, equal to some $\theta \in \mathbb{R}$ unknown to the modeler

State dynamics are therefore given by (5) with $A = 1$, $Q = 0$ and $x_0 = \theta$.

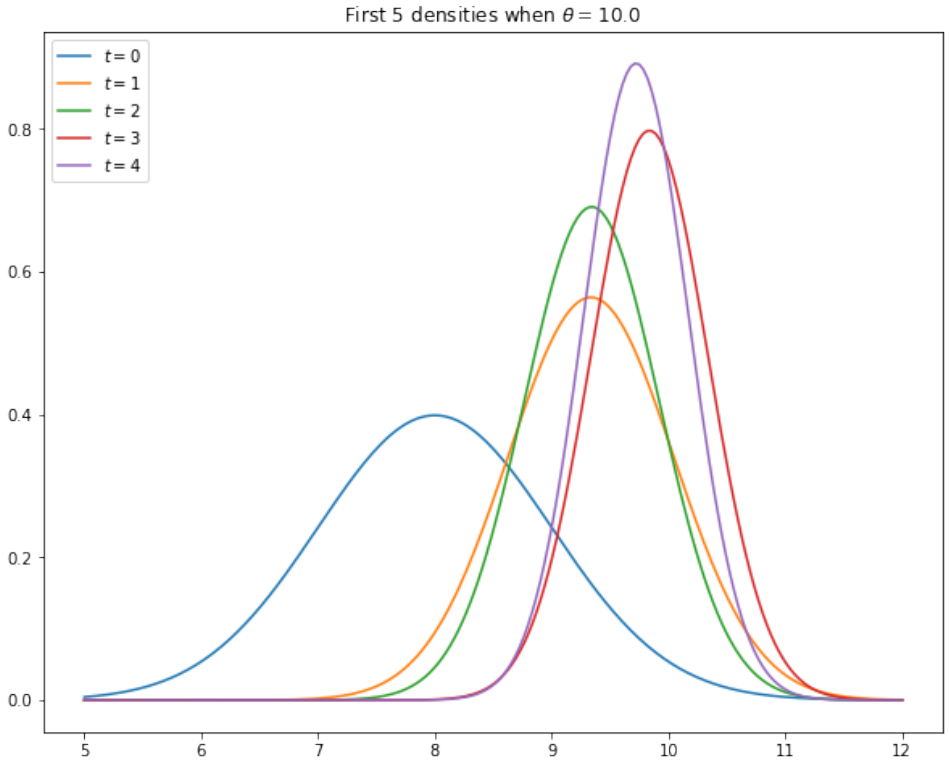
The measurement equation is $y_t = \theta + v_t$ where v_t is $N(0, 1)$ and iid.

The task of this exercise to simulate the model and, using the code from `kalman.jl`, plot the first five predictive densities $p_t(x) = N(\hat{x}_t, \Sigma_t)$.

As shown in [68], sections 2.9.1–2.9.2, these distributions asymptotically put all mass on the unknown value θ.

In the simulation, take $\theta = 10$, $\hat{x}_0 = 8$ and $\Sigma_0 = 1$.

Your figure should – modulo randomness – look something like this



21.6.2 Exercise 2

The preceding figure gives some support to the idea that probability mass converges to θ.

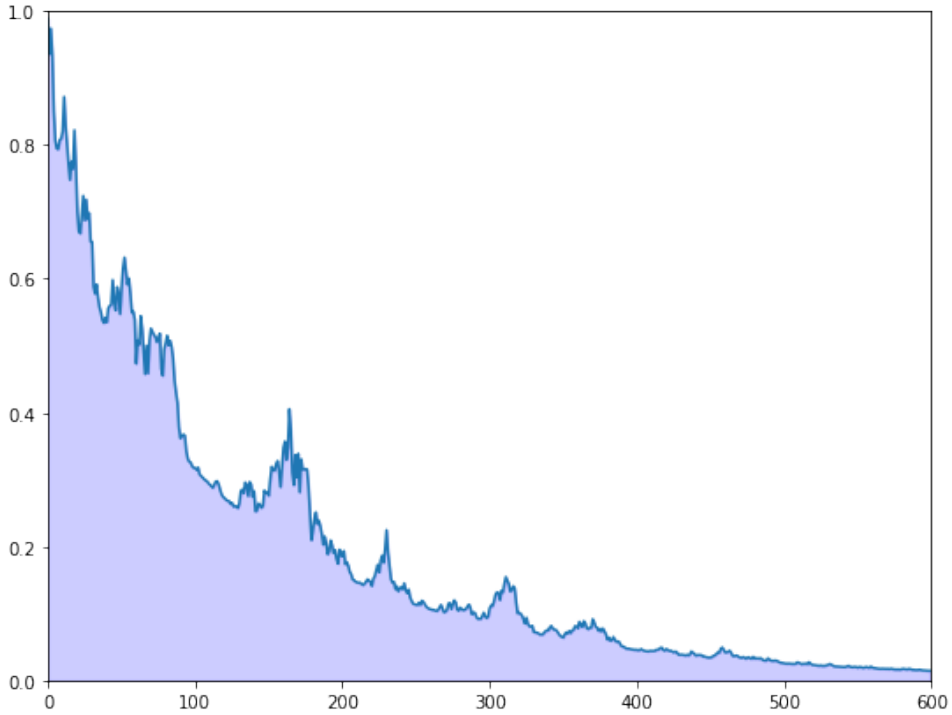
To get a better idea, choose a small $\epsilon > 0$ and calculate

$$z_t := 1 - \int_{\theta-\epsilon}^{\theta+\epsilon} p_t(x)dx$$

for $t = 0, 1, 2, \ldots, T$.

Plot z_t against T, setting $\epsilon = 0.1$ and $T = 600$.

Your figure should show error erratically declining something like this



21.6.3 Exercise 3

As discussed above, if the shock sequence $\{w_t\}$ is not degenerate, then it is not in general possible to predict x_t without error at time $t-1$ (and this would be the case even if we could observe x_{t-1}).

Let's now compare the prediction $\hat{x}_t$ made by the Kalman filter against a competitor who **is** allowed to observe x_{t-1}.

This competitor will use the conditional expectation $\mathbb{E}[x_t \,|\, x_{t-1}]$, which in this case is Ax_{t-1}.

The conditional expectation is known to be the optimal prediction method in terms of minimizing mean squared error.

(More precisely, the minimizer of $\mathbb{E}\,\|x_t - g(x_{t-1})\|^2$ with respect to g is $g^*(x_{t-1}) := \mathbb{E}[x_t \,|\, x_{t-1}]$)

Thus we are comparing the Kalman filter against a competitor who has more information (in the sense of being able to observe the latent state) and behaves optimally in terms of minimizing squared error.

Our horse race will be assessed in terms of squared error.

In particular, your task is to generate a graph plotting observations of both $\|x_t - Ax_{t-1}\|^2$ and $\|x_t - \hat{x}_t\|^2$ against t for $t = 1, \ldots, 50$.

For the parameters, set $G = I, R = 0.5I$ and $Q = 0.3I$, where I is the 2×2 identity.

Set

$$A = \begin{pmatrix} 0.5 & 0.4 \\ 0.6 & 0.3 \end{pmatrix}$$

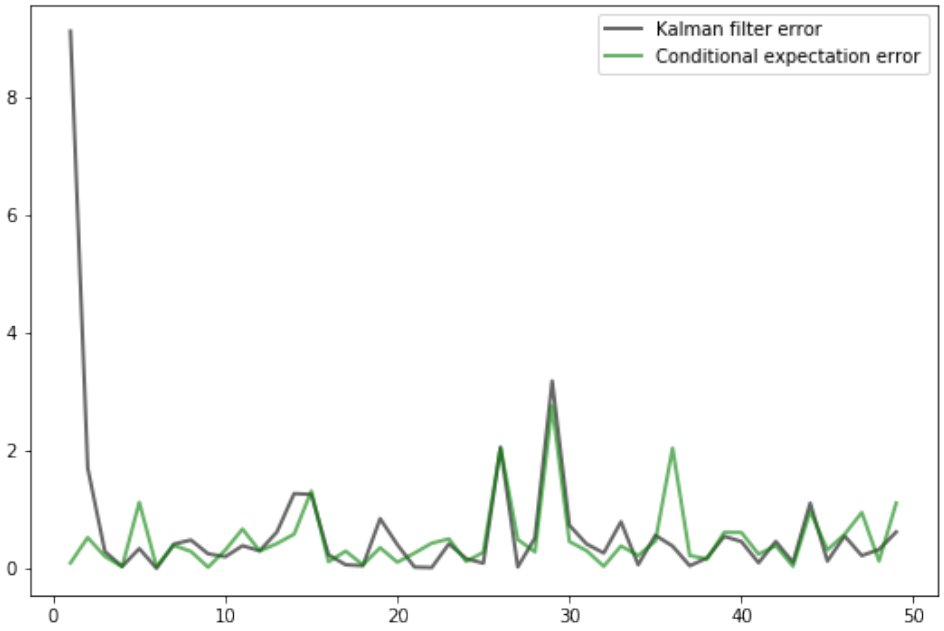
To initialize the prior density, set

$$\Sigma_0 = \begin{pmatrix} 0.9 & 0.3 \\ 0.3 & 0.9 \end{pmatrix}$$

and $\hat{x}_0 = (8, 8)$.

Finally, set $x_0 = (0, 0)$.

You should end up with a figure similar to the following (modulo randomness)



Observe how, after an initial learning period, the Kalman filter performs quite well, even relative to the competitor who predicts optimally with knowledge of the latent state.

21.6.4 Exercise 4

Try varying the coefficient 0.3 in $Q = 0.3I$ up and down.

Observe how the diagonal values in the stationary solution Σ (see (9)) increase and decrease in line with this coefficient.

The interpretation is that more randomness in the law of motion for x_t causes more (permanent) uncertainty in prediction.

21.7 Solutions

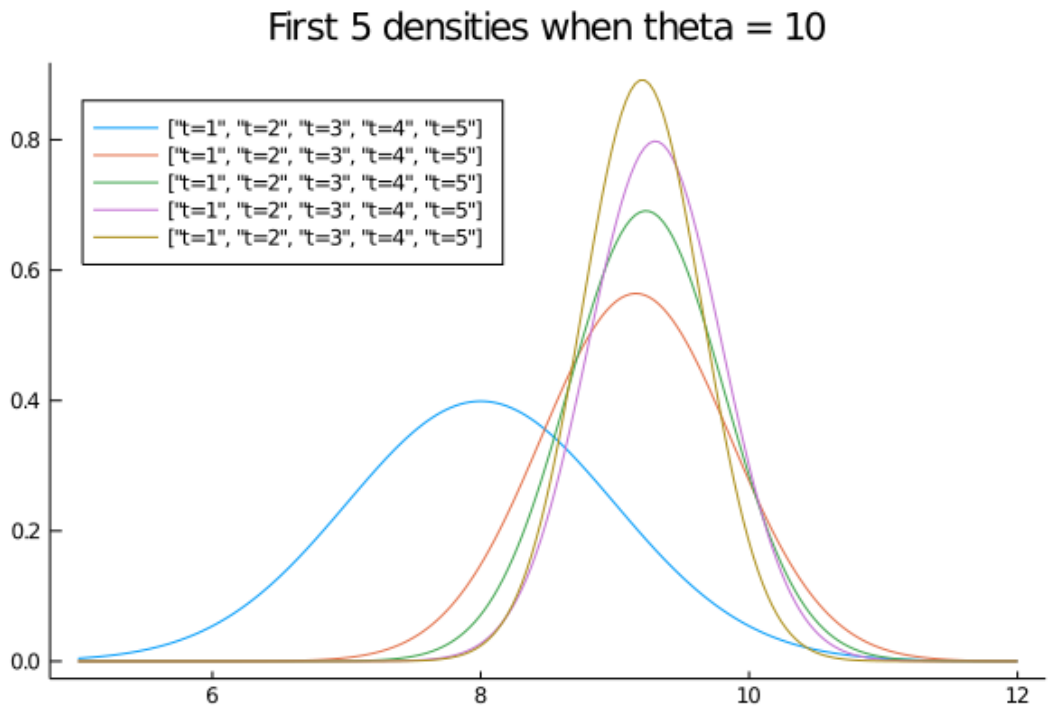
```
In [8]: using QuantEcon
```

21.7.1 Exercise 1

```
In [9]: # parameters
        θ = 10
```

```
A, G, Q, R = 1.0, 1.0, 0.0, 1.0
x̂_0, Σ_0 = 8.0, 1.0

# initialize Kalman filter
kalman = Kalman(A, G, Q, R)
set_state!(kalman, x̂_0, Σ_0)

xgrid = range(θ - 5, θ + 2, length = 200)
densities = zeros(200, 5) # one column per round of updating
for i in 1:5
    # record the current predicted mean and variance, and plot their
densities
    m, v = kalman.cur_x_hat, kalman.cur_sigma
    densities[:, i] = pdf.(Normal(m, sqrt(v)), xgrid)

    # generate the noisy signal
    y = θ + randn()

    # update the Kalman filter
    update!(kalman, y)
end

labels = ["t=1", "t=2", "t=3", "t=4", "t=5"]
plot(xgrid, densities, label = labels, legend = :topleft, grid = false,
     title = "First 5 densities when theta = $θ")
```

Out[9]:

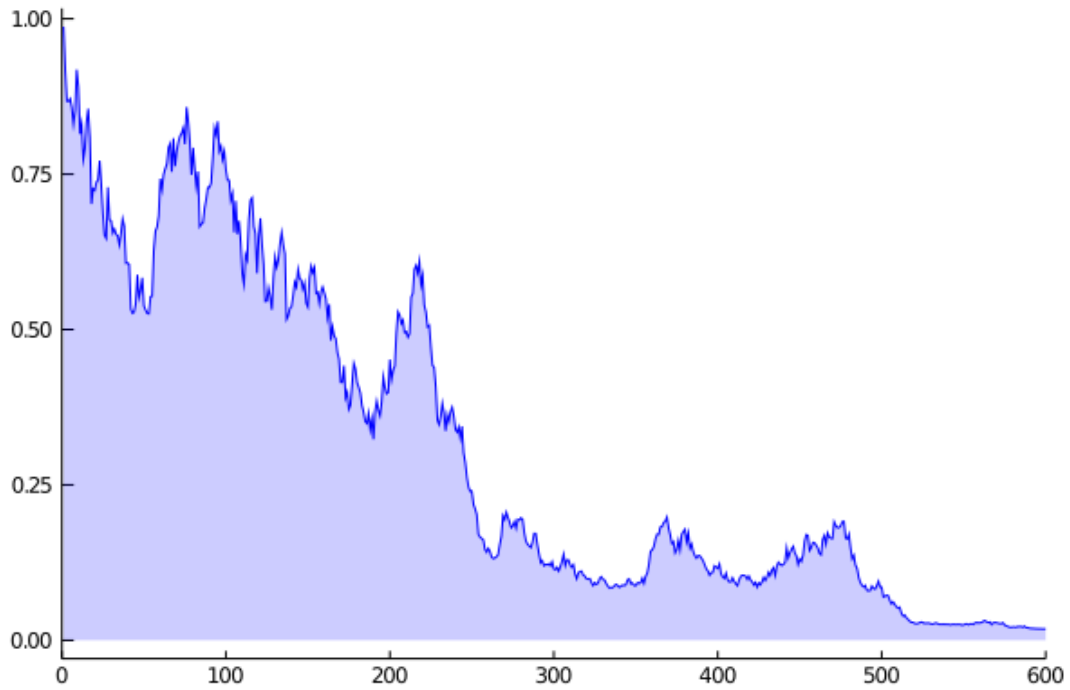


21.7.2 Exercise 2

```
In [10]: using Random, Expectations
         Random.seed!(43)  # reproducible results
```

```
        ϵ = 0.1
        kalman = Kalman(A, G, Q, R)
        set_state!(kalman, x̂_0, Σ_0)
        nodes, weights = qnwlege(21, θ-ϵ, θ+ϵ)

        T = 600
        z = zeros(T)
        for t in 1:T
            # record the current predicted mean and variance, and plot their densities
            m, v = kalman.cur_x_hat, kalman.cur_sigma
            dist = Truncated(Normal(m, sqrt(v)), θ-30*ϵ, θ+30*ϵ) # define on compact interval,
        so we can use gridded expectation
            E = expectation(dist, nodes) # nodes ∈ [ϑ-ϵ, ϑ+ϵ]
            integral = E(x -> 1) # just take the pdf integral
            z[t] = 1. - integral
            # generate the noisy signal and update the Kalman filter
            update!(kalman, θ + randn())
        end

        plot(1:T, z, fillrange = 0, color = :blue, fillalpha = 0.2, grid = false, xlims=(0, T),
             legend = false)
```

Out[10]:



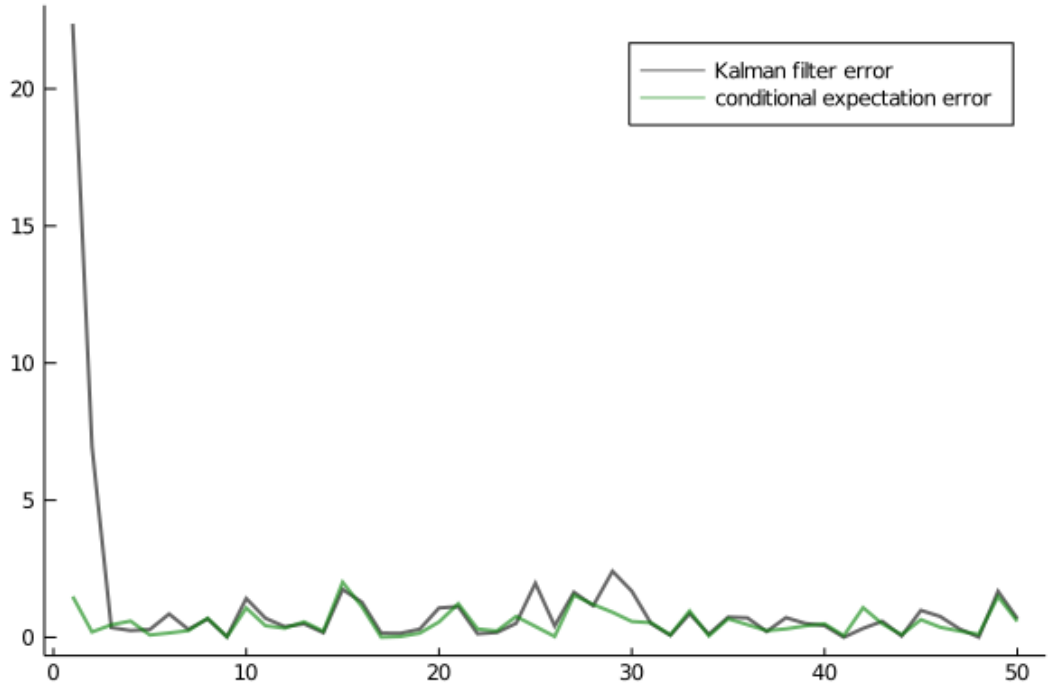
21.7.3 Exercise 3

```
In [11]: # define A, Q, G, R
         G = I + zeros(2, 2)
         R = 0.5 .* G
```

```
A = [0.5 0.4
     0.6 0.3]
Q = 0.3 .* G

# define the prior density
Σ = [0.9 0.3
     0.3 0.9]
x̂ = [8, 8]

# initialize the Kalman filter
kn = Kalman(A, G, Q, R)
set_state!(kn, x̂, Σ)

# set the true initial value of the state
x = zeros(2)

# print eigenvalues of A
println("Eigenvalues of A:\n$(eigvals(A))")

# print stationary Σ
S, K = stationary_values(kn)
println("Stationary prediction error variance:\n$S")

# generate the plot
T = 50
e1 = zeros(T)
e2 = similar(e1)
for t in 1:T

    # generate signal and update prediction
    dist = MultivariateNormal(G * x, R)
    y = rand(dist)
    update!(kn, y)

    # update state and record error
    Ax = A * x
    x = rand(MultivariateNormal(Ax, Q))
    e1[t] = sum((a - b)^2 for (a, b) in zip(x, kn.cur_x_hat))
    e2[t] = sum((a - b)^2 for (a, b) in zip(x, Ax))
end

plot(1:T, e1, color = :black, linewidth = 2, alpha = 0.6, label = "Kalman
↪filter error",
     grid = false)
plot!(1:T, e2, color = :green, linewidth = 2, alpha = 0.6,
      label = "conditional expectation error")
```

```
Eigenvalues of A:
[-0.10000000000000003, 0.8999999999999999]
Stationary prediction error variance:
[0.4032910794778669 0.10507180275061759; 0.1050718027506176 0.41061709375220456]
```

Out[11]:



Footnotes

[1] See, for example, page 93 of [14]. To get from his expressions to the ones used above, you will also need to apply the Woodbury matrix identity.

Chapter 22

Numerical Linear Algebra and Factorizations

22.1 Contents

> You cannot learn too much linear algebra. – Benedict Gross

22.2 Overview

In this lecture, we examine the structure of matrices and linear operators (e.g., dense, sparse, symmetric, tridiagonal, banded) and discuss how the structure can be exploited to radically increase the performance of solving large problems.

We build on applications discussed in previous lectures: linear algebra, orthogonal projections, and Markov chains.

The methods in this section are called direct methods, and they are qualitatively similar to performing Gaussian elimination to factor matrices and solve systems of equations. In iterative methods and sparsity we examine a different approach, using iterative algorithms, where we can think of more general linear operators.

The list of specialized packages for these tasks is enormous and growing, but some of the important organizations to look at are JuliaMatrices , JuliaSparse, and JuliaMath

NOTE: As this section uses advanced Julia techniques, you may wish to review multiple-dispatch and generic programming in introduction to types, and consider further study on generic programming.

The theme of this lecture, and numerical linear algebra in general, comes down to three principles:

1. **Identify structure** (e.g., symmetric, sparse, diagonal) matrices in order to use **specialized algorithms.**
2. **Do not lose structure** by applying the wrong numerical linear algebra operations at the wrong times (e.g., sparse matrix becoming dense)
3. Understand the **computational complexity** of each algorithm, given the structure of the inputs.

22.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, BenchmarkTools, SparseArrays, Random
        Random.seed!(42);  # seed random numbers for reproducibility
```

22.2.2 Computational Complexity

Ask yourself whether the following is a **computationally expensive** operation as the matrix **size increases**

- Multiplying two matrices?
  - *Answer*: It depends. Multiplying two diagonal matrices is trivial.
- Solving a linear system of equations?
  - *Answer*: It depends. If the matrix is the identity, the solution is the vector itself.
- Finding the eigenvalues of a matrix?
  - *Answer*: It depends. The eigenvalues of a triangular matrix are the diagonal elements.

As the goal of this section is to move toward numerical methods with large systems, we need to understand how well algorithms scale with the size of matrices, vectors, etc. This is known as computational complexity. As we saw in the answer to the questions above, the algorithm - and hence the computational complexity - changes based on matrix structure.

While this notion of complexity can work at various levels, such as the number of significant digits for basic mathematical operations, the amount of memory and storage required, or the amount of time, we will typically focus on the time complexity.

For time complexity, the size N is usually the dimensionality of the problem, although occasionally the key will be the number of non-zeros in the matrix or the width of bands. For our applications, time complexity is best thought of as the number of floating point operations (e.g., addition, multiplication) required.

Notation

Complexity of algorithms is typically written in Big O notation, which provides bounds on the scaling of the computational complexity with respect to the size of the inputs.

Formally, if the number of operations required for a problem size N is $f(N)$, we can write this as $f(N) = O(g(N))$ for some $g(N)$ - typically a polynomial.

The interpretation is that there exist some constants M and N_0 such that

$$f(N) \leq Mg(N), \text{ for } N > N_0$$

For example, the complexity of finding an LU Decomposition of a dense matrix is $O(N^3)$, which should be read as there being a constant where eventually the number of floating point operations required to decompose a matrix of size $N \times N$ grows cubically.

Keep in mind that these are asymptotic results intended for understanding the scaling of the problem, and the constant can matter for a given fixed size.

For example, the number of operations required for an LU decomposition of a dense $N \times N$ matrix is $f(N) = \frac{2}{3}N^3$, ignoring the N^2 and lower terms. Other methods of solving a linear system may have different constants of proportionality, even if they have the same scaling, $O(N^3)$.

22.2.3 Rules of Computational Complexity

You will sometimes need to think through how combining algorithms changes complexity. For example, if you use

1. an $O(N^3)$ operation P times, then it simply changes the constant. The complexity remains $O(N^3)$.
2. one $O(N^3)$ operation and one $O(N^2)$ operation, then you take the max. The complexity remains $O(N^3)$.
3. a repetition of an $O(N)$ operation that itself uses an $O(N)$ operation, you take the product. The complexity becomes $O(N^2)$.

With this, we have an important word of caution: Dense-matrix multiplication is an expensive operation for unstructured matrices. The naive version is $O(N^3)$ while the fastest-known algorithms (e.g., Coppersmith-Winograd) are roughly $O(N^{2.37})$. In practice, it is reasonable to crudely approximate with $O(N^3)$ when doing an analysis, in part since the higher constant factors of the better scaling algorithms dominate the better complexity until matrices become very large.

Of course, modern libraries use highly tuned and numerically stable algorithms to multiply matrices and exploit the computer architecture, memory cache, etc., but this simply lowers the constant of proportionality and they remain roughly approximated by $O(N^3)$.

A consequence is that, since many algorithms require matrix-matrix multiplication, it is often not possible to go below that order without further matrix structure.

That is, changing the constant of proportionality for a given size can help, but in order to achieve better scaling you need to identify matrix structure (e.g., tridiagonal, sparse) and ensure that your operations do not lose it.

22.2.4 Losing Structure

As a first example of a structured matrix, consider a sparse array.

```
In [3]: A = sprand(10, 10, 0.45)  # random sparse 10x10, 45 percent filled with
  ↪non-zeros

        @show nnz(A)  # counts the number of non-zeros
        invA = sparse(inv(Array(A)))  # Julia won't invert sparse, so convert to
  ↪dense with
        Array.
        @show nnz(invA);
```

```
   nnz(A) = 47
nnz(invA) = 100
```

This increase from less than 50 to 100 percent dense demonstrates that significant sparsity can be lost when computing an inverse.

The results can be even more extreme. Consider a tridiagonal matrix of size $N \times N$ that might come out of a Markov chain or a discretization of a diffusion process,

```
In [4]: N = 5
        A = Tridiagonal([fill(0.1, N-2); 0.2], fill(0.8, N), [0.2; fill(0.1, N-2);])
```

```
Out[4]: 5×5 Tridiagonal{Float64,Array{Float64,1}}:
         0.8  0.2   ⋅    ⋅    ⋅
         0.1  0.8  0.1   ⋅    ⋅
          ⋅   0.1  0.8  0.1   ⋅
          ⋅    ⋅   0.1  0.8  0.1
          ⋅    ⋅    ⋅   0.2  0.8
```

The number of non-zeros here is approximately $3N$, linear, which scales well for huge matrices into the millions or billions

But consider the inverse

```
In [5]: inv(A)
```

```
Out[5]: 5×5 Array{Float64,2}:
          1.29099      -0.327957     0.0416667  -0.00537634   0.000672043
         -0.163978      1.31183     -0.166667    0.0215054   -0.00268817
          0.0208333    -0.166667     1.29167    -0.166667     0.0208333
         -0.00268817    0.0215054   -0.166667    1.31183     -0.163978
          0.000672043  -0.00537634   0.0416667  -0.327957     1.29099
```

Now, the matrix is fully dense and has N^2 non-zeros.

This also applies to the $A'A$ operation when forming the normal equations of linear least squares.

```
In [6]: A = sprand(20, 21, 0.3)
        @show nnz(A)/20^2
        @show nnz(A'*A)/21^2;
```

```
   nnz(A) / 20 ^ 2 = 0.2825
nnz(A' * A) / 21 ^ 2 = 0.800453514739229
```

We see that a 30 percent dense matrix becomes almost full dense after the product is taken.

Sparsity/Structure is not just for storage: Matrix size can sometimes become important (e.g., a 1 million by 1 million tridiagonal matrix needs to store 3 million numbers (i.e., about 6MB of memory), where a dense one requires 1 trillion (i.e., about 1TB of memory)).

But, as we will see, the main purpose of considering sparsity and matrix structure is that it enables specialized algorithms, which typically have a lower computational order than unstructured dense, or even unstructured sparse, operations.

First, create a convenient function for benchmarking linear solvers

In [7]:
```
using BenchmarkTools
function benchmark_solve(A, b)
    println("A\\b for typeof(A) = $(string(typeof(A)))")
    @btime $A \ $b
end
```

Out[7]:
```
benchmark_solve (generic function with 1 method)
```

Then, take away structure to see the impact on performance,

In [8]:
```
N = 1000
b = rand(N)
A = Tridiagonal([fill(0.1, N-2); 0.2], fill(0.8, N), [0.2; fill(0.1, N-2);])
A_sparse = sparse(A)  # sparse but losing tridiagonal structure
A_dense = Array(A)    # dropping the sparsity structure, dense 1000x1000

# benchmark solution to system A x = b
benchmark_solve(A, b)
benchmark_solve(A_sparse, b)
benchmark_solve(A_dense, b);
```

```
   A\b for typeof(A) = Tridiagonal{Float64,Array{Float64,1}}
  32.810 μs (9 allocations: 47.75 KiB)
A\b for typeof(A) = SparseMatrixCSC{Float64,Int64}
  778.201 μs (69 allocations: 1.06 MiB)
A\b for typeof(A) = Array{Float64,2}
  32.689 ms (5 allocations: 7.65 MiB)
```

This example shows what is at stake: using a structured tridiagonal matrix may be 10-20 times faster than using a sparse matrix, which is 100 times faster than using a dense matrix.

In fact, the difference becomes more extreme as the matrices grow. Solving a tridiagonal system is $O(N)$, while that of a dense matrix without any structure is $O(N^3)$. The complexity of a sparse solution is more complicated, and scales in part by the `nnz(N)`, i.e., the number of nonzeros.

22.2.5 Matrix Multiplication

While we write matrix multiplications in our algebra with abundance, in practice the computational operation scales very poorly without any matrix structure.

Matrix multiplication is so important to modern computers that the constant of scaling is small using proper packages, but the order is still roughly $O(N^3)$ in practice (although smaller in theory, as discussed above).

Sparse matrix multiplication, on the other hand, is $O(NM_AM_B)$ where M_A is the number of nonzeros per row of A and M_B is the number of non-zeros per column of B.

By the rules of computational order, that means any algorithm requiring a matrix multiplication of dense matrices requires at least $O(N^3)$ operation.

The other important question is what is the structure of the resulting matrix. For example, multiplying an upper triangular matrix by a lower triangular matrix

```
In [9]: N = 5
        U = UpperTriangular(rand(N,N))
```

```
Out[9]: 5×5 UpperTriangular{Float64,Array{Float64,2}}:
         0.299976  0.176934  0.0608682  0.20465   0.409653
          ⋅        0.523923  0.127154   0.512531  0.235328
          ⋅         ⋅        0.600588   0.682868  0.330638
          ⋅         ⋅         ⋅         0.345419  0.0312986
          ⋅         ⋅         ⋅          ⋅        0.471043
```

```
In [10]: L = U'
```

```
Out[10]: 5×5 Adjoint{Float64,UpperTriangular{Float64,Array{Float64,2}}}:
          0.299976   0.0       0.0       0.0         0.0
          0.176934   0.523923  0.0       0.0         0.0
          0.0608682  0.127154  0.600588  0.0         0.0
          0.20465    0.512531  0.682868  0.345419    0.0
          0.409653   0.235328  0.330638  0.0312986   0.471043
```

But the product is fully dense (e.g., think of a Cholesky multiplied by itself to produce a covariance matrix)

```
In [11]: L * U
```

```
Out[11]: 5×5 Array{Float64,2}:
          0.0899855  0.0530758  0.018259   0.0613901  0.122886
          0.0530758  0.305801   0.0773883  0.304736   0.195775
          0.018259   0.0773883  0.380579   0.487749   0.253435
          0.0613901  0.304736   0.487749   0.890193   0.441042
          0.122886   0.195775   0.253435   0.441042   0.555378
```

On the other hand, a tridiagonal matrix times a diagonal matrix is still tridiagonal - and can use specialized $O(N)$ algorithms.

```
In [12]: A = Tridiagonal([fill(0.1, N-2); 0.2], fill(0.8, N), [0.2; fill(0.1, N-2);
         ↪])
         D = Diagonal(rand(N))
         D * A
```

```
Out[12]: 5×5 Tridiagonal{Float64,Array{Float64,1}}:
          0.0156225  0.00390564   ⋅           ⋅           ⋅
          0.0436677  0.349342    0.0436677    ⋅           ⋅
           ⋅         0.0213158   0.170526    0.0213158    ⋅
           ⋅          ⋅          0.00790566  0.0632453   0.00790566
           ⋅          ⋅           ⋅          0.19686     0.787442
```

22.3 Factorizations

When you tell a numerical analyst you are solving a linear system using direct methods, their first question is "which factorization?".

Just as you can factor a number (e.g., $6 = 3 \times 2$) you can factor a matrix as the product of other, more convenient matrices (e.g., $A = LU$ or $A = QR$, where L, U, Q, and R have properties such as being triangular, orthogonal, etc.).

22.3.1 Inverting Matrices

On paper, since the Invertible Matrix Theorem tells us that a unique solution is equivalent to A being invertible, we often write the solution to $Ax = b$ as

$$x = A^{-1}b$$

What if we do not (directly) use a factorization?

Take a simple linear system of a dense matrix,

```
In [13]: N = 4
         A = rand(N,N)
         b = rand(N)
```

```
Out[13]: 4-element Array{Float64,1}:
          0.5682240701809245
          0.40245385575255055
          0.1825995192132288
          0.06160128039631019
```

On paper, we try to solve the system $Ax = b$ by inverting the matrix,

```
In [14]: x = inv(A) * b
```

```
Out[14]: 4-element Array{Float64,1}:
          -0.0339069840407679
           0.7988200873225003
           0.9963711951331815
          -0.9276352098500461
```

As we will see throughout, inverting matrices should be used for theory, not for code. The classic advice that you should never invert a matrix may be slightly exaggerated, but is generally good advice.

Solving a system by inverting a matrix is always a little slower, is potentially less accurate, and will sometimes lose crucial sparsity compared to using factorizations. Moreover, the methods used by libraries to invert matrices are frequently the same factorizations used for computing a system of equations.

Even if you need to solve a system with the same matrix multiple times, you are better off factoring the matrix and using the solver rather than calculating an inverse.

In [15]:
```
N = 100
A = rand(N,N)
M = 30
B = rand(N,M)
function solve_inverting(A, B)
    A_inv = inv(A)
    X = similar(B)
    for i in 1:size(B,2)
        X[:,i] = A_inv * B[:,i]
    end
    return X
end

function solve_factoring(A, B)
    X = similar(B)
    A = factorize(A)
    for i in 1:size(B,2)
        X[:,i] = A \ B[:,i]
    end
    return X
end



@btime solve_inverting($A, $B)
@btime solve_factoring($A, $B)

# even better, use the built-in feature for multiple RHS
@btime $A \ $B;
```

```
    499.932 μs (68 allocations: 205.28 KiB)
  421.385 μs (96 allocations: 155.59 KiB)
  245.005 μs (6 allocations: 102.63 KiB)
```

22.3.2 Triangular Matrices and Back/Forward Substitution

Some matrices are already in a convenient form and require no further factoring.

For example, consider solving a system with an `UpperTriangular` matrix,

In [16]:
```
b = [1.0, 2.0, 3.0]
U = UpperTriangular([1.0 2.0 3.0; 0.0 5.0 6.0; 0.0 0.0 9.0])
```

Out[16]:
```
3×3 UpperTriangular{Float64,Array{Float64,2}}:
 1.0  2.0  3.0
  ⋅   5.0  6.0
  ⋅    ⋅   9.0
```

This system is especially easy to solve using back substitution. In particular, $x_3 = b_3/U_{33}, x_2 = (b_2 - x_3 U_{23})/U_{22}$, etc.

```
In [17]: U \ b
```

```
Out[17]: 3-element Array{Float64,1}:
          0.0
          0.0
          0.3333333333333333
```

A `LowerTriangular` matrix has similar properties and can be solved with forward substitution.

The computational order of back substitution and forward substitution is $O(N^2)$ for dense matrices. Those fast algorithms are a key reason that factorizations target triangular structures.

22.3.3 LU Decomposition

The LU decomposition finds a lower triangular matrix L and an upper triangular matrix U such that $LU = A$.

For a general dense matrix without any other structure (i.e., not known to be symmetric, tridiagonal, etc.) this is the standard approach to solve a system and exploit the speed of back and forward substitution using the factorization.

The computational order of LU decomposition itself for a dense matrix is $O(N^3)$ - the same as Gaussian elimination - but it tends to have a better constant term than others (e.g., half the number of operations of the QR decomposition). For structured or sparse matrices, that order drops.

We can see which algorithm Julia will use for the \ operator by looking at the `factorize` function for a given matrix.

```
In [18]: N = 4
         A = rand(N,N)
         b = rand(N)

         Af = factorize(A)  # chooses the right factorization, LU here
```

```
Out[18]: LU{Float64,Array{Float64,2}}
         L factor:
         4×4 Array{Float64,2}:
          1.0       0.0       0.0       0.0
          0.563082  1.0       0.0       0.0
          0.730109  0.912509  1.0       0.0
          0.114765  0.227879  0.115228  1.0
         U factor:
         4×4 Array{Float64,2}:
          0.79794  0.28972   0.765939   0.496278
          0.0      0.82524   0.23962   -0.130989
          0.0      0.0      -0.447888   0.374303
          0.0      0.0       0.0        0.725264
```

In this case, it provides an L and U factorization (with pivoting).

With the factorization complete, we can solve different `b` right hand sides.

```
In [19]: Af \ b
```

```
Out[19]: 4-element Array{Float64,1}:
          -0.49842605495731557
          -0.11835721499695576
           1.5055538550184817
           0.07694455957797537
```

```
In [20]: b2 = rand(N)
         Af \ b2
```

```
Out[20]: 4-element Array{Float64,1}:
          -0.6456780666059364
          -0.2601515737654759
           1.116889566296631
           0.5405293106660054
```

In practice, the decomposition also includes a P which is a permutation matrix such that $PA = LU$.

```
In [21]: Af.P * A ≈ Af.L * Af.U
```

```
Out[21]: true
```

We can also directly calculate an LU decomposition with `lu` but without the pivoting,

```
In [22]: L, U = lu(A, Val(false))  # the Val(false) provides a solution without
           ↪permutation
         matrices
```

```
Out[22]: LU{Float64,Array{Float64,2}}
         L factor:
         4×4 Array{Float64,2}:
          1.0       0.0       0.0       0.0
          0.730109  1.0       0.0       0.0
          0.563082  1.09588   1.0       0.0
          0.114765  0.249728  0.122733  1.0
         U factor:
         4×4 Array{Float64,2}:
          0.79794  0.28972    0.765939   0.496278
          0.0      0.753039  -0.229233   0.254774
          0.0      0.0        0.490832  -0.410191
          0.0      0.0        0.0        0.725264
```

And we can verify the decomposition

```
In [23]: A ≈ L * U
```

```
Out[23]: true
```

To see roughly how the solver works, note that we can write the problem $Ax = b$ as $LUx = b$. Let $Ux = y$, which breaks the problem into two sub-problems.

$$Ly = b$$
$$Ux = y$$

As we saw above, this is the solution to two triangular systems, which can be efficiently done with back or forward substitution in $O(N^2)$ operations.

To demonstrate this, first using

```
In [24]: y = L \ b
```

```
Out[24]: 4-element Array{Float64,1}:
           0.759344042755733
          -0.4146467815590597
           0.707411438334498
           0.05580508465599857
```

```
In [25]: x = U \ y
         x ≈ A \ b  # Check identical
```

```
Out[25]: true
```

The LU decomposition also has specialized algorithms for structured matrices, such as a `Tridiagonal`

```
In [26]: N = 1000
         b = rand(N)
         A = Tridiagonal([fill(0.1, N-2); 0.2], fill(0.8, N), [0.2; fill(0.1, N-2);
 ↪])
         factorize(A) |> typeof
```

```
Out[26]: LU{Float64,Tridiagonal{Float64,Array{Float64,1}}}
```

This factorization is the key to the performance of the `A \ b` in this case. For Tridiagonal matrices, the LU decomposition is $O(N^2)$.

Finally, just as a dense matrix without any structure uses an LU decomposition to solve a system, so will the sparse solvers

```
In [27]: A_sparse = sparse(A)
         factorize(A_sparse) |> typeof  # dropping the tridiagonal structure to
 ↪just become
         sparse
```

```
Out[27]: SuiteSparse.UMFPACK.UmfpackLU{Float64,Int64}
```

```
In [28]: benchmark_solve(A, b)
         benchmark_solve(A_sparse, b);
```

```
    A\b for typeof(A) = Tridiagonal{Float64,Array{Float64,1}}
  32.753 μs (9 allocations: 47.75 KiB)
A\b for typeof(A) = SparseMatrixCSC{Float64,Int64}
  824.810 μs (69 allocations: 1.06 MiB)
```

With sparsity, the computational order is related to the number of non-zeros rather than the size of the matrix itself.

22.3.4 Cholesky Decomposition

For real, symmetric, positive semi-definite matrices, a Cholesky decomposition is a specialized example of an LU decomposition where $L = U'$.

The Cholesky is directly useful on its own (e.g., Classical Control with Linear Algebra), but it is also an efficient factorization to use in solving symmetric positive semi-definite systems.

As always, symmetry allows specialized algorithms.

```
In [29]: N = 500
         B = rand(N,N)
         A_dense = B' * B  # an easy way to generate a symmetric positive semi-
definite matrix
         A = Symmetric(A_dense)  # flags the matrix as symmetric

         factorize(A) |> typeof
```

```
Out[29]: BunchKaufman{Float64,Array{Float64,2}}
```

Here, the A decomposition is Bunch-Kaufman rather than Cholesky, because Julia doesn't know that the matrix is positive semi-definite. We can manually factorize with a Cholesky,

```
In [30]: cholesky(A) |> typeof
```

```
Out[30]: Cholesky{Float64,Array{Float64,2}}
```

Benchmarking,

```
In [31]: b = rand(N)
         cholesky(A) \ b  # use the factorization to solve

         benchmark_solve(A, b)
         benchmark_solve(A_dense, b)
         @btime cholesky($A, check=false) \ $b;
```

```
    A\b for typeof(A) = Symmetric{Float64,Array{Float64,2}}
  5.748 ms (8 allocations: 2.16 MiB)
A\b for typeof(A) = Array{Float64,2}
  8.141 ms (5 allocations: 1.92 MiB)
  3.865 ms (7 allocations: 1.91 MiB)
```

22.3.5 QR Decomposition

Previously, we learned about applications of the QR decomposition to solving the linear least squares.

While in principle the solution to the least-squares problem

$$\min_x \|Ax - b\|^2$$

is $x = (A'A)^{-1}A'b$, in practice note that $A'A$ becomes dense and calculating the inverse is rarely a good idea.

The QR decomposition is a decomposition $A = QR$ where Q is an orthogonal matrix (i.e., $Q'Q = QQ' = I$) and R is an upper triangular matrix.

Given the previous derivation, we showed that we can write the least-squares problem as the solution to

$$Rx = Q'b$$

where, as discussed above, the upper-triangular structure of R can be solved easily with back substitution.

The \ operator solves the linear least-squares problem whenever the given A is rectangular

```
In [32]: N = 10
         M = 3
         x_true = rand(3)

         A = rand(N,M) .+ randn(N)
         b = rand(N)
         x = A \ b
```

```
Out[32]: 3-element Array{Float64,1}:
           0.4011747124872585
           0.0736108001071848
          -0.2347806801272458
```

To manually use the QR decomposition in solving linear least squares:

```
In [33]: Af = qr(A)
         Q = Af.Q
         R = [Af.R; zeros(N - M, M)] # Stack with zeros
         @show Q * R ≈ A
         x = R \ Q'*b  # simplified QR solution for least squares
```

```
Q * R ≈ A = true
```

```
Out[33]: 3-element Array{Float64,1}:
           0.4011747124872585
           0.07361080010718478
          -0.2347806801272457
```

This stacks the `R` with zeros, but the more specialized algorithm would not multiply directly in that way.

In some cases, if an LU is not available for a particular matrix structure, the QR factorization can also be used to solve systems of equations (i.e., not just LLS). This tends to be about 2 times slower than the LU but is of the same computational order.

Deriving the approach, where we can now use the inverse since the system is square and we assumed A was non-singular,

$$\begin{aligned} Ax &= b \\ QRx &= b \\ Q^{-1}QRx &= Q^{-1}b \\ Rx &= Q'b \end{aligned}$$

where the last step uses the fact that $Q^{-1} = Q'$ for an orthogonal matrix.

Given the decomposition, the solution for dense matrices is of computational order $O(N^2)$. To see this, look at the order of each operation.

- Since R is an upper-triangular matrix, it can be solved quickly through back substitution with computational order $O(N^2)$
- A transpose operation is of order $O(N^2)$
- A matrix-vector product is also $O(N^2)$

In all cases, the order would drop depending on the sparsity pattern of the matrix (and corresponding decomposition). A key benefit of a QR decomposition is that it tends to maintain sparsity.

Without implementing the full process, you can form a QR factorization with `qr` and then use it to solve a system

```
In [34]: N = 5
         A = rand(N,N)
         b = rand(N)
         @show A \ b
         @show qr(A) \ b;
```

```
   A \ b = [-1.478040941944558, 2.09875752634393, -0.6857071090150306,
-0.16849538664184543, 2.012803045177841]
qr(A) \ b = [-1.4780409419445582, 2.09875752634393, -0.685707109015032,
-0.16849538664184413, 2.0128030451778414]
```

22.3.6 Spectral Decomposition

A spectral decomposition, also known as an eigendecomposition, finds all of the eigenvectors and eigenvalues to decompose a square matrix `A` such that

$$A = Q\Lambda Q^{-1}$$

where Q is a matrix made of the eigenvectors of A as columns, and Λ is a diagonal matrix of the eigenvalues. Only square, diagonalizable matrices have an eigendecomposition (where a matrix is not diagonalizable if it does not have a full set of linearly independent eigenvectors).

In Julia, whenever you ask for a full set of eigenvectors and eigenvalues, it decomposes using an algorithm appropriate for the matrix type. For example, symmetric, Hermitian, and tridiagonal matrices have specialized algorithms.

To see this,

```
In [35]: A = Symmetric(rand(5, 5))  # symmetric matrices have real eigenvectors/
  ↪eigenvalues
         A_eig = eigen(A)
         Λ = Diagonal(A_eig.values)
         Q = A_eig.vectors
         norm(Q * Λ * inv(Q) - A)
```

```
Out[35]: 2.803627108839096e-15
```

Keep in mind that a real matrix may have complex eigenvalues and eigenvectors, so if you attempt to check `Q * Λ * inv(Q) - A` - even for a positive-definite matrix - it may not be a real number due to numerical inaccuracy.

22.4 Continuous-Time Markov Chains (CTMCs)

In the previous lecture on discrete-time Markov chains, we saw that the transition probability between state x and state y was summarized by the matrix $P(x, y) := \mathbb{P}\{X_{t+1} = y \,|\, X_t = x\}$.

As a brief introduction to continuous time processes, consider the same state space as in the discrete case: S is a finite set with n elements $\{x_1, \dots, x_n\}$.

A **Markov chain** $\{X_t\}$ on S is a sequence of random variables on S that have the **Markov property**.

In continuous time, the Markov Property is more complicated, but intuitively is the same as the discrete-time case.

That is, knowing the current state is enough to know probabilities for future states. Or, for realizations $x(\tau) \in S, \tau \leq t$,

$$\mathbb{P}\{X(t+s) = y \,|\, X(t) = x, X(\tau) = x(\tau) \text{ for } 0 \leq \tau \leq t\} = \mathbb{P}\{X(t+s) = y \,|\, X(t) = x\}$$

Heuristically, consider a time period t and a small step forward, Δ. Then the probability to transition from state i to state j is

$$\mathbb{P}\{X(t+\Delta) = j \,|\, X(t)\} = \begin{cases} q_{ij}\Delta + o(\Delta) & i \neq j \\ 1 + q_{ii}\Delta + o(\Delta) & i = j \end{cases}$$

where the q_{ij} are "intensity" parameters governing the transition rate, and $o(\Delta)$ is little-o notation. That is, $\lim_{\Delta \to 0} o(\Delta)/\Delta = 0$.

Just as in the discrete case, we can summarize these parameters by an $N \times N$ matrix, $Q \in R^{N \times N}$.

Recall that in the discrete case every element is weakly positive and every row must sum to one. With continuous time, however, the rows of Q sum to zero, where the diagonal contains the negative value of jumping out of the current state. That is,

- $q_{ij} \geq 0$ for $i \neq j$
- $q_{ii} \leq 0$
- $\sum_j q_{ij} = 0$

The Q matrix is called the intensity matrix, or the infinitesimal generator of the Markov chain. For example,

$$Q = \begin{bmatrix} -0.1 & 0.1 & 0 & 0 & 0 & 0 \\ 0.1 & -0.2 & 0.1 & 0 & 0 & 0 \\ 0 & 0.1 & -0.2 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & -0.2 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 & -0.2 & 0.1 \\ 0 & 0 & 0 & 0 & 0.1 & -0.1 \end{bmatrix}$$

In the above example, transitions occur only between adjacent states with the same intensity (except for a "bouncing back" of the bottom and top states).

Implementing the Q using its tridiagonal structure

In [36]:
```
using LinearAlgebra
α = 0.1
N = 6
Q = Tridiagonal(fill(α, N-1), [-α; fill(-2α, N-2); -α], fill(α, N-1))
```

Out[36]:
```
6×6 Tridiagonal{Float64,Array{Float64,1}}:
 -0.1   0.1    ⋅      ⋅      ⋅      ⋅
  0.1  -0.2   0.1     ⋅      ⋅      ⋅
   ⋅    0.1  -0.2    0.1     ⋅      ⋅
   ⋅     ⋅    0.1   -0.2    0.1     ⋅
   ⋅     ⋅     ⋅     0.1   -0.2    0.1
   ⋅     ⋅     ⋅      ⋅     0.1   -0.1
```

Here we can use `Tridiagonal` to exploit the structure of the problem.

Consider a simple payoff vector r associated with each state, and a discount rate ρ. Then we can solve for the expected present discounted value in a way similar to the discrete-time case.

$$\rho v = r + Qv$$

or rearranging slightly, solving the linear system

$$(\rho I - Q)v = r$$

For our example, exploiting the tridiagonal structure,

In [37]:
```
r = range(0.0, 10.0, length=N)
ρ = 0.05

A = ρ * I - Q
```

Out[37]:
```
6×6 Tridiagonal{Float64,Array{Float64,1}}:
  0.15  -0.1     ⋅      ⋅      ⋅      ⋅
 -0.1    0.25  -0.1     ⋅      ⋅      ⋅
```

```
 □     -0.1     0.25   -0.1      □        □
 □       □     -0.1     0.25   -0.1      □
 □       □       □     -0.1     0.25   -0.1
 □       □       □       □     -0.1     0.15
```

Note that this A matrix is maintaining the tridiagonal structure of the problem, which leads to an efficient solution to the linear problem.

```
In [38]: v = A \ r
```

```
Out[38]: 6-element Array{Float64,1}:
           38.15384615384615
           57.23076923076923
           84.92307692307693
          115.07692307692311
          142.76923076923077
          161.84615384615384
```

The Q is also used to calculate the evolution of the Markov chain, in direct analogy to the $\psi_{t+k} = \psi_t P^k$ evolution with the transition matrix P of the discrete case.

In the continuous case, this becomes the system of linear differential equations

$$\dot{\psi}(t) = Q(t)^T \psi(t)$$

given the initial condition $\psi(0)$ and where the $Q(t)$ intensity matrix is allowed to vary with time. In the simplest case of a constant Q matrix, this is a simple constant-coefficient system of linear ODEs with coefficients Q^T.

If a stationary equilibrium exists, note that $\dot{\psi}(t) = 0$, and the stationary solution ψ^* needs to satisfy

$$0 = Q^T \psi^*$$

Notice that this is of the form $0\psi^* = Q^T\psi^*$ and hence is equivalent to finding the eigenvector associated with the $\lambda = 0$ eigenvalue of Q^T.

With our example, we can calculate all of the eigenvalues and eigenvectors

```
In [39]: λ, vecs = eigen(Array(Q'))
```

```
Out[39]: Eigen{Float64,Float64,Array{Float64,2},Array{Float64,1}}
         values:
         6-element Array{Float64,1}:
          -0.3732050807568874
          -0.2999999999999993
          -0.1999999999999998
          -0.0999999999999995
          -0.026794919243112274
           0.0
         vectors:
         6×6 Array{Float64,2}:
          -0.149429  -0.288675   0.408248   0.5          -0.557678  0.408248
```

```
 0.408248   0.57735   -0.408248   1.38778e-16  -0.408248  0.408248
-0.557678  -0.288675  -0.408248  -0.5          -0.149429  0.408248
 0.557678  -0.288675   0.408248  -0.5           0.149429  0.408248
-0.408248   0.57735    0.408248   7.63278e-16   0.408248  0.408248
 0.149429  -0.288675  -0.408248   0.5           0.557678  0.408248
```

Indeed, there is a $\lambda = 0$ eigenvalue, which is associated with the last column in the eigenvector. To turn that into a probability, we need to normalize it.

```
In [40]: vecs[:,N] ./ sum(vecs[:,N])
```

```
Out[40]: 6-element Array{Float64,1}:
          0.16666666666666657
          0.16666666666666657
          0.1666666666666667
          0.16666666666666682
          0.16666666666666685
          0.16666666666666663
```

22.4.1 Multiple Dimensions

A frequent case in discretized models is dealing with Markov chains with multiple "spatial" dimensions (e.g., wealth and income).

After discretizing a process to create a Markov chain, you can always take the Cartesian product of the set of states in order to enumerate it as a single state variable.

To see this, consider states i and j governed by infinitesimal generators Q and A.

```
In [41]: function markov_chain_product(Q, A)
             M = size(Q, 1)
             N = size(A, 1)
             Q = sparse(Q)
             Qs = blockdiag(fill(Q, N)...)  # create diagonal blocks of every
         ↪operator
             As = kron(A, sparse(I(M)))
             return As + Qs
         end

         α = 0.1
         N = 4
         Q = Tridiagonal(fill(α, N-1), [-α; fill(-2α, N-2); -α], fill(α, N-1))
         A = sparse([-0.1 0.1
             0.2 -0.2])
         M = size(A,1)
         L = markov_chain_product(Q, A)
         L |> Matrix  # display as a dense matrix
```

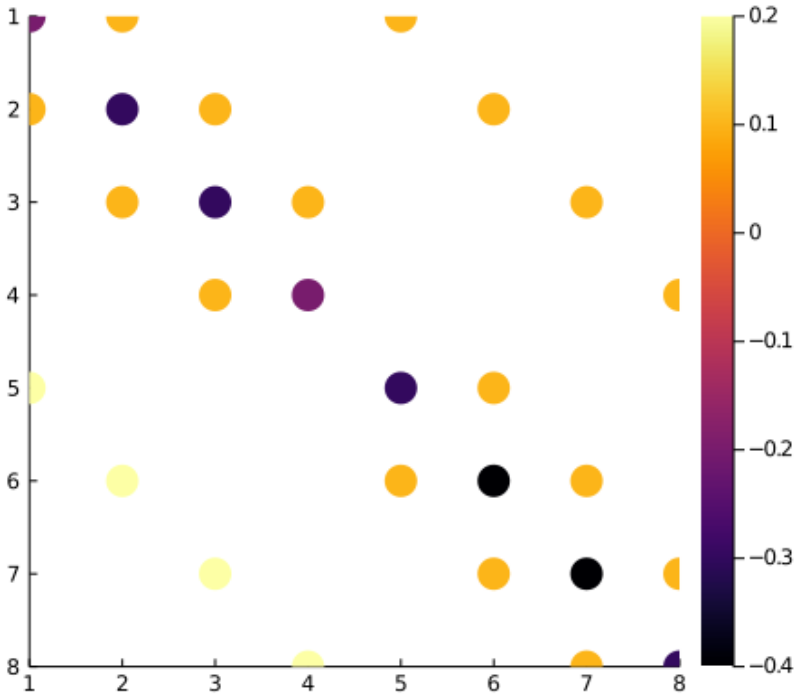
```
Out[41]: 8×8 Array{Float64,2}:
          -0.2   0.1   0.0   0.0   0.1   0.0   0.0   0.0
           0.1  -0.3   0.1   0.0   0.0   0.1   0.0   0.0
           0.0   0.1  -0.3   0.1   0.0   0.0   0.1   0.0
           0.0   0.0   0.1  -0.2   0.0   0.0   0.0   0.1
           0.2   0.0   0.0   0.0  -0.3   0.1   0.0   0.0
           0.0   0.2   0.0   0.0   0.1  -0.4   0.1   0.0
```

```
0.0   0.0   0.2   0.0   0.0   0.1  -0.4   0.1
0.0   0.0   0.0   0.2   0.0   0.0   0.1  -0.3
```

This provides the combined Markov chain for the (i, j) process. To see the sparsity pattern,

In [42]:
```
using Plots
gr(fmt = :png);
spy(L, markersize = 10)
```

Out[42]:



To calculate a simple dynamic valuation, consider whether the payoff of being in state (i, j) is $r_{ij} = i + 2j$

In [43]:
```
r = [i + 2.0j for i in 1:N, j in 1:M]
r = vec(r)  # vectorize it since stacked in same order
```

Out[43]:
```
8-element Array{Float64,1}:
 3.0
 4.0
 5.0
 6.0
 5.0
 6.0
 7.0
 8.0
```

Solving the equation $\rho v = r + Lv$

```
In [44]: ρ = 0.05
         v = (ρ * I - L) \ r
         reshape(v, N, M)
```

```
Out[44]: 4×2 Array{Float64,2}:
           87.8992   93.6134
           96.1345  101.849
          106.723   112.437
          114.958   120.672
```

The `reshape` helps to rearrange it back to being two-dimensional.

To find the stationary distribution, we calculate the eigenvalue and choose the eigenvector associated with $\lambda = 0$. In this case, we can verify that it is the last one.

```
In [45]: L_eig = eigen(Matrix(L'))
         @assert norm(L_eig.values[end]) < 1E-10

         ψ = L_eig.vectors[:,end]
         ψ = ψ / sum(ψ)
```

```
Out[45]: 8-element Array{Float64,1}:
          0.16666666666666677
          0.1666666666666665
          0.16666666666666682
          0.16666666666666666
          0.08333333333333325
          0.08333333333333345
          0.0833333333333333
          0.08333333333333334
```

Reshape this to be two-dimensional if it is helpful for visualization.

```
In [46]: reshape(ψ, N, size(A,1))
```

```
Out[46]: 4×2 Array{Float64,2}:
          0.166667  0.0833333
          0.166667  0.0833333
          0.166667  0.0833333
          0.166667  0.0833333
```

22.4.2 Irreducibility

As with the discrete-time Markov chains, a key question is whether CTMCs are reducible, i.e., whether states communicate. The problem is isomorphic to determining whether the directed graph of the Markov chain is strongly connected.

```
In [47]: using LightGraphs
         α = 0.1
         N = 6
         Q = Tridiagonal(fill(α, N-1), [-α; fill(-2α, N-2); -α], fill(α, N-1))
```

```
Out[47]: 6×6 Tridiagonal{Float64,Array{Float64,1}}:
          -0.1   0.1    ⋅      ⋅      ⋅      ⋅
           0.1  -0.2   0.1     ⋅      ⋅      ⋅
            ⋅    0.1  -0.2   0.1     ⋅      ⋅
            ⋅     ⋅    0.1  -0.2   0.1     ⋅
            ⋅     ⋅     ⋅    0.1  -0.2   0.1
            ⋅     ⋅     ⋅     ⋅    0.1  -0.1
```

We can verify that it is possible to move between every pair of states in a finite number of steps with

```
In [48]: Q_graph = DiGraph(Q)
         @show is_strongly_connected(Q_graph);  # i.e., can follow directional
  ↪edges to get to
         every state
```

```
is_strongly_connected(Q_graph) = true
```

Alternatively, as an example of a reducible Markov chain where states 1 and 2 cannot jump to state 3.

```
In [49]: Q = [-0.2 0.2 0
              0.2 -0.2 0
              0.2 0.6 -0.8]
         Q_graph = DiGraph(Q)
         @show is_strongly_connected(Q_graph);
```

```
is_strongly_connected(Q_graph) = false
```

22.5 Banded Matrices

A tridiagonal matrix has 3 non-zero diagonals: the main diagonal, the first sub-diagonal (i.e., below the main diagonal), and also the first super-diagonal (i.e., above the main diagonal).

This is a special case of a more general type called a banded matrix, where the number of sub- and super-diagonals can be greater than 1. The total width of main-, sub-, and super-diagonals is called the bandwidth. For example, a tridiagonal matrix has a bandwidth of 3.

An $N \times N$ banded matrix with bandwidth P has about NP nonzeros in its sparsity pattern.

These can be created directly as a dense matrix with `diagm`. For example, with a bandwidth of three and a zero diagonal,

```
In [50]: diagm(1 => [1,2,3], -1 => [4,5,6])
```

```
Out[50]: 4×4 Array{Int64,2}:
          0  1  0  0
          4  0  2  0
          0  5  0  3
          0  0  6  0
```

Or as a sparse matrix,

```
In [51]: spdiagm(1 => [1,2,3], -1 => [4,5,6])
```

```
Out[51]: 4×4 SparseMatrixCSC{Int64,Int64} with 6 stored entries:
           [2, 1]  =  4
           [1, 2]  =  1
           [3, 2]  =  5
           [2, 3]  =  2
           [4, 3]  =  6
           [3, 4]  =  3
```

Or directly using BandedMatrices.jl

```
In [52]: using BandedMatrices
         BandedMatrix(1 => [1,2,3], -1 => [4,5,6])
```

```
Out[52]: 4×4 BandedMatrix{Int64,Array{Int64,2},Base.OneTo{Int64}}:
          0  1  □  □
          4  0  2  □
          □  5  0  3
          □  □  6  0
```

There is also a convenience function for generating random banded matrices

```
In [53]: A = brand(7, 7, 3, 1)  # 7x7 matrix, 3 subdiagonals, 1 superdiagonal
```

```
Out[53]: 7×7 BandedMatrix{Float64,Array{Float64,2},Base.OneTo{Int64}}:
          0.386608  0.346262    □          □          □          □          □
          0.479616  0.750276   0.50362     □          □          □          □
          0.857743  0.913585   0.087322  0.0676183     □          □          □
          0.779364  0.293782   0.269804  0.813762   0.147221     □          □
           □        0.0341229  0.711412  0.438157   0.0312296  0.930633    □
           □         □         0.412892  0.351496   0.701733   0.335451  0.0827553
           □         □          □        0.394056   0.460506   0.25927   0.418861
```

And, of course, specialized algorithms will be used to exploit the structure when solving linear systems. In particular, the complexity is related to the $O(NP_LP_U)$ for upper and lower bandwidths P

```
In [54]: @show factorize(Symmetric(A)) |> typeof
         A \ rand(7)
```

```
factorize(Symmetric(A)) |> typeof =
↪LDLt{Float64,Symmetric{Float64,BandedMatrix{Float6
4,Array{Float64,2},Base.OneTo{Int64}}}}
```

```
Out[54]: 7-element Array{Float64,1}:
          -0.6345917189136551
           1.2689275835805582
           0.5499404721793494
           0.24947160343942412
          -0.45227412611006496
           0.4973200025591808
           1.3752489574369149
```

The factorization algorithm uses a specialized LU decomposition for banded matrices.

22.6 Implementation Details and Performance

Recall the famous quote from Knuth: "97% of the time, premature optimization is the root of all evil. Yet we should not pass up our opportunities in that critical 3%." The most common example of premature optimization is trying to use your own mental model of a compiler while writing your code, worried about the efficiency of code, and (usually incorrectly) second-guessing the compiler.

Concretely, the lessons in this section are:

1. Don't worry about optimizing your code unless you need to. Code clarity is your first-order concern.
2. If you use other people's packages, they can worry about performance and you don't need to.
3. If you absolutely need that "critical 3%," your intuition about performance is usually wrong on modern CPUs and GPUs, so let the compiler do its job.
4. Benchmarking (e.g., `@btime`) and profiling are the tools to figure out performance bottlenecks. If 99% of computing time is spent in one small function, then there is no point in optimizing anything else.
5. If you benchmark to show that a particular part of the code is an issue, and you can't find another library that does a better job, then you can worry about performance.

You will rarely get to step 3, let alone step 5.

However, there is also a corollary: "don't pessimize prematurely." That is, don't make choices that lead to poor performance without any tradeoff in improved code clarity. For example, writing your own algorithms when a high-performance algorithm exists in a package or Julia itself, or lazily making a matrix dense and carelessly dropping its structure.

22.6.1 Implementation Difficulty

Numerical analysts sometimes refer to the lowest level of code for basic operations (e.g., a dot product, matrix-matrix product, convolutions) as `kernels`.

That sort of code is difficult to write, and performance depends on the characteristics of the underlying hardware, such as the instruction set available on the particular CPU, the size of the CPU cache, and the layout of arrays in memory.

Typically, these operations are written in a BLAS library, organized into different levels. The levels roughly correspond to the computational order of the operations: BLAS Level 1 are $O(N)$ operations such as linear products, Level 2 are $O(N^2)$ operations such as matrix-vector products, and Level 3 are roughly $O(N^3)$, such as general matrix-matrix products.

An example of a BLAS library is OpenBLAS, which is used by default in Julia, or the Intel MKL, which is used in Matlab (and in Julia if the `MKL.jl` package is installed).

On top of BLAS are LAPACK operations, which are higher-level kernels, such as matrix factorizations and eigenvalue algorithms, and are often in the same libraries (e.g., MKL has both BLAS and LAPACK functionality).

The details of these packages are not especially relevant, but if you are talking about performance, people will inevitably start discussing these different packages and kernels. There are a few important things to keep in mind:

1. Leave writing kernels to the experts. Even simple-sounding algorithms can be very complicated to implement with high performance.
2. Your intuition about performance of code is probably going to be wrong. If you use high quality libraries rather than writing your own kernels, you don't need to use your intuition.
3. Don't get distracted by the jargon or acronyms above if you are reading about performance.

22.6.2 Row- and Column-Major Ordering

There is a practical performance issue which may influence your code. Since memory in a CPU is linear, dense matrices need to be stored by either stacking columns (called column-major order) or rows.

The reason this matters is that compilers can generate better performance if they work in contiguous chunks of memory, and this becomes especially important with large matrices due to the interaction with the CPU cache. Choosing the wrong order when there is no benefit in code clarity is an example of premature pessimization. The performance difference can be orders of magnitude in some cases, and nothing in others.

One option is to use the functions that let the compiler choose the most efficient way to traverse memory. If you need to choose the looping order yourself, then you might want to experiment with going through columns first and going through rows first. Other times, let Julia decide, i.e., `enumerate` and `eachindex` will choose the right approach.

Julia, Fortran, and Matlab all use column-major order, while C/C++ and Python use row-major order. This means that if you find an algorithm written for C/C++/Python, you will sometimes need to make small changes if performance is an issue.

22.6.3 Digression on Allocations and In-place Operations

While we have usually not considered optimizing code for performance (and have focused on the choice of algorithms instead), when matrices and vectors become large we need to be more careful.

The most important thing to avoid are excess allocations, which usually occur due to the use of temporary vectors and matrices when they are not necessary. Sometimes those extra temporary values can cause enormous degradations in performance.

However, caution is suggested since excess allocations are never relevant for scalar values, and allocations frequently create faster code for smaller matrices/vectors since it can lead to better cache locality.

To see this, a convenient tool is the benchmarking

In [55]:
```
using BenchmarkTools
A = rand(10,10)
B = rand(10,10)
C = similar(A)
function f!(C, A, B)
    D = A*B
    C .= D .+ 1
end
@btime f!($C, $A, $B)
```

```
  535.183 ns (1 allocation: 896 bytes)
```

Out[55]:
```
10×10 Array{Float64,2}:
 3.26172  4.24569  3.37182  4.10324  …  4.03344  4.39198  2.88797  2.63934
 4.19687  4.58126  3.88015  5.0409      4.0105   3.56832  2.35475  3.32362
 2.17535  2.58069  3.08736  3.04461     2.71563  3.03535  2.62734  2.37854
 4.07043  4.57067  4.23989  5.24296     4.34443  4.21237  3.30526  3.82245
 3.16928  4.20751  3.08482  3.89843     3.81516  4.14681  2.64178  2.94961
 3.01031  3.08903  2.83417  3.80852  …  3.22832  3.29357  2.57282  2.60746
 3.88276  4.45627  3.88941  5.12798     4.11822  3.70176  2.69528  3.81814
 2.7023   3.10147  2.95828  3.63363     3.64397  3.40609  2.44341  3.03272
 3.02687  3.13864  2.78748  3.90634     3.18422  2.90128  1.99457  2.80653
 3.80929  3.83031  3.88255  4.8596      4.16155  3.73634  2.65279  3.07034
```

The `!` on the `f!` is an informal way to say that the function is mutating, and the first argument (`C` here) is by convention the modified variable.

In the `f!` function, notice that the `D` is a temporary variable which is created, and then modified afterwards. But notice that since `C` is modified directly, there is no need to create the temporary `D` matrix.

This is an example of where an in-place version of the matrix multiplication can help avoid the allocation.

In [56]:
```
function f2!(C, A, B)
    mul!(C, A, B)  # in-place multiplication
    C .+= 1
end
A = rand(10,10)
B = rand(10,10)
C = similar(A)
@btime f!($C, $A, $B)
@btime f2!($C, $A, $B)
```

```
  539.402 ns (1 allocation: 896 bytes)
  498.782 ns (0 allocations: 0 bytes)
```

Out[56]:
```
10×10 Array{Float64,2}:
 2.42733  3.74571  2.5811   2.745    …  2.45258  3.17339  2.792    3.46213
 3.52188  4.16932  3.17155  3.98401     2.1202   2.85629  3.35848  3.88871
 3.74317  4.66988  3.3338   4.69372     2.61622  3.70894  4.06268  4.79582
 3.30158  4.09369  3.81428  3.65591     2.743    3.42494  3.65687  3.83879
 2.47181  4.33343  2.46863  2.68593     2.38238  3.6709   3.2434   4.17783
 3.5594   4.72281  3.71072  4.31957  …  2.83065  4.21896  4.34601  4.90251
```

```
 3.76742  4.85555  4.03515  4.55265     2.62424  4.19292  4.57003  4.88181
 3.29688  5.38813  3.4278   3.8622      2.87482  4.07336  3.89498  5.41919
 2.96602  3.60521  2.90236  3.2117      2.68528  2.99728  3.34362  3.47657
 4.73208  5.38525  4.42378  5.18235     2.91664  4.70184  5.28638  5.4401
```

Note that in the output of the benchmarking, the `f2!` is non-allocating and is using the pre-allocated `C` variable directly.

Another example of this is solutions to linear equations, where for large solutions you may pre-allocate and reuse the solution vector.

```
In [57]: A = rand(10,10)
         y = rand(10)
         z = A \ y  # creates temporary

         A = factorize(A)  # in-place requires factorization
         x = similar(y)  # pre-allocate
         ldiv!(x, A, y)  # in-place left divide, using factorization
```

```
Out[57]: 10-element Array{Float64,1}:
          -0.09745394360765254
           0.7799354221131604
           1.1994346228906085
           0.0913844576787099
          -0.5083914639425638
          -0.3509162355608617
           0.793473061987608
          -0.5304171009174155
           0.4517444530913052
          -0.8005334538688558
```

However, if you benchmark carefully, you will see that this is sometimes slower. Avoiding allocations is not always a good idea - and worrying about it prior to benchmarking is premature optimization.

There are a variety of other non-allocating versions of functions. For example,

```
In [58]: A = rand(10,10)
         B = similar(A)

         transpose!(B, A)  # non-allocating version of B = transpose(A)
```

```
Out[58]: 10×10 Array{Float64,2}:
          0.373481   0.715094  0.880197   0.219559   …  0.903144   0.0534784  0.
        ↪646242
          0.0572854  0.437244  0.0465054  0.271735      0.0419775  0.91462    0.
        ↪804396
          0.0722476  0.435665  0.631825   0.0804549     0.773098   0.254097   0.
        ↪674881
         0.0341739  0.185395  0.736277   0.142816      0.687287   0.236726   0.19037
         0.843743   0.860459  0.709686   0.630887      0.274137   0.958363   0.948974
          0.918731   0.933097  0.280531   0.486534   …  0.0313851  0.479192   0.
        ↪988241
         0.868133   0.243504  0.628518   0.954309      0.667845   0.935099   0.990551
         0.0636638  0.659151  0.377286   0.0453235     0.865368   0.64157    0.570134
         0.759633   0.389194  0.153783   0.284574      0.245533   0.516012   0.55121
         0.301123   0.505073  0.0402959  0.225074      0.57159    0.893165   0.374389
```

Finally, a common source of unnecessary allocations is when taking slices or portions of matrices. For example, the following allocates a new matrix `B` and copies the values.

```
In [59]: A = rand(5,5)
         B = A[2,:]  # extract a vector
```

```
Out[59]: 5-element Array{Float64,1}:
          0.07265755245781103
          0.2967203620355736
          0.7745398448673058
          0.6244448536072318
          0.5287113274542306
```

To see that these are different matrices, note that

```
In [60]: A[2,1] = 100.0
         @show A[2,1]
         @show B[1];
```

```
    A[2, 1] = 100.0
B[1] = 0.07265755245781103
```

Instead of allocating a new matrix, you can take a `view` of a matrix, which provides an appropriate `AbstractArray` type that doesn't allocate new memory with the `@view` matrix.

```
In [61]: A = rand(5,5)
         B = @view A[2,:]  #  does not copy the data

         A[2,1] = 100.0
         @show A[2,1]
         @show B[1];
```

```
    A[2, 1] = 100.0
B[1] = 100.0
```

But again, you will often find that doing `@view` leads to slower code. Benchmark instead, and generally rely on it for large matrices and for contiguous chunks of memory (e.g., columns rather than rows).

22.7 Exercises

22.7.1 Exercise 1

This exercise is for practice on writing low-level routines (i.e., "kernels"), and to hopefully convince you to leave low-level code to the experts.

The formula for matrix multiplication is deceptively simple. For example, with the product of square matrices $C = AB$ of size $N \times N$, the i, j element of C is

$$C_{ij} = \sum_{k=1}^{N} A_{ik} B_{kj}$$

Alternatively, you can take a row $A_{i,:}$ and column $B_{:,j}$ and use an inner product

$$C_{ij} = A_{i,:} \cdot B_{:,j}$$

Note that the inner product in a discrete space is simply a sum, and has the same complexity as the sum (i.e., $O(N)$ operations).

For a dense matrix without any structure and using a naive multiplication algorithm, this also makes it clear why the complexity is $O(N^3)$: You need to evaluate it for N^2 elements in the matrix and do an $O(N)$ operation each time.

For this exercise, implement matrix multiplication yourself and compare performance in a few permutations.

1. Use the built-in function in Julia (i.e., `C = A * B`, or, for a better comparison, the in-place version `mul!(C, A, B)`, which works with pre-allocated data).
2. Loop over each C_{ij} by the row first (i.e., the `i` index) and use a `for` loop for the inner product.
3. Loop over each C_{ij} by the column first (i.e., the `j` index) and use a `for` loop for the inner product.
4. Do the same but use the `dot` product instead of the sum.
5. Choose your best implementation of these, and then for matrices of a few different sizes (`N=10`, `N=1000`, etc.), and compare the ratio of performance of your best implementation to the built-in BLAS library.

A few more hints:

- You can just use random matrices (e.g., `A = rand(N, N)`).
- For all of them, pre-allocate the C matrix beforehand with `C = similar(A)` or something equivalent.
- To compare performance, put your code in a function and use the `@btime` macro to time it.

22.7.2 Exercise 2a

Here we will calculate the evolution of the pdf of a discrete-time Markov chain, ψ_t, given the initial condition ψ_0.

Start with a simple symmetric tridiagonal matrix

```
In [62]: N = 100
         A = Tridiagonal([fill(0.1, N-2); 0.2], fill(0.8, N), [0.2; fill(0.1, N-2)])
          A_adjoint = A';
```

1. Pick some large `T` and use the initial condition $\psi_0 = \begin{bmatrix} 1 & 0 & \dots & 0 \end{bmatrix}$

2. Write code to calculate ψ_t to some T by iterating the map for each t, i.e.,

$$\psi_{t+1} = A'\psi_t$$

1. What is the computational order of calculating ψ_T using this iteration approach $T < N$?
2. What is the computational order of $(A')^T = (A' \dots A')$ and then $\psi_T = (A')^T\psi_0$ for $T < N$?
3. Benchmark calculating ψ_T with the iterative calculation above as well as the direct $\psi_T = (A')^T\psi_0$ to see which is faster. You can take the matrix power with just `A_adjoint^T`, which uses specialized algorithms faster and more accurately than repeated matrix multiplication (but with the same computational order).
4. Check the same if $T = 2N$

Note: The algorithm used in Julia to take matrix powers depends on the matrix structure, as always. In the symmetric case, it can use an eigendecomposition, whereas with a general dense matrix it uses squaring and scaling.

22.7.3 Exercise 2b

With the same setup as in Exercise 2a, do an eigendecomposition of `A_transpose`. That is, use `eigen` to factor the adjoint $A' = Q\Lambda Q^{-1}$, where Q is the matrix of eigenvectors and Λ is the diagonal matrix of eigenvalues. Calculate Q^{-1} from the results.

Use the factored matrix to calculate the sequence of $\psi_t = (A')^t\psi_0$ using the relationship

$$\psi_t = Q\Lambda^t Q^{-1}\psi_0$$

where matrix powers of diagonal matrices are simply the element-wise power of each element.

Benchmark the speed of calculating the sequence of ψ_t up to `T = 2N` using this method. In principle, the factorization and easy calculation of the power should give you benefits, compared to simply iterating the map as we did in Exercise 2a. Explain why it does or does not, using computational order of each approach.

Chapter 23

Krylov Methods and Matrix Conditioning

23.1 Contents

23.2 Overview

This lecture takes the structure of numerical methods for linear algebra and builds further toward working with large, sparse matrices. In the process, we will examine foundational numerical analysis such as ill-conditioned matrices.

23.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, BenchmarkTools, Random
        Random.seed!(42);  # seed random numbers for reproducibility
```

23.2.2 Applications

In this section, we will consider variations on classic problems

1. Solving a linear system for a square A where we will maintain throughout that there is a unique solution to

$$Ax = b$$

1. Linear least-squares solution, for a rectangular A

$$\min_x \|Ax - b\|^2$$

From theory, we know that if A has linearly independent columns, then the solution is the normal equation

$$x = (A'A)^{-1}A'b$$

1. In the case of a square matrix A, the eigenvalue problem is that of finding x and λ such that

$$Ax = \lambda x$$

For eigenvalue problems, keep in mind that you do not always require all of the λ, and sometimes the largest (or smallest) would be enough. For example, calculating the spectral radius requires only the eigenvalue with maximum absolute value.

23.3 Ill-Conditioned Matrices

An important consideration in numerical linear algebra, and iterative methods in general, is the condition number.

An ill-conditioned matrix is one where the basis eigenvectors are close to, but not exactly, collinear. While this poses no problem on pen and paper, or with infinite-precision numerical methods, it is important in practice, for two reasons:

1. Ill-conditioned matrices introduce numerical errors roughly in proportion to the base-10 log of the condition number.
2. The convergence speed of many iterative methods is based on the spectral properties of the matrices (e.g., the basis formed by the eigenvectors), and hence ill-conditioned systems can converge slowly.

The solutions to these problems are to

- be careful with operations which introduce error based on the condition number (e.g., matrix inversions when the condition number is high)
- choose, where possible, alternative representations which have less collinearity (e.g., an orthogonal polynomial basis rather than a monomial one)
- use a preconditioner for iterative methods, which changes the spectral properties to increase convergence speed

23.3.1 Condition Number

First, let's define and explore the condition number κ

$$\kappa(A) \equiv \|A\|\|A^{-1}\|$$

where you can use the Cauchy–Schwarz inequality to show that $\kappa(A) \geq 1$. While the condition number can be calculated with any norm, we will focus on the 2-norm.

First, a warning on calculations: Calculating the condition number for a matrix can be an expensive operation (as would calculating a determinant) and should be thought of as roughly equivalent to doing an eigendecomposition. So use it for detective work judiciously.

Let's look at the condition number of a few matrices using the `cond` function (which allows a choice of the norm, but we'll stick with the default 2-norm).

```
In [3]: A = I(2)
        cond(A)
```

```
Out[3]: 1.0
```

Here we see an example of the best-conditioned matrix, the identity matrix with its completely orthonormal basis, which has a condition number of 1.

On the other hand, notice that

```
In [4]: ϵ = 1E-6
        A = [1.0 0.0
             1.0 ϵ]
        cond(A)
```

```
Out[4]: 2.0000000000005004e6
```

has a condition number of order `10E6` - and hence (taking the base-10 log) you would expect to be introducing numerical errors of about 6 significant digits if you are not careful. For example, note that the inverse has both extremely large and extremely small negative numbers

```
In [5]: inv(A)
```

```
Out[5]: 2×2 Array{Float64,2}:
          1.0    0.0
         -1.0e6  1.0e6
```

Since we know that the determinant of nearly collinear matrices is close to zero, this shows another symptom of poor conditioning

```
In [6]: det(A)
```

```
Out[6]: 1.0e-6
```

However, be careful since the determinant has a scale, while the condition number is dimensionless. That is,

```
In [7]: @show det(1000 * A)
        @show cond(1000 * A);
```

```
    det(1000A) = 1.0
cond(1000A) = 2.0000000000005001e6
```

In that case, the determinant of `A` is 1, while the condition number is unchanged. This example also provides some intuition that ill-conditioned matrices typically occur when a matrix has radically different scales (e.g., contains both `1` and `1E-6`, or `1000` and `1E-3`). This can occur frequently with both function approximation and linear least squares.

23.3.2 Condition Numbers and Matrix Operations

Multiplying a matrix by a constant does not change the condition number. What about other operations?

For this example, we see that the inverse has the same condition number (though this will not always be the case).

```
In [8]: @show cond(A)
        @show cond(inv(A));
```

```
    cond(A) = 2.0000000000005004e6
cond(inv(A)) = 2.0000000002463197e6
```

The condition number of the product of two matrices can change radically and lead things to becoming even more ill-conditioned.

This comes up frequently when calculating the product of a matrix and its transpose (e.g., forming the covariance matrix). A classic example is the Läuchli matrix.

```
In [9]: lauchli(N, ϵ) = [ones(N)'; ϵ * I(N)]'
        ϵ = 1E-8
        L = lauchli(3, ϵ) |> Matrix
```

```
Out[9]: 3×4 Array{Float64,2}:
         1.0  1.0e-8  0.0     0.0
         1.0  0.0     1.0e-8  0.0
         1.0  0.0     0.0     1.0e-8
```

Note that the condition number increases substantially

```
In [10]: @show cond(L)
         @show cond(L' * L);
```

```
   cond(L) = 1.732050807568878e8
cond(L' * L) = 5.345191558726545e32
```

You can show that the analytic eigenvalues of this are $\{3+\epsilon^2, \epsilon^2, \epsilon^2\}$ but the poor conditioning means it is difficult to distinguish these from 0.

This comes up when conducting Principal Component Analysis, which requires calculations of the eigenvalues of the covariance matrix

```
In [11]: sort(sqrt.(Complex.(eigen(L*L').values)), lt = (x,y) -> abs(x) < abs(y))
```

```
Out[11]: 3-element Array{Complex{Float64},1}:
                          0.0 + 4.870456104375987e-9im
          4.2146848510894035e-8 + 0.0im
             1.7320508075688772 + 0.0im
```

Note that these are significantly different than the known analytic solution and, in particular, are difficult to distinguish from 0.

```
In [12]: sqrt.([3 + ϵ^2, ϵ^2, ϵ^2]) |> sort
```

```
Out[12]: 3-element Array{Float64,1}:
          1.0e-8
          1.0e-8
          1.7320508075688772
```

Alternatively, we could calculate these by taking the square of the singular values of L itself, which is much more accurate and lets us clearly distinguish from zero

```
In [13]: svd(L).S  |> sort
```

```
Out[13]: 3-element Array{Float64,1}:
          9.999999999999997e-9
          1.0e-8
          1.7320508075688774
```

Similarly, we are better off calculating least squares directly rather than forming the normal equation (i.e., $A'Ax = A'b$) ourselves

```
In [14]: N = 3
         A = lauchli(N, 1E-7)' |> Matrix
         b = rand(N+1)
         x_sol_1 = A \ b  # using a least-squares solver
         x_sol_2 = (A' * A) \ (A' * b)  # forming the normal equation ourselves
         norm(x_sol_1 - x_sol_2)
```

```
Out[14]: 2502.05373776057
```

23.3.3 Why a Monomial Basis Is a Bad Idea

A classic example of poorly conditioned matrices is using a monomial basis of a polynomial with interpolation.

Take a grid of points, $x_0, \dots x_N$ and values $y_0, \dots y_N$ where we want to calculate the interpolating polynomial.

If we were to use the simplest, and most obvious, polynomial basis, then the calculation consists of finding the coefficients $c_1, \dots c_n$ where

$$P(x) = \sum_{i=0}^{N} c_i x^i$$

To solve for the coefficients, we notice that this is a simple system of equations

c
$$y_0 = c_0 + c_1 x_0 + ... c_N x_0^N$$
$$...$$
$$y_N = c_0 + c_1 x_N + ... c_N x_N^N$$

Or, stacking $c = \begin{bmatrix} c_0 & ... & c_N \end{bmatrix}, y = \begin{bmatrix} y_0 & ... & y_N \end{bmatrix}$ and

$$A = \begin{bmatrix} 1 & x_0 & x_0^2 & ... & x_0^N \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_N & x_N^2 & ... & x_N^N \end{bmatrix}$$

We can then calculate the interpolating coefficients as the solution to

$$Ac = y$$

Implementing this for the interpolation of the $exp(x)$ function

In [15]:
```
N = 5
f(x) = exp(x)
x = range(0.0, 10.0, length = N+1)
y = f.(x)  # generate some data to interpolate

A = [x_i^n for x_i in x, n in 0:N]
A_inv = inv(A)
c = A_inv * y
norm(A * c - f.(x), Inf)
```

Out[15]:
```
1.356966095045209e-9
```

The final step just checks the interpolation vs. the analytic function at the nodes. Keep in mind that this should be very close to zero since we are interpolating the function precisely at those nodes. In our example, the Inf-norm (i.e., maximum difference) of the interpolation errors at the nodes is around `1E-9`, which is reasonable for many problems.

But note that with $N = 5$ the condition number is already of order `1E6`.

In [16]:
```
cond(A)
```

Out[16]:
```
564652.3214053963
```

What if we increase the degree of the polynomial with the hope of increasing the precision of the interpolation?

In [17]:
```
N = 10
f(x) = exp(x)
x = range(0.0, 10.0, length = N+1)
y = f.(x)  # generate some data to interpolate

A = [x_i^n for x_i in x, n in 0:N]
A_inv = inv(A)
c = A_inv * y
norm(A * c - f.(x), Inf)
```

```
Out[17]: 8.61171429278329e-7
```

Here, we see that hoping to increase the precision between points by adding extra polynomial terms is backfiring. By going to a 10th-order polynomial, we have introduced an error of about `1E-5`, even at the interpolation points themselves.

This blows up quickly

```
In [18]: N = 20
         f(x) = exp(x)
         x = range(0.0, 10.0, length = N+1)
         y = f.(x)  # generate some data to interpolate

         A = [x_i^n for x_i in x, n in 0:N]
         A_inv = inv(A)
         c = A_inv * y
         norm(A * c - f.(x), Inf)
```

```
Out[18]: 19978.410967681375
```

To see the source of the problem, note that the condition number is astronomical.

```
In [19]: cond(A)
```

```
Out[19]: 2.0386741019186427e24
```

At this point, you should be suspicious of the use of `inv(A)`, since we have considered solving linear systems by taking the inverse as verboten. Indeed, this made things much worse. The error drops dramatically if we solve it as a linear system

```
In [20]: c = A \ y
         norm(A * c - f.(x), Inf)
```

```
Out[20]: 1.864464138634503e-10
```

But an error of `1E-10` at the interpolating nodes themselves can be a problem in many applications, and if you increase `N` then the error will become non-trivial eventually - even without taking the inverse.

The heart of the issue is that the monomial basis leads to a Vandermonde matrix, which is especially ill-conditioned.

Aside on Runge's Phenomenon

The monomial basis is also a good opportunity to look at a separate type of error due to Runge's Phenomenon. It is an important issue in approximation theory, albeit not one driven by numerical approximation errors.

It turns out that using a uniform grid of points is, in general, the worst possible choice of interpolation nodes for a polynomial approximation. This phenomenon can be seen with the interpolation of the seemingly innocuous Runge's function, $g(x) = \frac{1}{1+25x^2}$.

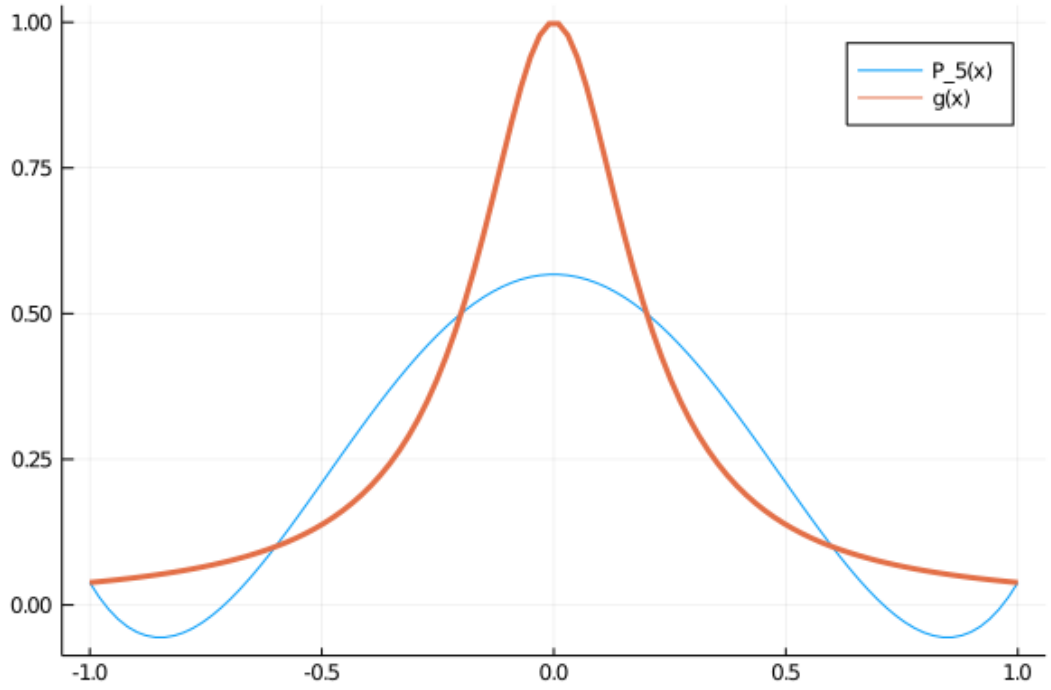
Let's calculate the interpolation with a monomial basis to find the c_i such that

$$\frac{1}{1+25x^2} \approx \sum_{i=0}^{N} c_i x^i, \quad \text{for} \quad -1 \le x \le 1$$

First, interpolate with $N = 5$ and avoid taking the inverse. In that case, as long as we avoid taking an inverse, the numerical errors from the ill-conditioned matrix are manageable.

In [21]:
```
using Plots
gr(fmt=:png);

N_display = 100
g(x) = 1/(1 + 25x^2)
x_display = range(-1, 1, length = N_display)
y_display = g.(x_display)

# interpolation
N = 5
x = range(-1.0, 1.0, length = N+1)
y = g.(x)
A_5 = [x_i^n for x_i in x, n in 0:N]
c_5 = A_5 \ y

# use the coefficients to evaluate on x_display grid
B_5 = [x_i^n for x_i in x_display, n in 0:N]   # calculate monomials for
↪display grid
y_5 = B_5 * c_5  # calculates for each in x_display_grid
plot(x_display, y_5, label = "P_5(x)")
plot!(x_display, y_display, w = 3, label = "g(x)")
```

Out[21]:

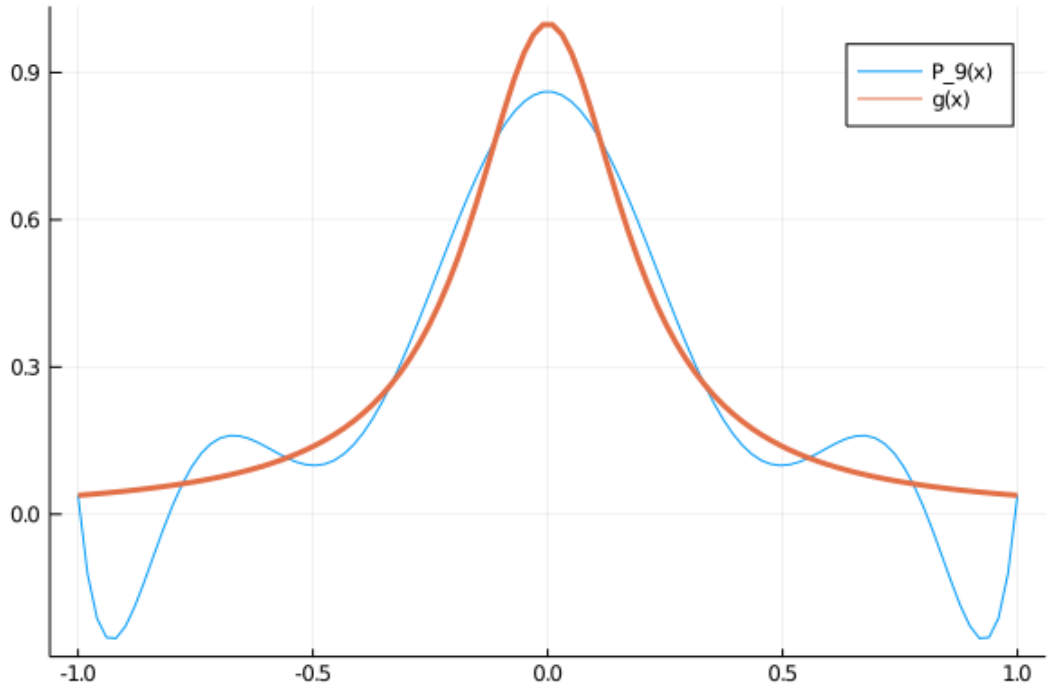


Note that while the function, $g(x)$, and the approximation with a 5th-order polynomial, $P_5(x)$, coincide at the 6 nodes, the approximation has a great deal of error everywhere else.

The oscillations near the boundaries are the hallmarks of Runge's Phenomenon. You might guess that increasing the number of grid points and the order of the polynomial will lead to better approximations:

In [22]:
```
N = 9
x = range(-1.0, 1.0, length = N+1)
y = g.(x)
A_9 = [x_i^n for x_i in x, n in 0:N]
c_9 = A_9 \ y

# use the coefficients to evaluate on x_display grid
B_9 = [x_i^n for x_i in x_display, n in 0:N]   # calculate monomials for display grid
y_9 = B_9 * c_9  # calculates for each in x_display_grid
plot(x_display, y_9, label = "P_9(x)")
plot!(x_display, y_display, w = 3, label = "g(x)")
```

Out[22]:



While the approximation is better near `x=0`, the oscillations near the boundaries have become worse. Adding on extra polynomial terms will not globally increase the quality of the approximation.

Using an Orthogonal Polynomial Basis

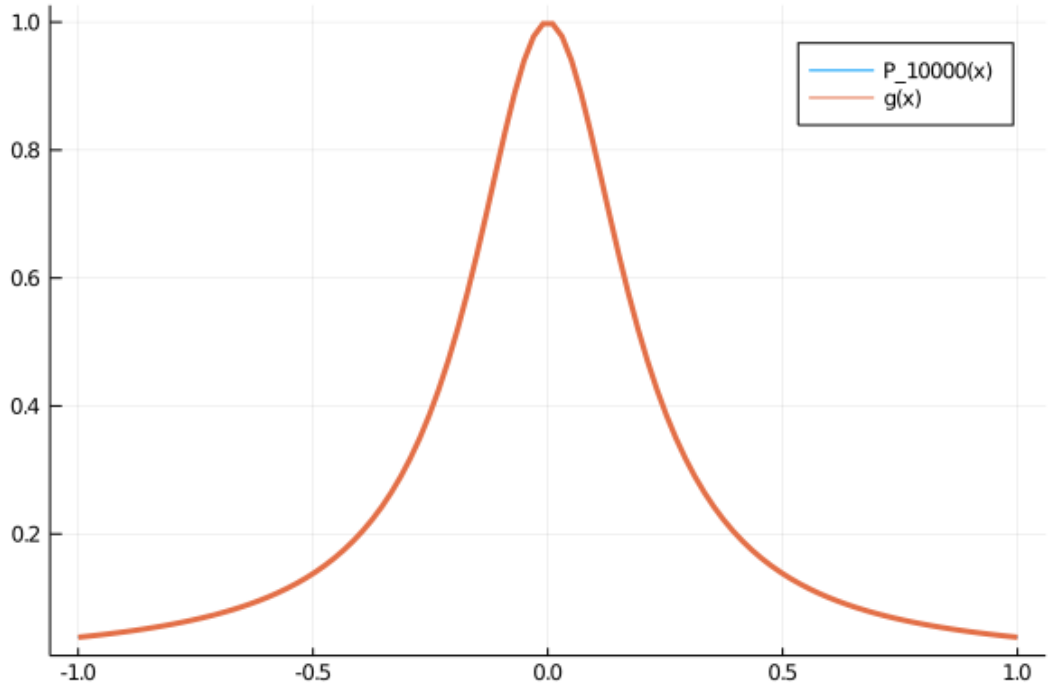
We can minimize the numerical problems of an ill-conditioned basis matrix by choosing a different basis for the polynomials.

For example, Chebyshev polynomials form an orthonormal basis under an appropriate inner product, and we can form precise high-order approximations, with very little numerical error

In [23]:
```
using ApproxFun
N = 10000
S = Chebyshev(-1.0..1.0)  # form Chebyshev basis
x = points(S, N)  # chooses Chebyshev nodes
y = g.(x)
g_approx = Fun(S,ApproxFun.transform(S,y))  # transform fits the polynomial
@show norm(g_approx.(x) - g.(x), Inf)
plot(x_display, g_approx.(x_display), label = "P_10000(x)")
plot!(x_display, g.(x_display), w = 3, label = "g(x)")
```

```
norm(g_approx.(x) - g.(x), Inf) = 4.440892098500626e-16
```

Out[23]:



Besides the use of a different polynomial basis, we are approximating at different nodes (i.e., Chebyshev nodes). Interpolation with Chebyshev polynomials at the Chebyshev nodes ends up minimizing (but not eliminating) Runge's Phenomenon.

Lessons for Approximation and Interpolation

To summarize:

1. Check the condition number on systems you suspect might be ill-conditioned (based on intuition of collinearity).

2. If you are working with ill-conditioned matrices, be especially careful not to take the inverse or multiply by the transpose.
3. Avoid a monomial polynomial basis. Instead, use polynomials (e.g., Chebyshev or Lagrange) orthogonal under an appropriate inner product, or use a non-global basis such as cubic splines.
4. If possible, avoid using a uniform grid for interpolation and approximation, and choose nodes appropriate for the basis.

However, sometimes you can't avoid ill-conditioned matrices. This is especially common with discretization of PDEs and with linear least squares.

23.4 Stationary Iterative Algorithms for Linear Systems

As before, consider solving the equation

$$Ax = b$$

We will now focus on cases where A is both massive (e.g., potentially millions of equations) and sparse, and sometimes ill-conditioned - but where there is always a unique solution.

While this may seem excessive, it occurs in practice due to the curse of dimensionality, discretizations of PDEs, and when working with big data.

The methods in the previous lectures (e.g., factorization and approaches similar to Gaussian elimination) are called direct methods, and are able in theory to converge to the exact solution in a finite number of steps while directly working with the matrix in memory.

Instead, iterative solutions start with a guess on a solution and iterate until convergence. The benefit will be that each iteration uses a lower-order operation (e.g., an $O(N^2)$ matrix-vector product) which will make it possible to

1. solve much larger systems, even if done less precisely.
2. define linear operators in terms of the matrix-vector products, rather than storing as a matrix.
3. get approximate solutions in progress prior to the completion of all algorithm steps, unlike the direct methods, which provide a solution only at the end.

Of course, there is no free lunch, and the computational order of the iterations themselves would be comparable to the direct methods for a given level of tolerance (e.g., $O(N^3)$ operations may be required to solve a dense unstructured system).

There are two types of iterative methods we will consider. The first type is stationary methods, which iterate on a map in a way that's similar to fixed-point problems, and the second type is Krylov methods, which iteratively solve using left-multiplications of the linear operator.

For our main examples, we will use the valuation of the continuous-time Markov chain from the numerical methods for linear algebra lecture. That is, given a payoff vector r, a discount rate ρ, and the infinitesimal generator of the Markov chain Q, solve the equation

$$\rho v = r + Qv$$

With the sizes and types of matrices here, iterative methods are inappropriate in practice, but they will help us understand the characteristics of convergence and how they relate to matrix conditioning.

23.4.1 Stationary Methods

First, we will solve with a direct method, which will give the solution to machine precision.

```
In [24]: using LinearAlgebra, IterativeSolvers, Statistics
         α = 0.1
         N = 100
         Q = Tridiagonal(fill(α, N-1), [-α; fill(-2α, N-2); -α], fill(α, N-1))

         r = range(0.0, 10.0, length=N)
         ρ = 0.05

         A = ρ * I - Q
         v_direct = A \ r
         mean(v_direct)
```

```
Out[24]: 100.00000000000004
```

Without proof, consider that given the discount rate of $\rho > 0$, this problem could be set up as a contraction for solving the Bellman equation through methods such as value-function iteration.

The condition we will examine here is called **diagonal dominance**.

$$|A_{ii}| \geq \sum_{j \neq i} |A_{ij}| \quad \text{for all } i = 1 \dots N$$

That is, in every row, the diagonal element is weakly greater in absolute value than the sum of all of the other elements in the row. In cases where it is strictly greater, we say that the matrix is strictly diagonally dominant.

With our example, given that Q is the infinitesimal generator of a Markov chain, we know that each row sums to 0, and hence it is weakly diagonally dominant.

However, notice that when $\rho > 0$, and since the diagonal of Q is negative, $A = \rho I - Q$ makes the matrix strictly diagonally dominant.

23.4.2 Jacobi Iteration

For matrices that are **strictly diagonally dominant**, you can prove that a simple decomposition and iteration procedure will converge.

To solve a system $Ax = b$, split the matrix A into its diagonal and off-diagonal elements. That is,

$$A = D + R$$

where

$$D = \begin{bmatrix} A_{11} & 0 & \dots & 0 \\ 0 & A_{22} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & A_{NN} \end{bmatrix}$$

and

$$R = \begin{bmatrix} 0 & A_{12} & \dots & A_{1N} \\ A_{21} & 0 & \dots & A_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ A_{N1} & A_{N2} & \dots & 0 \end{bmatrix}$$

Rearrange the $(D + R)x = b$ as

$$\begin{aligned} Dx &= b - Rx \\ x &= D^{-1}(b - Rx) \end{aligned}$$

where, since D is diagonal, its inverse is trivial to calculate with $O(N)$ complexity.

To solve, take an iteration x^k, starting from x^0, and then form a new guess with

$$x^{k+1} = D^{-1}(b - Rx^k)$$

The complexity here is $O(N^2)$ for the matrix-vector product, and $O(N)$ for the vector subtraction and division.

The package IterativeSolvers.jl package implements this method.

For our example, we start with a guess and solve for the value function and iterate

```
In [25]: using IterativeSolvers, LinearAlgebra, SparseArrays
         v = zeros(N)
         jacobi!(v, A, r, maxiter = 40)
         @show norm(v - v_direct, Inf)
```

```
norm(v - v_direct, Inf) = 0.022858373200932647
```

```
Out[25]: 0.022858373200932647
```

With this, after 40 iterations we see that the error is in the order of `1E-2`

23.4.3 Other Stationary Methods

In practice, there are many methods that are better than Jacobi iteration. For example Gauss-Siedel., which splits the matrix $A = L + U$ into a lower-triangular matrix L and an upper-triangular matrix U without the diagonal.

The iteration becomes

$$Lx^{k+1} = b - Ux^k$$

In that case, since the L matrix is triangular, the system can be solved in $O(N^2)$ operations after $b - Ux^k$ is formed

```
In [26]: v = zeros(N)
         gauss_seidel!(v, A, r, maxiter = 40)
         @show norm(v - v_direct, Inf);
```

```
norm(v - v_direct, Inf) = 1.5616376089155892e-5
```

The accuracy increases substantially. After 40 iterations, we see that the error is of the order of `1E-5`

Another example is Successive Over-relaxation (SOR), which takes a relaxation parameter $\omega > 1$ and decomposes the matrix as $A = L + D + U$, where L, U are strictly upper- and lower-diagonal matrices and D is diagonal.

Decompose the A matrix, multiply the system by ω, and rearrange to find

$$(D + \omega L)x^{k+1} = \omega b - (\omega U + (\omega - 1)D)\, x^k$$

In that case, $D + \omega L$ is a triangular matrix, and hence the linear solution is $O(N^2)$.

```
In [27]: v = zeros(N)
         sor!(v, A, r, 1.1, maxiter = 40)
         @show norm(v - v_direct, Inf);
```

```
norm(v - v_direct, Inf) = 3.745356593753968e-7
```

The accuracy is now `1E-7`. If we change the parameter to $\omega = 1.2$, the accuracy further increases to `1E-9`.

This technique is common with iterative methods: Frequently, adding a damping or a relaxation parameter will counterintuitively speed up the convergence process.

Note: The stationary iterative methods are not always used directly, but are sometimes used as a "smoothing" step (e.g., running 5-10 times) prior to using other Krylov methods.

23.5 Krylov Methods

A more commonly used set of iterative methods is based on Krylov subspaces, which involve iterating the $A^k x$ matrix-vector product, and orthogonalizing to ensure that the resulting iteration is not too collinear.

The prototypical Krylov method is Conjugate Gradient, which requires the A matrix to be symmetric and positive definite.

Solving an example:

```
In [28]: N = 100
         A = sprand(100, 100, 0.1)   # 10 percent non-zeros
         A = A * A'  # easy way to generate a symmetric positive-definite matrix
         @show isposdef(A)
         b = rand(N)
         x_direct = A \ b  # sparse direct solver more appropriate here
         cond(Matrix(A * A'))
```

```
isposdef(A) = true
```

```
Out[28]: 3.5791585364800934e10
```

Notice that the condition numbers tend to be large for large random matrices.

Solving this system with the conjugate gradient method:

```
In [29]: x = zeros(N)
         sol = cg!(x, A, b, log=true, maxiter = 1000)
         sol[end]
```

```
Out[29]: Converged after 174 iterations.
```

23.5.1 Introduction to Preconditioning

If you tell a numerical analyst that you are using direct methods, their first question may be, "which factorization?" But if you tell them you are using an iterative method, they may ask "which preconditioner?".

As discussed at the beginning of the lecture, the spectral properties of matrices determine the rate of convergence of iterative methods. In particular, ill-conditioned matrices can converge slowly with iterative methods, for the same reasons that naive value-function iteration will converge slowly if the discount rate is close to `1`.

Preconditioning solves this problem by adjusting the spectral properties of the matrix, at the cost of some extra computational operations.

To see an example of a right-preconditioner, consider a matrix P which has a convenient and numerically stable inverse. Then

$$\begin{aligned} Ax &= b \\ AP^{-1}Px &= b \\ AP^{-1}y &= b \\ Px &= y \end{aligned}$$

That is, solve $(AP^{-1})y = b$ for y, and then solve $Px = y$ for x.

There are all sorts of preconditioners, and they are specific to the particular problem at hand. The key features are that they have convenient (and lower-order!) ways to solve the resulting system and they lower the condition number of the matrix. To see this in action, we can look at a simple preconditioner.

The diagonal precondition is simply `P = Diagonal(A)`. Depending on the matrix, this can change the condition number a little or a lot.

```
In [30]: AP = A * inv(Diagonal(A))
         @show cond(Matrix(A))
         @show cond(Matrix(AP));
```

```
   cond(Matrix(A)) = 189186.6473381337
cond(Matrix(AP)) = 175174.59095330362
```

But it may or may not decrease the number of iterations

```
In [31]: using Preconditioners
         x = zeros(N)
         P = DiagonalPreconditioner(A)
         sol = cg!(x, A, b, log=true, maxiter = 1000)
         sol[end]
```

```
Out[31]: Converged after 174 iterations.
```

Another classic preconditioner is the incomplete LU decomposition

```
In [32]: using IncompleteLU
         x = zeros(N)
         P = ilu(A, τ = 0.1)
         sol = cg!(x, A, b, Pl = P, log=true, maxiter = 1000)
         sol[end]
```

```
Out[32]: Converged after 86 iterations.
```

The τ parameter determines the degree of the LU decomposition to conduct, providing a tradeoff between preconditioner and solve speed.

A good rule of thumb is that you should almost always be using a preconditioner with iterative methods, and you should experiment to find preconditioners that are appropriate for your problem.

Finally, naively trying another preconditioning approach (called Algebraic Multigrid) gives us a further drop in the number of iterations.

```
In [33]: x = zeros(N)
         P = AMGPreconditioner{RugeStuben}(A)
         sol = cg!(x, A, b, Pl = P, log=true, maxiter = 1000)
         sol[end]
```

```
Out[33]: Converged after 59 iterations.
```

Note: Preconditioning is also available for stationary, iterative methods (see this example), but is frequently not implemented since such methods are not often used for the complete solution.

23.5.2 Methods for General Matrices

There are many algorithms which exploit matrix structure (e.g., the conjugate gradient method for positive-definite matrices, and MINRES for matrices that are only symmetric/Hermitian).

On the other hand, if there is no structure to a sparse matrix, then GMRES is a good approach.

To experiment with these methods, we will use our ill-conditioned interpolation problem with a monomial basis.

In [34]:
```
using IterativeSolvers

N = 10
f(x) = exp(x)
x = range(0.0, 10.0, length = N+1)
y = f.(x)  # generate some data to interpolate
A = sparse([x_i^n for x_i in x, n in 0:N])
c = zeros(N+1)  # initial guess required for iterative solutions
results = gmres!(c, A, y, log=true, maxiter = 1000)
println("cond(A) = $(cond(Matrix(A))), $(results[end]) Norm error
↪$(norm(A*c - y,
Inf))")
```

```
cond(A) = 4.462833495403007e12, Converged after 11 iterations. Norm error
7.62520357966423e-8
```

That method converged in 11 iterations. Now if we try it with an incomplete LU preconditioner, we see that it converges immediately.

In [35]:
```
N = 10
f(x) = exp(x)
x = range(0.0, 10.0, length = N+1)
y = f.(x)  # generate some data to interpolate
A = [x_i^n for x_i in x, n in 0:N]
P = ilu(sparse(A), τ = 0.1)
c = zeros(N+1)  # initial guess required for iterative solutions
results = gmres!(c, A, y, Pl = P,log=true, maxiter = 1000)
println("$(results[end]) Norm error $(norm(A*c - y, Inf))")
```

```
Converged after 1 iterations. Norm error 4.5034175855107605e-7
```

With other preconditioners (e.g., `DiagonalPreconditioner`), we may save only one or two iterations. Keep in mind, however, to consider the cost of the preconditioning process in your problem.

23.5.3 Matrix-Free Methods

First, lets use a Krylov method to solve our simple valuation problem

```
In [36]: α = 0.1
         N = 100
         Q = Tridiagonal(fill(α, N-1), [-α; fill(-2α, N-2); -α], fill(α, N-1))

         r = range(0.0, 10.0, length=N)
         ρ = 0.05

         A = ρ * I - Q
         v = zeros(N)
         results = gmres!(v, A, r, log=true)
         v_sol = results[1]
         println("$(results[end])")
```

```
Converged after 20 iterations.
```

While the `A` matrix was important to be kept in memory for direct methods, Krylov methods such as GMRES are built on matrix-vector products, i.e., Ax for iterations on the x.

This product can be written directly for a given x,

$$Ax = \begin{bmatrix} (\rho+\alpha)x_1 - \alpha x_2 \\ -\alpha x_1 + (\rho+2\alpha)x_2 - \alpha x_3 \\ \vdots \\ -\alpha x_{N-2} + (\rho+2\alpha)x_{N-1} - \alpha x_N \\ -\alpha x_{N-1} + (\rho+\alpha)x_N \end{bmatrix}$$

This can be implemented as a function (either in-place or out-of-place) which calculates $y = Ax$

```
In [37]: A_mul(x) = [ (ρ + α) * x[1] - α * x[2];
                      [-α * x[i-1] + (ρ + 2*α) * x[i] - α * x[i+1] for i in 2:N-1];  #
         comprehension
                      - α * x[end-1] + (ρ + α) * x[end]]

         x = rand(N)
         @show norm(A * x - A_mul(x))  # compare to matrix;
```

```
norm(A * x - A_mul(x)) = 0.0
```

The final line verifies that the `A_mul` function provides the same result as the matrix multiplication with our original `A` for a random vector.

In abstract mathematics, a finite-dimensional linear operator is a mapping $A : R^N \to R^N$ that satisfies a number of criteria such as $A(c_1x_1 + c_2x_2) = c_1Ax_1 + c_2Ax_2$ for scalars c_i and vectors x_i.

Moving from abstract mathematics to generic programming, we can think of a linear operator as a map that satisfies a number of requirements (e.g., it has a left-multiply to apply the map `*`, an in-place left-multiply `mul!`, an associated `size`). A Julia matrix is just one possible implementation of the abstract concept of a linear operator.

Convenience wrappers can provide some of the boilerplate which turns the `A_mul` function into something that behaves like a matrix. One package is LinearMaps.jl and another is LinearOperators.jl

```
In [38]: using LinearMaps
         A_map = LinearMap(A_mul, N)  # map uses the A_mul function
```

```
Out[38]: LinearMaps.FunctionMap{Float64}(A_mul, 100, 100; ismutating=false,
↪issymmetric=false,
         ishermitian=false, isposdef=false)
```

Now, with the `A_map` object, we can fulfill many of the operations we would expect from a matrix

```
In [39]: x = rand(N)
         @show norm(A_map * x  - A * x)
         y = similar(x)
         mul!(y, A_map, x) # in-place multiplication
         @show norm(y - A * x)
         @show size(A_map)
         @show norm(Matrix(A_map) - A)
         @show nnz(sparse(A_map));
```

```
    norm(A_map * x - A * x) = 0.0
norm(y - A * x) = 0.0
size(A_map) = (100, 100)
norm(Matrix(A_map) - A) = 0.0
nnz(sparse(A_map)) = 298
```

Note: In the case of `sparse(A_map)` and `Matrix(A_map)`, the code is using the left-multiplication operator with `N` standard basis vectors to construct the full matrix. This should be used only for testing purposes.

But notice that as the linear operator does not have indexing operations, it is not an array or a matrix.

```
In [40]: typeof(A_map) <: AbstractArray
```

```
Out[40]: false
```

As long as algorithms using linear operators are written generically (e.g., using the matrix-vector `*` or `mul!` functionss) and the types of functions are not unnecessarily constrained to be `Matrix` or `AbstractArray` when it isn't strictly necessary, then the `A_map` type can work in places which would otherwise require a matrix.

For example, the Krylov methods in `IterativeSolvers.jl` are written for generic left-multiplication

```
In [41]: results = gmres(A_map, r, log = true)  # Krylov method using the matrix-
free type
         println("$(results[end])")
```

```
Converged after 20 iterations.
```

These methods are typically not competitive with sparse, direct methods unless the problems become very large. In that case, we often want to work with pre-allocated vectors. Instead of using `y = A * x` for matrix-vector products, we would use the in-place `mul!(y, A, x)` function. The wrappers for linear operators all support in-place non-allocating versions for this purpose.

```
In [42]: function A_mul!(y, x)  # in-place version
             y[1] = (ρ + α) * x[1] - α * x[2]
             for i in 2:N-1
                 y[i] = -α * x[i-1] + (ρ + 2α) * x[i] -α * x[i+1]
             end
             y[end] = - α * x[end-1] + (ρ + α) * x[end]
             return y
         end
         A_map_2 = LinearMap(A_mul!, N, ismutating = true)  # ismutating == in-place

         v = zeros(N)
         @show norm(A_map_2 * v - A * v)  # can still call with * and have it
 ↪allocate
         results = gmres!(v, A_map_2, r, log=true)  # in-place gmres
         println("$(results[end])")
```

```
  norm(A_map_2 * v - A * v) = 0.0
Converged after 20 iterations.
```

Finally, keep in mind that the linear operators can compose, so that $A(c_1 x) + B(c_2 x) + x = (c_1 A + c_2 B + I)x$ is well defined for any linear operators - just as it would be for matrices A, B and scalars c_1, c_2.

For example, take $2Ax + x = (2A + I)x \equiv Bx$ as a new linear map,

```
In [43]: B = 2.0 * A_map  + I  # composite linear operator
         B * rand(N)  # left-multiply works with the composition
         typeof(B)
```

```
Out[43]: LinearMaps.LinearCombination{Float64,Tuple{LinearMaps.
 ↪CompositeMap{Float64,Tuple{LinearM
         aps.FunctionMap{Float64,typeof(A_mul),Nothing},LinearMaps.
 ↪UniformScalingMap{Float64}}},L
         inearMaps.UniformScalingMap{Bool}}}
```

The wrappers, such as `LinearMap` wrappers, make this composition possible by keeping the composition graph of the expression (i.e., `LinearCombination`) and implementing the left-multiply recursively using the rules of linearity.

Another example is to solve the $\rho v = r + Qv$ equation for v with composition of matrix-free methods for L rather than by creating the full $A = \rho - Q$ operator, which we implemented as `A_mul`

```
In [44]: Q_mul(x) = [ -α * x[1] +     α * x[2];
                      [α * x[i-1] - 2*α * x[i] + α*x[i+1] for i in 2:N-1];  #
 ↪comprehension
                      α * x[end-1] - α * x[end];]
```

```
Q_map = LinearMap(Q_mul, N)
A_composed = ρ * I - Q_map   # map composition, performs no calculations
@show norm(A - sparse(A_composed))  # test produces the same matrix
gmres(A_composed, r, log=true)[2]
```

```
norm(A - sparse(A_composed)) = 0.0
```

```
Out[44]: Converged after 20 iterations.
```

In this example, the left-multiply of the `A_composed` used by `gmres` uses the left-multiply of `Q_map` and `I` with the rules of linearity. The `A_composed = ρ * I - Q_map` operation simply creates the `LinearMaps.LinearCombination` type, and doesn't perform any calculations on its own.

23.6 Iterative Methods for Linear Least Squares

In theory, the solution to the least-squares problem, $\min_x \|Ax - b\|^2$, is simply the solution to the normal equations $(A'A)x = A'b$.

We saw, however, that in practice, direct methods use a QR decomposition - in part because an ill-conditioned matrix A becomes even worse when $A'A$ is formed.

For large problems, we can also consider Krylov methods for solving the linear least-squares problem. One formulation is the LSMR algorithm, which can solve the regularized

$$\min_x \|Ax - b\|^2 + \|\lambda x\|^2$$

The purpose of the $\lambda \geq 0$ parameter is to dampen the iteration process and/or regularize the solution. This isn't required, but can help convergence for ill-conditioned matrices A. With the damping parameter, the normalized equations would become $(A'A + \lambda^2 I)x = A'b$.

We can compare solving the least-squares problem with LSMR and direct methods

```
In [45]: M = 1000
         N = 10000
         σ = 0.1
         β = rand(M)
         # simulate data
         X = sprand(N, M, 0.1)
         y = X * β + σ * randn(N)
         β_direct = X \ y
         results = lsmr(X, y, log = true)
         β_lsmr = results[1]
         @show norm(β_direct - β_lsmr)
         println("$(results[end])")
```

```
    norm(β_direct - β_lsmr) = 9.139228893911292e-6
Converged after 14 iterations.
```

Note that rather than forming this version of the normal equations, the LSMR algorithm uses the Ax and $A'y$ (i.e., the matrix-vector product and the matrix-transpose vector product) to

implement an iterative solution. Unlike the previous versions, the left-multiply is insufficient since the least squares also deals with the transpose of the operator. For this reason, in order to use matrix-free methods, we need to define the `A * x` and `transpose(A) * y` functions separately.

In [46]:
```
# Could implement as matrix-free functions.
X_func(u) = X * u  # matrix-vector product
X_T_func(v) = X' * v  # i.e., adjoint-vector product

X_map = LinearMap(X_func, X_T_func, N, M)
results = lsmr(X_map, y, log = true)
println("$(results[end])")
```

```
  Converged after 14 iterations.
```

23.7 Iterative Methods for Eigensystems

When you use `eigen` on a dense matrix, it calculates an eigendecomposition and provides all the eigenvalues and eigenvectors.

While this is sometimes necessary, a spectral decomposition of a dense, unstructured matrix is one of the costliest $O(N^3)$ operations (i.e., it has one of the largest constants). For large matrices, it is often infeasible.

Luckily, we frequently need only a few eigenvectors/eigenvalues (in some cases just one), which enables a different set of algorithms.

For example, in the case of a discrete-time Markov chain, in order to find the stationary distribution, we are looking for the eigenvector associated with the eigenvalue 1. As usual, a little linear algebra goes a long way.

From the Perron-Frobenius theorem, the largest eigenvalue of an irreducible stochastic matrix is 1 - the same eigenvalue we are looking for.

Iterative methods for solving eigensystems allow targeting the smallest magnitude, the largest magnitude, and many others. The easiest library to use is Arpack.jl.

As an example,

In [47]:
```
using Arpack, LinearAlgebra
N = 1000
A = Tridiagonal([fill(0.1, N-2); 0.2], fill(0.8, N), [0.2; fill(0.1, N-2);
↪])
A_adjoint = A'

# Find 1 of the largest magnitude eigenvalue
λ, ϕ = eigs(A_adjoint, nev=1, which=:LM, maxiter=1000)
ϕ = real(ϕ) ./ sum(real(ϕ))
@show λ
@show mean(ϕ);
```

```
    λ = Complex{Float64}[1.0000000000000189 + 0.0im]
mean(ϕ) = 0.0010000000000000002
```

Indeed, the λ is equal to `1`. If we choose `nev = 2`, it will provide the eigenpairs with the two eigenvalues of largest absolute value.

Hint: If you get errors using `Arpack`, increase the `maxiter` parameter for your problems.

Iterative methods for eigensystems rely on matrix-vector products rather than decompositions, and are amenable to matrix-free approaches. For example, take the Markov chain for a simple counting process:

1. The count starts at 1 and has a maximum of N.
2. With probability $\theta \geq 0$, an existing count is lost with probability $\zeta \geq 0$ such that $\theta + \zeta \leq 1$.
3. If the count is at 1, then the only transition is to add a count with probability θ.
4. If the current count is N, then the only transition is to lose the count with probability ζ.

First, finding the transition matrix P and its adjoint directly as a check

```
In [48]: θ = 0.1
         ζ = 0.05
         N = 5
         P = Tridiagonal(fill(ζ, N-1), [1-θ; fill(1-θ-ζ, N-2); 1-ζ], fill(θ, N-1))
         P'
```

```
Out[48]: 5×5 Tridiagonal{Float64,Array{Float64,1}}:
          0.9   0.05   ⋅     ⋅     ⋅
          0.1   0.85   0.05   ⋅     ⋅
           ⋅    0.1    0.85  0.05   ⋅
           ⋅     ⋅     0.1   0.85  0.05
           ⋅     ⋅      ⋅    0.1   0.95
```

Implementing the adjoint-vector product directly, and verifying that it gives the same matrix as the adjoint

```
In [49]: P_adj_mul(x) = [ (1-θ) * x[1] + ζ * x[2];
                          [θ * x[i-1] + (1-θ-ζ) * x[i] + ζ * x[i+1] for i in 2:N-1];  #
         comprehension
                      θ * x[end-1] + (1-ζ) * x[end];]
         P_adj_map = LinearMap(P_adj_mul, N)
         @show norm(P' - sparse(P_adj_map))
```

```
norm(P' - sparse(P_adj_map)) = 0.0
```

```
Out[49]: 0.0
```

Finally, solving for the stationary distribution using the matrix-free method (which could be verified against the decomposition approach of P')

```
In [50]: λ, ϕ = eigs(P_adj_map, nev=1, which=:LM, maxiter=1000)
         ϕ = real(ϕ) ./ sum(real(ϕ))
         @show λ
         @show ϕ


           λ = Complex{Float64}[1.0 + 0.0im]
       ϕ = [0.03225806451612657; 0.06451612903225695; 0.1290322580645172;
       0.25806451612903425; 0.516129032258065]


Out[50]: 5×1 Array{Float64,2}:
          0.03225806451612657
          0.06451612903225695
          0.1290322580645172
          0.25806451612903425
          0.516129032258065
```

Of course, for a problem this simple, the direct eigendecomposition will be significantly faster. Use matrix-free iterative methods only for large systems where you do not need all of the eigenvalues.

23.8 Krylov Methods for Markov-Chain Dynamics

This example applies the methods in this lecture to a large continuous-time Markov chain, and provides some practice working with arrays of arbitrary dimensions.

Consider a version of the Markov-chain dynamics in [85], where a firm has a discrete number of customers of different types. To keep things as simple as possible, assume that there are $m = 1, \dots M$ types of customers and that the firm may have $n = 1, \dots N$ customers of each type.

To set the notation, let $n_m \in \{1, \dots N\}$ be the number of customers of type m, so that the state of a firm is $\{n_1, \dots n_m \dots, n_M\}$. The cardinality of possible states is then $\mathbf{N} \equiv N^M$, which can blow up quickly as the number of types increases.

The stochastic process is a simple counting/forgetting process, as follows:

1. For every $1 \leq n_m(t) < N$, there is a θ intensity of arrival of a new customer, so that $n_m(t + \Delta) = n_m(t) + 1$.
2. For every $1 < n_m(t) \leq N$, there is a ζ intensity of losing a customer, so that $n_m(t+\Delta) = n_m(t) - 1$.

23.8.1 Matrix-free Infinitesimal Generator

In order to define an intensity matrix Q of size $\mathbf{N} \times \mathcal{N}$, we need to choose a consistent ordering of the states. But before we enumerate them linearly, take a $v \in R^{\mathbf{N}}$ interpreted as a multidimensional array and look at the left product of the linear operator $Qv \to R^{\mathbf{N}}$.

For example, if we were implementing the product at the row of Q corresponding to the $(n_1, \dots, n_M)$ state, then

$$
\begin{aligned}
Q_{(n_1,\dots n_M)} \cdot v = \theta \sum_{m=1}^{M} (n_m < N) v(n_1, \dots, n_m + 1, \dots, n_M) \\
+ \zeta \sum_{m=1}^{M} (1 < n_m) v(n_1, \dots, n_m - 1, \dots, n_M) \\
- \left(\theta \,\text{Count}(n_m < N) + \zeta \,\text{Count}(n_m > 1)\right) v(n_1, \dots, n_M)
\end{aligned}
$$

Here:

- the first term includes all of the arrivals of new customers into the various m
- the second term is the loss of a customer for the various m
- the last term is the intensity of all exits from this state (i.e., counting the intensity of all other transitions, to ensure that the row will sum to 0)

In practice, rather than working with the f as a multidimensional type, we will need to enumerate the discrete states linearly, so that we can iterate f between 1 and $\mathbf{N}$. An especially convenient approach is to enumerate them in the same order as the K-dimensional Cartesian product of the N states in the multi-dimensional array above.

This can be done with the `CartesianIndices` function, which is used internally in Julia for the `eachindex` function. For example,

```
In [51]: N = 2
         M = 3
         shape = Tuple(fill(N, M))
         v = rand(shape...)
         @show typeof(v)
         for ind in CartesianIndices(v)
             println("v$(ind.I) = $(v[ind])")  # .I gets the tuple to display
         end
```

```
    typeof(v) = Array{Float64,3}
v(1, 1, 1) = 0.639089412234831
v(2, 1, 1) = 0.4302368488000152
v(1, 2, 1) = 0.21490768283644002
v(2, 2, 1) = 0.7542051014748841
v(1, 1, 2) = 0.4330861190374067
v(2, 1, 2) = 0.07556766967902084
v(1, 2, 2) = 0.2143739072351467
v(2, 2, 2) = 0.43231874437572815
```

The added benefit of this approach is that it will be the most efficient way to iterate through vectors in the implementation.

For the counting process with arbitrary dimensions, we will frequently be incrementing or decrementing the m unit vectors of the `CartesianIndex` type with

```
In [52]: e_m = [CartesianIndex((1:M .== i)*1...)  for i in 1:M]
```

```
Out[52]: 3-element Array{CartesianIndex{3},1}:
          CartesianIndex(1, 0, 0)
          CartesianIndex(0, 1, 0)
          CartesianIndex(0, 0, 1)
```

and then use the vector to increment. For example, if the current count is `(1, 2, 2)` and we want to add a count of `1` to the first index and remove a count of `1` from the third index, then

```
In [53]: ind = CartesianIndex(1, 2, 2)  # example counts coming from
  ↪CartesianIndices
         @show ind + e_m[1]  # increment the first index
         @show ind - e_m[3];  # decrement the third index
```

```
    ind + e_m[1] = CartesianIndex(2, 2, 2)
ind - e_m[3] = CartesianIndex(1, 2, 1)
```

This works, of course, because the `CartesianIndex` type is written to support efficient addition and subtraction. Finally, to implement the operator, we need to count the indices in the states where increment and decrement occurs.

```
In [54]: @show ind
         @show count(ind.I .> 1)
         @show count(ind.I .< N);
```

```
    ind = CartesianIndex(1, 2, 2)
count(ind.I .> 1) = 2
count(ind.I .< N) = 1
```

With this, we are now able to write the Q operator on the f vector, which is enumerated by the Cartesian indices. First, collect the parameters in a named tuple generator

```
In [55]: using Parameters, BenchmarkTools
         default_params = @with_kw (θ = 0.1, ζ = 0.05, ρ = 0.03, N = 10, M = 6,
                                    shape = Tuple(fill(N, M)),  # for reshaping
  ↪vector to M-d
         array
                                   e_m = ([CartesianIndex((1:M .== i)*1...)  for i
  ↪in 1:M]))
```

```
Out[55]: ##NamedTuple_kw#256 (generic function with 2 methods)
```

Next, implement the in-place matrix-free product

```
In [56]: function Q_mul!(dv, v, p)
             @unpack θ, ζ, N, M, shape, e_m = p
             v = reshape(v, shape)  # now can access v, dv as M-dim arrays
             dv = reshape(dv, shape)

             @inbounds for ind in CartesianIndices(v)
                 dv[ind] = 0.0
                 for m in 1:M
                     n_m = ind[m]
                     if(n_m < N)
                         dv[ind] += θ * v[ind + e_m[m]]
```

```
                end
                if(n_m > 1)
                    dv[ind] += ζ *v[ind - e_m[m]]
                end
            end
            dv[ind] -= (θ * count(ind.I .< N) + ζ * count(ind.I .> 1)) * v[ind]
        end
    end

    p = default_params()
    v = zeros(p.shape)
    dv = similar(v)
    @btime Q_mul!($dv, $v, $p)
```

```
  55.717 ms (0 allocations: 0 bytes)
```

From the output of the benchmarking, note that the implementation of the left-multiplication takes less than 100 milliseconds, and allocates little or no memory, even though the Markov chain has a million possible states (i.e., $N^M = 10^6$).

23.8.2 Solving a Valuation Problem

As before, we could use this Markov chain to solve a Bellman equation. Assume that the firm discounts at rate $\rho > 0$ and gets a flow payoff of a different z_m per customer of type m. For example, if the state of the firm is $(n_1, n_2, n_3) = (2, 3, 2)$, then it gets $\begin{bmatrix}2 & 3 & 2\end{bmatrix} \cdot \begin{bmatrix}z_1 & z_2 & z_3\end{bmatrix}$ in flow profits.

Given this profit function, we can write the simple Bellman equation in our standard form of $\rho v = r + Qv$, defining the appropriate payoff r. For example, if $z_m = m^2$, then

In [57]:
```
function r_vec(p)
    z = (1:p.M).^2  # payoffs per type m
    r = [0.5 * dot(ind.I, z)  for ind in CartesianIndices(p.shape)]
    return reshape(r, p.N^p.M)  # return as a vector
end
@show typeof(r_vec(p))
r_vec(p) |> mean
```

```
  typeof(r_vec(p)) = Array{Float64,1}
```

Out[57]:
```
250.25
```

Note that the returned r is a vector, enumerated in the same order as the n_m states.

Since the ordering of r is consistent with that of Q, we can solve $(\rho - Q)v = r$ as a linear system.

Below, we create a linear operator and compare the algorithm for a few different iterative methods (GMRES, BiCGStab(l), IDR(s), etc.) with a small problem of only 10,000 possible states.

```
In [58]: p = default_params(N=10, M=4)
         Q = LinearMap((df, f) -> Q_mul!(df, f, p), p.N^p.M, ismutating = true)
         A = p.ρ * I - Q
         A_sparse = sparse(A)  # expensive: use only in tests
         r = r_vec(p)
         v_direct = A_sparse \ r
         iv = zero(r)

         @btime $A_sparse \ $r  # direct
         @show norm(gmres(A, r) - v_direct)
         @btime gmres!(iv, $A, $r) setup = (iv = zero(r))

         @show norm(bicgstabl(A, r) - v_direct)
         @btime bicgstabl!(iv, $A, $r) setup = (iv = zero(r))

         @show norm(idrs(A, r) - v_direct)
         @btime idrs($A, $r);
```

```
      800.500 ms (75 allocations: 181.85 MiB)
norm(gmres(A, r) - v_direct) = 2.390837794373907e-5
  5.714 ms (226 allocations: 3.37 MiB)
norm(bicgstabl(A, r) - v_direct) = 1.108634674599104e-5
  26.098 ms (432 allocations: 9.86 MiB)
norm(idrs(A, r) - v_direct) = 4.5809720133213244e-8
  8.684 ms (297 allocations: 4.75 MiB)
```

Here, we see that even if the A matrix has been created, the direct sparse solver (which uses a sparse LU or QR) is at least an order of magnitude slower and allocates over an order of magnitude more memory. This is in addition to the allocation for the `A_sparse` matrix itself, which is not needed for iterative methods.

The different iterative methods have tradeoffs when it comes to accuracy, speed, convergence rate, memory requirements, and usefulness of preconditioning. Going much above $\mathbf{N} = 10^4$, the direct methods quickly become infeasible.

Putting everything together to solving much larger systems with GMRES as our linear solvers

```
In [59]: function solve_bellman(p; iv = zeros(p.N^p.M))
             @unpack ρ, N, M = p
             Q = LinearMap((df, f) -> Q_mul!(df, f, p), N^M, ismutating = true)
             A = ρ * I - Q
             r = r_vec(p)

             sol = gmres!(iv, A, r, log = false)  # iterative solver, matrix-free
             return sol
         end
         p = default_params(N=10, M=6)
         @btime solve_bellman($p);
```

```
    1.684 s (270 allocations: 366.23 MiB)
```

This solves a value function with a Markov chain of a million states in a little over a second! This general approach seems to scale roughly linearly. For example, try $N = 10, M = 8$ to solve an equation with a Markov chain with 100 million possible states, which can be solved

in about 3-4 minutes. Above that order of magnitude, you may need to tinker with the linear solver parameters to ensure that you are not memory limited (e.g., change the `restart` parameter of GMRES).

23.8.3 Markov Chain Steady State and Dynamics

Recall that given an N-dimensional intensity matrix Q of a CTMC, the evolution of the pdf from an initial condition $\psi(0)$ is the system of linear differential equations

$$\dot{\psi}(t) = Q^T \psi(t)$$

If Q is a matrix, we could just take its transpose to find the adoint. However, with matrix-free methods, we need to implement the adjoint-vector product directly.

The logic for the adjoint is that for a given $n = (n_1, \dots, n_m, \dots n_M)$, the Q^T product for that row has terms enter when

1. $1 < n_m \leq N$, entering into the identical n except with one less customer in the m position
2. $1 \leq n_m < N$, entering into the identical n except with one more customer in the m position

Implementing this logic, first in math and then in code,

$$\begin{aligned} Q^T_{(n_1,\dots,n_M)} \cdot \psi = \theta &\sum_{m=1}^{M} (n_m > 1)\psi(n_1, \dots, n_m - 1, \dots, n_M) \\ &+ \zeta \sum_{m=1}^{M} (n_m < N)\psi(n_1, \dots, n_m + 1, \dots, n_M) \\ &- \left(\theta \,\text{Count}(n_m < N) + \zeta \,\text{Count}(n_m > 1)\right) \psi(n_1, \dots, n_M) \end{aligned}$$

```
In [60]: function Q_T_mul!(dψ, ψ, p)
             @unpack θ, ζ, N, M, shape, e_m = p
             ψ = reshape(ψ, shape)
             dψ = reshape(dψ, shape)

             @inbounds for ind in CartesianIndices(ψ)
                 dψ[ind] = 0.0
                 for m in 1:M
                     n_m = ind[m]
                     if(n_m > 1)
                         dψ[ind] += θ * ψ[ind - e_m[m]]
                     end
                     if(n_m < N)
                         dψ[ind] += ζ *ψ[ind + e_m[m]]
                     end
                 end
                dψ[ind] -= (θ * count(ind.I .< N) + ζ * count(ind.I .> 1)) * ψ[ind]
             end
         end
```

```
Out[60]: Q_T_mul! (generic function with 1 method)
```

The `sparse` function for the operator is useful for testing that the function is correct, and is the adjoint of our `Q` operator.

```
In [61]: p = default_params(N=5, M=4)  # sparse is too slow for the full matrix
         Q = LinearMap((df, f) -> Q_mul!(df, f, p), p.N^p.M, ismutating = true)
         Q_T = LinearMap((dψ, ψ) -> Q_T_mul!(dψ, ψ, p), p.N^p.M, ismutating = true)
         @show norm(sparse(Q)' - sparse(Q_T));  # reminder: use sparse only for
 ↪testing!
```

```
norm((sparse(Q))' - sparse(Q_T)) = 0.0
```

As discussed previously, the steady state can be found as the eigenvector associated with the zero eigenvalue (i.e., the one that solves $Q^T\psi = 0\psi$). We could do this with a dense eigenvalue solution for relatively small matrices

```
In [62]: p = default_params(N=5, M=4)
         eig_Q_T = eigen(Matrix(Q_T))
         vec = real(eig_Q_T.vectors[:,end])
         direct_ψ = vec ./ sum(vec)
         @show eig_Q_T.values[end];
```

```
eig_Q_T.values[end] = -4.163336342344337e-16 + 0.0im
```

This approach relies on a full factorization of the underlying matrix, delivering the entire spectrum. For our purposes, this is not necessary.

Instead, we could use the `Arpack.jl` package to target the eigenvalue of smallest absolute value, which relies on an iterative method.

A final approach in this case is to notice that the $\mathbf{N} \times \mathbf{N}$ matrix is of rank $\mathbf{N} - 1$ when the Markov chain is irreducible. The stationary solution is a vector in the 1-dimensional nullspace of the matrix.

Using Krylov methods to solve a linear system with the right-hand side all 0 values will converge to a point in the nullspace. That is, $\min_x ||Ax - 0||_2$ solved iteratively from a non-zero initial condition will converge to a point in the nullspace.

We can use various Krylov methods for this trick (e.g., if the matrix is symmetric and positive definite, we could use Conjugate Gradient) but in our case we will use GMRES since we do not have any structure.

```
In [63]: p = default_params(N=5, M=4)  # sparse is too slow for the full matrix
         Q_T = LinearMap((dψ, ψ) -> Q_T_mul!(dψ, ψ, p), p.N^p.M, ismutating = true)
         ψ = fill(1/(p.N^p.M), p.N^p.M) # can't use 0 as initial guess
         sol = gmres!(ψ, Q_T, zeros(p.N^p.M))  # i.e., solve Ax = 0 iteratively
         ψ = ψ / sum(ψ)
         @show norm(ψ - direct_ψ);
```

```
norm(ψ - direct_ψ) = 6.098250476301026e-11
```

The speed and memory differences between these methods can be orders of magnitude.

```
In [64]: p = default_params(N=4, M=4)  # Dense and sparse matrices are too slow
  ↪for the full
         dataset.
         Q_T = LinearMap((dψ, ψ) -> Q_T_mul!(dψ, ψ, p), p.N^p.M, ismutating = true)
         Q_T_dense = Matrix(Q_T)
         Q_T_sparse = sparse(Q_T)
         b = zeros(p.N^p.M)
         @btime eigen($Q_T_dense)
         @btime eigs($Q_T_sparse, nev=1, which=:SM, v0 = iv) setup = (iv = fill(1/
  ↪(p.N^p.M),
         p.N^p.M))
         @btime gmres!(iv, $Q_T, $b) setup = (iv = fill(1/(p.N^p.M), p.N^p.M));
```

```
    43.285 ms (270 allocations: 2.28 MiB)
  5.317 ms (341 allocations: 1.21 MiB)
  205.602 μs (359 allocations: 66.03 KiB)
```

The differences become even more stark as the matrix grows. With `default_params(N=5, M=5)`, the `gmres` solution is at least 3 orders of magnitude faster, and uses close to 3 orders of magnitude less memory than the dense solver. In addition, the `gmres` solution is about an order of magnitude faster than the iterative sparse eigenvalue solver.

The algorithm can solve for the steady state of 10^5 states in a few seconds

```
In [65]: function stationary_ψ(p)
             Q_T = LinearMap((dψ, ψ) -> Q_T_mul!(dψ, ψ, p), p.N^p.M, ismutating =
  ↪true)
             ψ = fill(1/(p.N^p.M), p.N^p.M) # can't use 0 as initial guess
             sol = gmres!(ψ, Q_T, zeros(p.N^p.M))  # i.e., solve Ax = 0 iteratively
             return ψ / sum(ψ)
         end
         p = default_params(N=10, M=5)
         @btime stationary_ψ($p);
```

```
    3.374 s (4880 allocations: 19.32 MiB)
```

As a final demonstration, consider calculating the full evolution of the $\psi(t)$ Markov chain. For the constant Q' matrix, the solution to this system of equations is $\psi(t) = \exp(Q')\psi(0)$

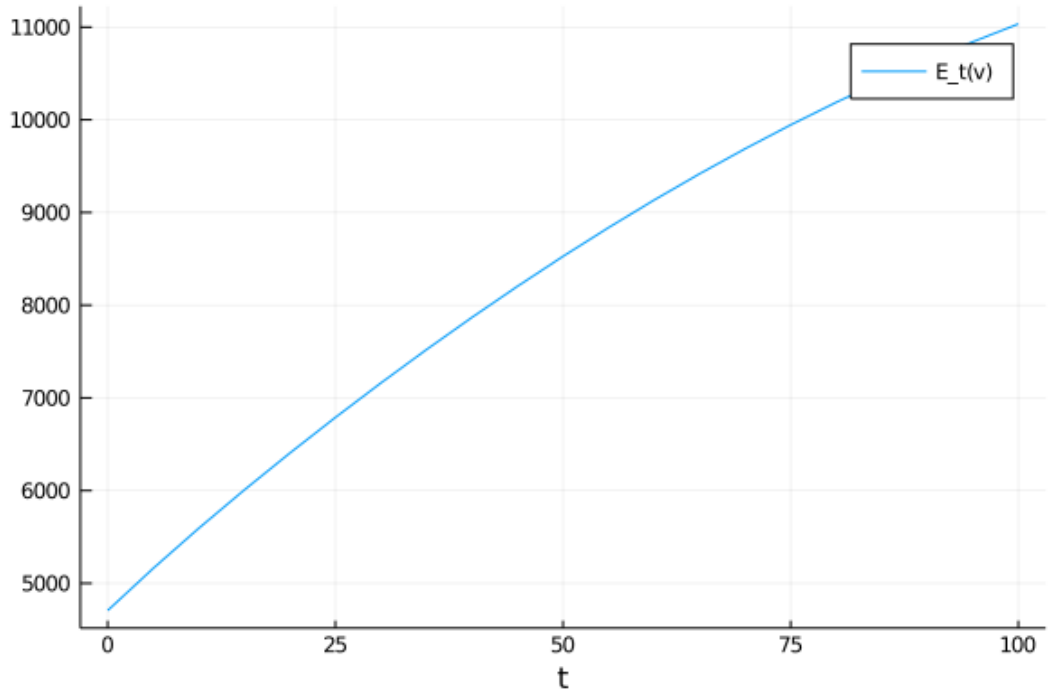
Matrix-free Krylov methods using a technique called exponential integration can solve this for high-dimensional problems.

For this, we can set up a `MatrixFreeOperator` for our `Q_T_mul!` function (equivalent to the `LinearMap`, but with some additional requirements for the ODE solver) and use the LinearExponential time-stepping method.

```
In [66]: using OrdinaryDiffEq, DiffEqOperators

         function solve_transition_dynamics(p, t)
             @unpack N, M = p
```

```
    ψ_0 = [1.0; fill(0.0, N^M - 1)]
    O! = MatrixFreeOperator((dψ, ψ, p, t) -> Q_T_mul!(dψ, ψ, p), (p, 0.0),
                            size=(N^M,N^M), opnorm=(p)->1.25)

    # define the corresponding ODE problem
    prob = ODEProblem(O!,ψ_0,(0.0,t[end]), p)
    return solve(prob, LinearExponential(krylov=:simple), tstops = t)
end
t = 0.0:5.0:100.0
p = default_params(N=10, M=6)
sol = solve_transition_dynamics(p, t)
v = solve_bellman(p)
plot(t, [dot(sol(tval), v) for tval in t], xlabel = "t", label = "E_t(v)")
```

Out[66]:



The above plot (1) calculates the full dynamics of the Markov chain from the $n_m = 1$ for all m initial condition; (2) solves the dynamics of a system of a million ODEs; and (3) uses the calculation of the Bellman equation to find the expected valuation during that transition. The entire process takes less than 30 seconds.

Part IV

Dynamic Programming

Chapter 24

Shortest Paths

24.1 Contents

24.2 Overview

The shortest path problem is a classic problem in mathematics and computer science with applications in

- Economics (sequential decision making, analysis of social networks, etc.)
- Operations research and transportation
- Robotics and artificial intelligence
- Telecommunication network design and routing
- etc., etc.

Variations of the methods we discuss in this lecture are used millions of times every day, in applications such as

- Google Maps
- routing packets on the internet

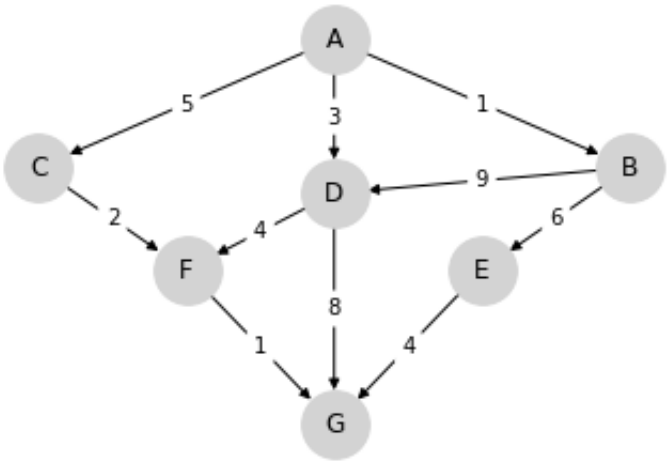
For us, the shortest path problem also provides a nice introduction to the logic of **dynamic programming**.

Dynamic programming is an extremely powerful optimization technique that we apply in many lectures on this site.

24.3 Outline of the Problem

The shortest path problem is one of finding how to traverse a graph from one specified node to another at minimum cost.

Consider the following graph



We wish to travel from node (vertex) A to node G at minimum cost.

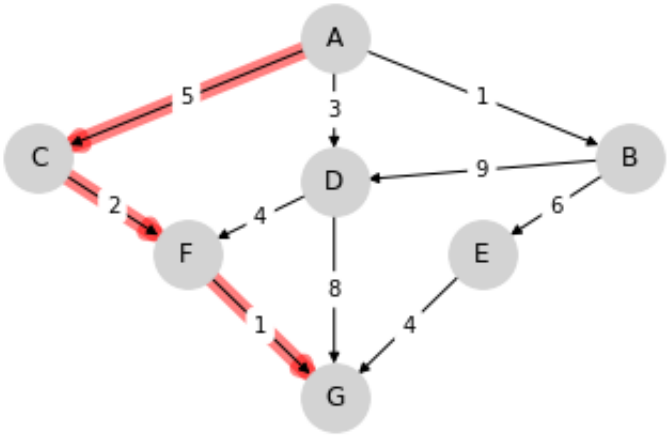
- Arrows (edges) indicate the movements we can take.
- Numbers on edges indicate the cost of traveling that edge.

Possible interpretations of the graph include

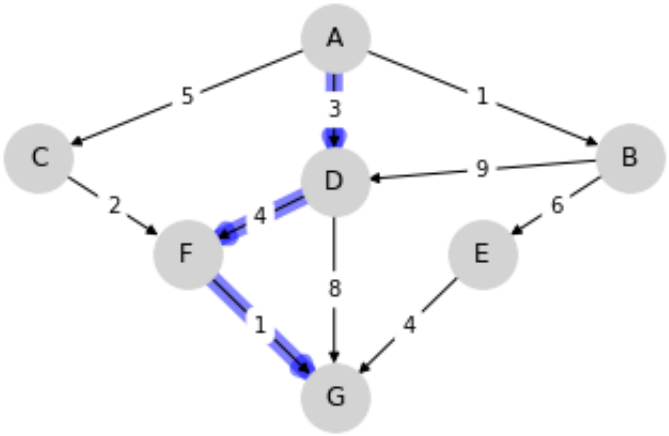
- Minimum cost for supplier to reach a destination.
- Routing of packets on the internet (minimize time).
- Etc., etc.

For this simple graph, a quick scan of the edges shows that the optimal paths are

- A, C, F, G at cost 8



- A, D, F, G at cost 8

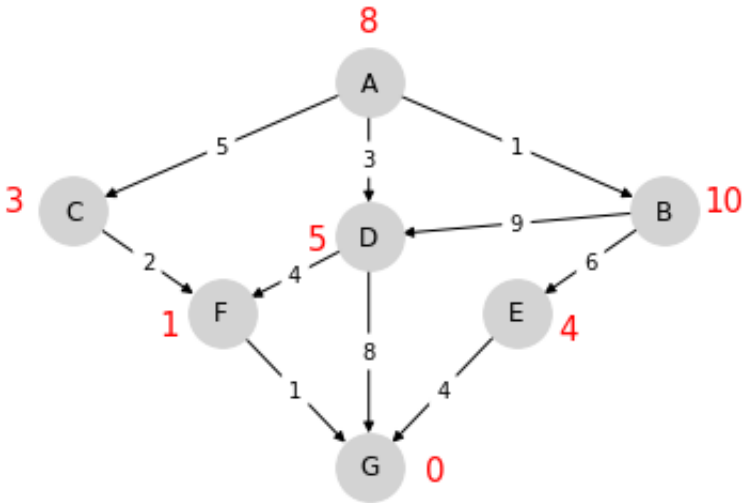


24.4 Finding Least-Cost Paths

For large graphs we need a systematic solution.

Let $J(v)$ denote the minimum cost-to-go from node v, understood as the total cost from v if we take the best route.

Suppose that we know $J(v)$ for each node v, as shown below for the graph from the preceding example



Note that $J(G) = 0$.

The best path can now be found as follows

- Start at A.
- From node v, move to any node that solves

$$\min_{w \in F_v} \{c(v, w) + J(w)\} \tag{1}$$

where

- F_v is the set of nodes that can be reached from v in one step
- $c(v, w)$ is the cost of traveling from v to w

Hence, if we know the function J, then finding the best path is almost trivial.

But how to find J?

Some thought will convince you that, for every node v, the function J satisfies

$$J(v) = \min_{w \in F_v} \{c(v, w) + J(w)\} \tag{2}$$

This is known as the *Bellman equation*, after the mathematician Richard Bellman.

24.5 Solving for J

The standard algorithm for finding J is to start with

$$J_0(v) = M \text{ if } v \neq \text{ destination, else } J_0(v) = 0 \tag{3}$$

where M is some large number.

Now we use the following algorithm

1. Set $n = 0$.
2. Set $J_{n+1}(v) = \min_{w \in F_v} \{c(v, w) + J_n(w)\}$ for all v.
3. If J_{n+1} and J_n are not equal then increment n, go to 2.

In general, this sequence converges to J—the proof is omitted.

24.6 Exercises

24.6.1 Exercise 1

Use the algorithm given above to find the optimal path (and its cost) for the following graph.

24.6.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

```
In [3]: graph = Dict(zip(0:99, [[(14, 72.21), (8, 11.11), (1, 0.04)],[(13, 64.94),
  ↪(6, 20.59),
        (46, 1247.25)],[(45, 1561.45), (31, 166.8), (66, 54.18)],[(11, 42.43), (6,
  ↪2.06), (20,
        133.65)],[(7, 1.02), (5, 0.73), (75, 3706.67)],[(11, 34.54),(7, 3.33),(45,
        1382.97)],[(10, 13.1), (9, 0.72), (31, 63.17)],[(10, 5.85), (9, 3.15),
  ↪(50, 478.14)],
        [(12, 3.18), (11, 7.45), (69, 577.91)],[(20, 16.53), (13, 4.42), (70, 2454.
  ↪28)],[(16,
        25.16), (12, 1.87), (89, 5352.79)],[(20, 65.08), (18, 37.55), (94, 4961.
  ↪32)],[(28,
        170.04), (24, 34.32), (84, 3914.62)],[(40, 475.33), (38, 236.33), (60,
  ↪2135.95)],[(24,
       38.65), (16, 2.7),(67, 1878.96)],[(18, 2.57),(17, 1.01),(91, 3597.11)],[(38,
        278.71),(19, 3.49),(36, 392.92)],[(23, 26.45), (22, 24.78), (76, 783.
  ↪29)],[(28, 55.84),
        (23, 16.23), (91, 3363.17)],[(28, 70.54), (20, 0.24), (26, 20.09)],[(33,
  ↪145.8), (24,
        9.81),(98, 3523.33)],[(31, 27.06),(28, 36.65),(56, 626.04)], [(40, 124.
  ↪22), (39,
        136.32), (72, 1447.22)],[(33, 22.37), (26, 2.66), (52, 336.73)],[(28, 14.
  ↪25), (26, 1.8),
        (66, 875.19)],[(35, 45.55),(32, 36.58),(70, 1343.63)],[(42, 122.0),(27, 0.
  ↪01), (47,
        135.78)],[(43, 246.24), (35, 48.1),(65, 480.55)],[(36, 15.52), (34, 21.
  ↪79), (82,
        2538.18)],[(33, 12.61), (32, 4.22),(64, 635.52)], [(35, 13.95), (33, 5.
  ↪61), (98,
        2616.03)],[(44, 125.88),(36, 20.44), (98, 3350.98)],[(35, 1.46), (34, 3.
  ↪33), (97,
        2613.92)], [(47, 111.54), (41, 3.23), (81, 1854.73)],[(48, 129.45), (42,
  ↪51.52), (73,
        1075.38)],[(50, 78.81), (41, 2.09), (52, 17.57)], [(57, 260.46), (54, 101.
  ↪08), (71,
        1171.6)],[(46, 80.49),(38, 0.36), (75, 269.97)],[(42, 8.78), (40, 1.79),
  ↪(93,
        2767.85)],[(41, 1.34), (40, 0.95), (50, 39.88)],[(54, 53.46), (47, 28.57),
  ↪(75,
        548.68)], [(54, 162.24), (46, 0.28), (53, 18.23)],[(72, 437.49), (47, 10.
  ↪08), (59,
        141.86)],[(60, 116.23), (54, 95.06), (98, 2984.83)], [(47, 2.14), (46, 1.
  ↪56), (91,
        807.39)],[(49, 15.51), (47, 3.68), (58, 79.93)],[(67, 65.48), (57, 27.5),
  ↪(52,
        22.68)],[(61, 172.64), (56, 49.31), (50, 2.82)],[(60, 66.44), (59, 34.52),
  ↪(99,
        2564.12)], [(56, 10.89), (50, 0.51), (78, 53.79)],[(55, 20.1), (53, 1.38),
  ↪(85,
        251.76)],[(60, 73.79),(59, 23.67),(98, 2110.67)], [(66, 123.03), (64, 102.
  ↪41), (94,
        1471.8)],[(67, 88.35),(56, 4.33), (72, 22.85)],[(73, 238.61), (59, 24.3),
  ↪(88,
        967.59)],[(64, 60.8), (57, 2.13), (84, 86.09)],[(61, 11.06), (57, 0.02),
  ↪(76, 197.03)],
        [(60, 7.01), (58, 0.46), (86, 701.09)],[(65, 34.32), (64, 29.85), (83, 556.
  ↪7)],[(71,
```

```
       0.67), (60, 0.72), (90, 820.66)],[(67, 1.63), (65, 4.76), (76, 48.
↪03)],[(64, 4.88), (63,
       0.95), (98, 1057.59)], [(76, 38.43), (64, 2.94), (91, 132.23)],[(75, 56.
↪34), (72,
       70.08), (66, 4.43)],[(76, 11.98), (65, 0.3), (80, 47.73)],[(73, 33.23),
↪(66, 0.64), (94,
       594.93)],[(73, 37.53), (68, 2.66), (98, 395.63)], [(70, 0.98), (68, 0.09),
↪(82,
      153.53)],[(71, 1.66), (70, 3.35), (94, 232.1)],[(73, 8.99), (70, 0.06), (99,
       247.8)],[(73, 8.37), (72, 1.5), (76, 27.18)],[(91, 284.64), (74, 8.86),
↪(89, 104.5)],
       [(92, 133.06), (84, 102.77), (76, 15.32)],[(90, 243.0), (76, 1.4), (83, 52.
↪22)],[(78,
       8.08), (76, 0.52), (81, 1.07)],[(77, 1.19), (76, 0.81), (92, 68.53)],[(78,
↪2.36), (77,
      0.45), (85, 13.18)], [(86, 64.32), (78, 0.98), (80, 8.94)],[(81, 2.59), (98,
       355.9)],[(91, 22.35), (85, 1.45), (81, 0.09)],[(98, 264.34), (88, 28.78),
↪(92,
       121.87)],[(92, 99.89), (89, 39.52), (94, 99.78)],[(93, 11.99), (88, 28.
↪05), (91,
       47.44)],[(88, 5.78), (86, 8.75), (94, 114.95)], [(98, 121.05), (94, 30.
↪41), (89,
       19.14)],[(89, 4.9), (87, 2.66), (97, 94.51)],[(97, 85.09)],[(92, 21.23),
↪(91, 11.14),
       (88, 0.21)], [(98, 6.12), (91, 6.83), (93, 1.31)],[(99, 82.12), (97, 36.
↪97)], [(99,
       50.99), (94, 10.47), (96, 23.53)],[(97, 22.17)],[(99, 34.68), (97, 11.24),
↪(96,
       10.83)],[(99, 32.77), (97, 6.71), (94, 0.19)], [(96, 2.03), (98, 5.
↪91)],[(99, 0.27),
       (98, 6.17)],[(99, 5.87), (97, 0.43), (98, 3.32)],[(98, 0.3)],[(99, 0.
↪33)],[(99, 0.0)]]))
```

```
Out[3]: Dict{Int64,Array{Tuple{Int64,Float64},1}} with 100 entries:
          68 => [(71, 1.66), (70, 3.35), (94, 232.1)]
          2  => [(45, 1561.45), (31, 166.8), (66, 54.18)]
          89 => [(99, 82.12), (97, 36.97)]
          11 => [(20, 65.08), (18, 37.55), (94, 4961.32)]
          39 => [(41, 1.34), (40, 0.95), (50, 39.88)]
          46 => [(67, 65.48), (57, 27.5), (52, 22.68)]
          85 => [(89, 4.9), (87, 2.66), (97, 94.51)]
          25 => [(35, 45.55), (32, 36.58), (70, 1343.63)]
          55 => [(64, 60.8), (57, 2.13), (84, 86.09)]
          42 => [(72, 437.49), (47, 10.08), (59, 141.86)]
          29 => [(33, 12.61), (32, 4.22), (64, 635.52)]
          58 => [(65, 34.32), (64, 29.85), (83, 556.7)]
          66 => [(73, 37.53), (68, 2.66), (98, 395.63)]
          59 => [(71, 0.67), (60, 0.72), (90, 820.66)]
          8  => [(12, 3.18), (11, 7.45), (69, 577.91)]
          74 => [(78, 8.08), (76, 0.52), (81, 1.07)]
          95 => [(99, 0.27), (98, 6.17)]
          57 => [(60, 7.01), (58, 0.46), (86, 701.09)]
          20 => [(33, 145.8), (24, 9.81), (98, 3523.33)]
          90 => [(99, 50.99), (94, 10.47), (96, 23.53)]
          14 => [(24, 38.65), (16, 2.7), (67, 1878.96)]
          31 => [(44, 125.88), (36, 20.44), (98, 3350.98)]
          78 => [(81, 2.59), (98, 355.9)]
```

```
70 => [(73, 8.37), (72, 1.5), (76, 27.18)]
33 => [(47, 111.54), (41, 3.23), (81, 1854.73)]
□  => □
```

The cost from node 68 to node 71 is 1.66 and so on.

24.7 Solutions

24.7.1 Exercise 1

```
In [4]: function update_J!(J, graph)
            next_J = Dict()
            for node in keys(graph)
                if node == 99
                    next_J[node] = 0
                else
                    next_J[node] = minimum(cost + J[dest] for (dest, cost) in□
 ↪graph[node])
                end
            end
            return next_J
        end

        function print_best_path(J, graph)
            sum_costs = 0.0
            current_location, destination = extrema(keys(graph))
            while current_location != destination
                println("node $current_location")
                running_min = 1e10
                minimizer_dest = Inf
                minimizer_cost = 1e10
                for (dest, cost) in graph[current_location]
                    cost_of_path = cost + J[dest]
                    if cost_of_path < running_min
                        running_min = cost_of_path
                        minimizer_cost = cost
                        minimizer_dest = dest
                    end
                end

                current_location = minimizer_dest
                sum_costs += minimizer_cost
            end

            sum_costs = round(sum_costs, digits = 2)

            println("node $destination\nCost: $sum_costs")
        end

        J = Dict((node => Inf) for node in keys(graph))

        while true
            next_J = update_J!(J, graph)
            if next_J == J
                break
```

```
    else
        J = next_J
    end
end

print_best_path(J, graph)
```

```
   node 0
node 8
node 11
node 18
node 23
node 33
node 41
node 53
node 56
node 57
node 60
node 67
node 70
node 73
node 76
node 85
node 87
node 88
node 93
node 94
node 96
node 97
node 98
node 99
Cost: 160.55
```

Chapter 25

Job Search I: The McCall Search Model

25.1 Contents

> "Questioning a McCall worker is like having a conversation with an out-of-work friend: 'Maybe you are setting your sights too high', or 'Why did you quit your old job before you had a new one lined up?' This is real social science: an attempt to model, to understand, human behavior by visualizing the situation people find themselves in, the options they face and the pros and cons as they themselves see them." – Robert E. Lucas, Jr.

25.2 Overview

The McCall search model [76] helped transform economists' way of thinking about labor markets.

To clarify vague notions such as "involuntary" unemployment, McCall modeled the decision problem of unemployed agents directly, in terms of factors such as

- current and likely future wages
- impatience
- unemployment compensation

To solve the decision problem he used dynamic programming.

Here we set up McCall's model and adopt the same solution method.

As we'll see, McCall's model is not only interesting in its own right but also an excellent vehicle for learning dynamic programming.

25.3 The McCall Model

An unemployed worker receives in each period a job offer at wage W_t.

At time t, our worker has two choices:

1. Accept the offer and work permanently at constant wage W_t.
2. Reject the offer, receive unemployment compensation c, and reconsider next period.

The wage sequence $\{W_t\}$ is assumed to be iid with probability mass function $p_1, \ldots, p_n$.

Here p_i is the probability of observing wage offer $W_t = w_i$ in the set $w_1, \ldots, w_n$.

The worker is infinitely lived and aims to maximize the expected discounted sum of earnings.

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t Y_t$$

The constant β lies in $(0, 1)$ and is called a **discount factor**.

The smaller is β, the more the worker discounts future utility relative to current utility.

The variable Y_t is income, equal to

- his wage W_t when employed
- unemployment compensation c when unemployed

25.3.1 A Trade Off

The worker faces a trade-off:

- Waiting too long for a good offer is costly, since the future is discounted.
- Accepting too early is costly, since better offers might arrive in the future.

To decide optimally in the face of this trade off, we use dynamic programming.

Dynamic programming can be thought of as a two step procedure that

1. first assigns values to "states" and
2. then deduces optimal actions given those values

We'll go through these steps in turn.

25.3.2 The Value Function

In order to optimally trade off current and future rewards, we need to think about two things:

1. the current payoffs we get from different choices
2. the different states that those choices will lead to next period (in this case, either employment or unemployment)

To weigh these two aspects of the decision problem, we need to assign *values* to states.

To this end, let $V(w)$ be the total lifetime *value* accruing to an unemployed worker who enters the current period unemployed but with wage offer w in hand.

More precisely, $V(w)$ denotes the value of the objective function (1) when an agent in this situation makes *optimal* decisions now and at all future points in time.

Of course $V(w)$ is not trivial to calculate because we don't yet know what decisions are optimal and what aren't!

But think of V as a function that assigns to each possible wage w the maximal lifetime value that can be obtained with that offer in hand.

A crucial observation is that this function V must satisfy the recursion

$$V(w) = \max \left\{ \frac{w}{1-\beta}, \, c + \beta \sum_{i=1}^{n} V(w_i) p_i \right\} \tag{1}$$

for every possible w_i in $w_1, \ldots, w_n$.

This important equation is a version of the **Bellman equation**, which is ubiquitous in economic dynamics and other fields involving planning over time.

The intuition behind it is as follows:

- the first term inside the max operation is the lifetime payoff from accepting current offer w, since

$$w + \beta w + \beta^2 w + \cdots = \frac{w}{1-\beta}$$

- the second term inside the max operation is the **continuation value**, which is the lifetime payoff from rejecting the current offer and then behaving optimally in all subsequent periods

If we optimize and pick the best of these two options, we obtain maximal lifetime value from today, given current offer w.

But this is precisely $V(w)$, which is the l.h.s. of (1).

25.3.3 The Optimal Policy

Suppose for now that we are able to solve (1) for the unknown function V.

Once we have this function in hand we can behave optimally (i.e., make the right choice between accept and reject).

All we have to do is select the maximal choice on the r.h.s. of (1).

The optimal action is best thought of as a **policy**, which is, in general, a map from states to actions.

In our case, the state is the current wage offer w.

Given *any* w, we can read off the corresponding best choice (accept or reject) by picking the max on the r.h.s. of (1).

Thus, we have a map from $\mathbb{R}$ to $\{0, 1\}$, with 1 meaning accept and zero meaning reject.

We can write the policy as follows

$$\sigma(w) := \mathbf{1}\left\{\frac{w}{1-\beta} \geq c + \beta \sum_{i=1}^{n} V(w_i)p_i\right\}$$

Here $\mathbf{1}\{P\} = 1$ if statement P is true and equals zero otherwise.

We can also write this as

$$\sigma(w) := \mathbf{1}\{w \geq \bar{w}\}$$

where

$$\bar{w} := (1-\beta)\left\{c + \beta \sum_{i=1}^{n} V(w_i)p_i\right\} \tag{2}$$

Here $\bar{w}$ is a constant depending on β, c and the wage distribution, called the *reservation wage*.

The agent should accept if and only if the current wage offer exceeds the reservation wage.

Clearly, we can compute this reservation wage if we can compute the value function.

25.4 Computing the Optimal Policy: Take 1

To put the above ideas into action, we need to compute the value function at points $w_1, \ldots, w_n$.

In doing so, we can identify these values with the vector $v = (v_i)$ where $v_i := V(w_i)$.

In view of (1), this vector satisfies the nonlinear system of equations

$$v_i = \max\left\{\frac{w_i}{1-\beta}, c + \beta \sum_{i=1}^{n} v_i p_i\right\} \quad \text{for } i = 1, \ldots, n \tag{3}$$

It turns out that there is exactly one vector $v := (v_i)_{i=1}^n$ in $\mathbb{R}^n$ that satisfies this equation.

25.4.1 The Algorithm

To compute this vector, we proceed as follows:

Step 1: pick an arbitrary initial guess $v \in \mathbb{R}^n$.

Step 2: compute a new vector $v' \in \mathbb{R}^n$ via

$$v'_i = \max\left\{\frac{w_i}{1-\beta}, c + \beta \sum_{i=1}^{n} v_i p_i\right\} \quad \text{for } i = 1, \ldots, n \tag{4}$$

Step 3: calculate a measure of the deviation between v and v', such as $\max_i |v_i - v'_i|$.

Step 4: if the deviation is larger than some fixed tolerance, set $v = v'$ and go to step 2, else continue.

Step 5: return v.

This algorithm returns an arbitrarily good approximation to the true solution to (3), which represents the value function.

(Arbitrarily good means here that the approximation converges to the true solution as the tolerance goes to zero)

25.4.2 The Fixed Point Theory

What's the math behind these ideas?

First, one defines a mapping T from $\mathbb{R}^n$ to itself via

$$Tv_i = \max \left\{ \frac{w_i}{1-\beta}, \, c + \beta \sum_{i=1}^{n} v_i p_i \right\} \quad \text{for } i = 1, \ldots, n \tag{5}$$

(A new vector Tv is obtained from given vector v by evaluating the r.h.s. at each i)

One can show that the conditions of the Banach contraction mapping theorem are satisfied by T as a self-mapping on $\mathbb{R}^n$.

One implication is that T has a unique fixed point in $\mathbb{R}^n$.

Moreover, it's immediate from the definition of T that this fixed point is precisely the value function.

The iterative algorithm presented above corresponds to iterating with T from some initial guess v.

The Banach contraction mapping theorem tells us that this iterative process generates a sequence that converges to the fixed point.

25.4.3 Implementation

25.4.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Expectations, NLsolve, Roots, Random, Plots, Parameters
```

```
In [3]: gr(fmt = :png);
```

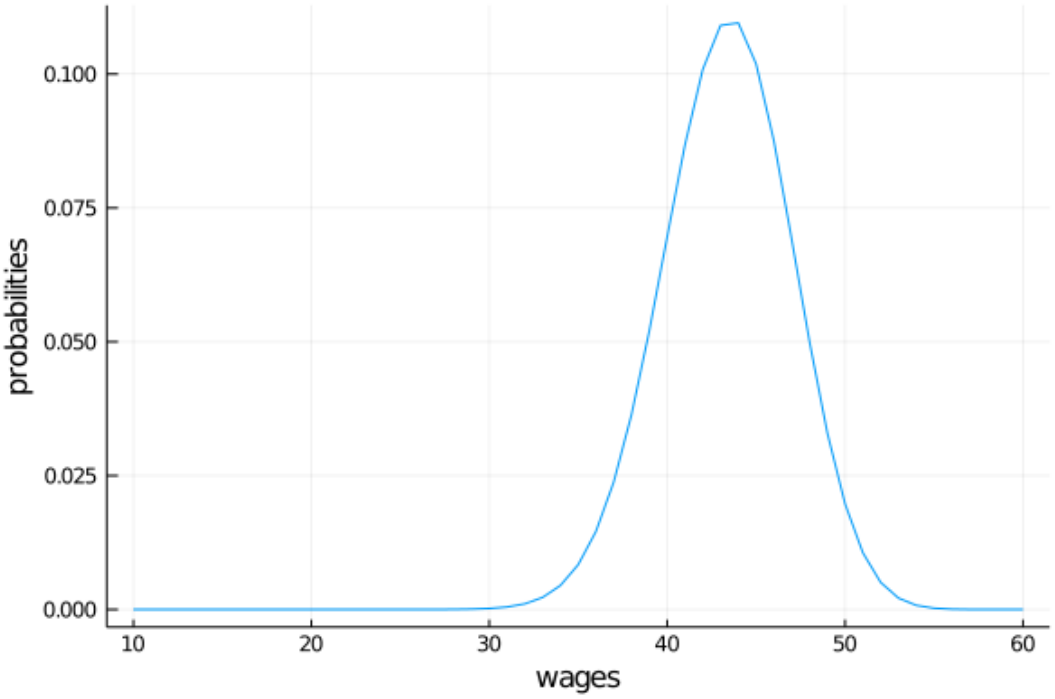
Here's the distribution of wage offers we'll work with

```
In [4]: n = 50
        dist = BetaBinomial(n, 200, 100) # probability distribution
        @show support(dist)
        w = range(10.0, 60.0, length = n+1) # linearly space wages
```

```
using StatsPlots
plt = plot(w, pdf.(dist, support(dist)), xlabel = "wages", ylabel =
↪"probabilities",
legend = false)
```

```
support(dist) = 0:50
```

Out[4]:



We can explore taking expectations over this distribution

In [5]:
```
E = expectation(dist) # expectation operator

# exploring the properties of the operator
wage(i) = w[i+1] # +1 to map from support of 0
E_w = E(wage)
E_w_2 = E(i -> wage(i)^2) - E_w^2 # variance
@show E_w, E_w_2

# use operator with left-multiply
@show E * w # the `w` are values assigned for the discrete states
@show dot(pdf.(dist, support(dist)), w); # identical calculation
```

```
(E_w, E_w_2) = (43.333333333335695, 12.919896640724573)
E * w = 43.3333333333357
dot(pdf.(dist, support(dist)), w) = 43.3333333333357
```

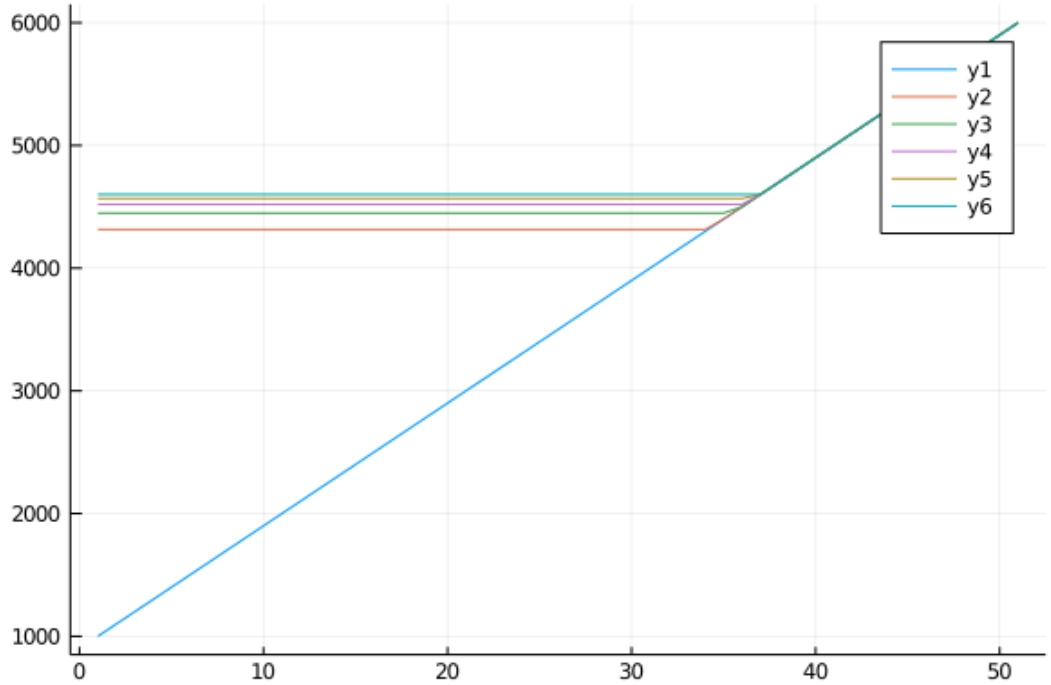
To implement our algorithm, let's have a look at the sequence of approximate value functions that this fixed point algorithm generates.

Default parameter values are embedded in the function.

Our initial guess v is the value of accepting at every given wage

In [6]:
```
# parameters and constant objects

c = 25
β = 0.99
num_plots = 6

# Operator
T(v) = max.(w/(1 - β), c + β * E*v) # (5) broadcasts over the w, fixes the v
# alternatively, T(v) = [max(wval/(1 - β), c + β * E*v) for wval in w]

# fill in  matrix of vs
vs = zeros(n + 1, 6) # data to fill
vs[:, 1] .= w / (1-β) # initial guess of "accept all"

# manually applying operator
for col in 2:num_plots
    v_last = vs[:, col - 1]
    vs[:, col] .= T(v_last)  # apply operator
end
plot(vs)
```

Out[6]:



One approach to solving the model is to directly implement this sort of iteration, and continues until measured deviation between successive iterates is below tol

In [7]:
```
function compute_reservation_wage_direct(params; v_iv = collect(w ./(1-
β)), max_iter =
        500,
```

```
                                                tol = 1e-6)
    @unpack c, β, w = params

    # create a closure for the T operator
    T(v) = max.(w/(1 - β), c + β * E*v) # (5) fixing the parameter values

    v = copy(v_iv) # start at initial value.  copy to prevent v_iv
↪modification
    v_next = similar(v)
    i = 0
    error = Inf
    while i < max_iter && error > tol
        v_next .= T(v) # (4)
        error = norm(v_next - v)
        i += 1
        v .= v_next  # copy contents into v.  Also could have used v[:] =
↪v_next
    end
    # now compute the reservation wage
    return (1 - β) * (c + β * E*v) # (2)
end
```

```
Out[7]: compute_reservation_wage_direct (generic function with 1 method)
```

In the above, we use `v = copy(v_iv)` rather than just `v_iv = v`.

To understand why, first recall that `v_iv` is a function argument – either defaulting to the given value, or passed into the function

- If we had gone `v = v_iv` instead, then it would have simply created a new name `v` which binds to whatever is located at `v_iv`.

- Since we later use `v .= v_next` later in the algorithm, the values in it would be modified.
- Hence, we would be modifying the `v_iv` vector we were passed in, which may not be what the caller of the function wanted.
- The big issue this creates are "side-effects" where you can call a function and strange things can happen outside of the function that you didn't expect.
- If you intended for the modification to potentially occur, then the Julia style guide says that we should call the function `compute_reservation_wage_direct!` to make the possible side-effects clear.

As usual, we are better off using a package, which may give a better algorithm and is likely to less error prone.

In this case, we can use the `fixedpoint` algorithm discussed in our Julia by Example lecture to find the fixed point of the T operator.

```
In [8]: function compute_reservation_wage(params; v_iv = collect(w ./(1-β)),
↪iterations = 500,
                                        ftol = 1e-6, m = 6)
    @unpack c, β, w = params
    T(v) = max.(w/(1 - β), c + β * E*v) # (5) fixing the parameter values

    v_star = fixedpoint(T, v_iv, iterations = iterations, ftol = ftol,
```

```
                            m = 0).zero # (5)
        return (1 - β) * (c + β * E*v_star) # (3)
    end
```

```
Out[8]: compute_reservation_wage (generic function with 1 method)
```

Let's compute the reservation wage at the default parameters

```
In [9]: mcm = @with_kw (c=25.0, β=0.99, w=w) # named tuples

        compute_reservation_wage(mcm()) # call with default parameters
```

```
Out[9]: 47.31649970147162
```

25.4.5 Comparative Statics

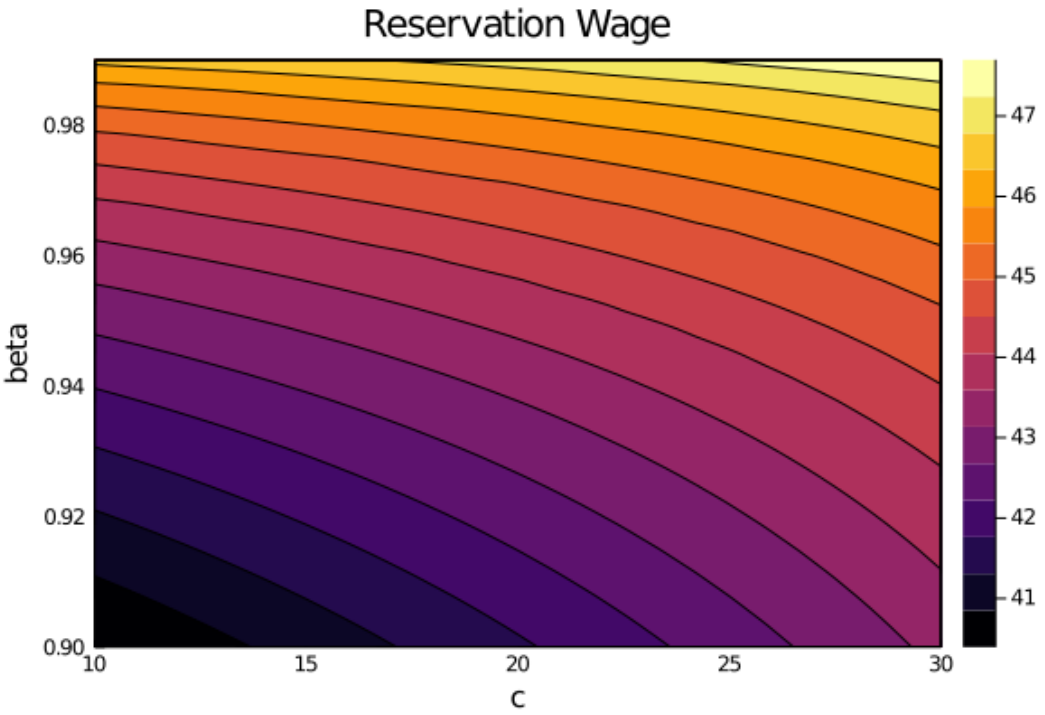
Now we know how to compute the reservation wage, let's see how it varies with parameters.

In particular, let's look at what happens when we change β and c.

```
In [10]: grid_size = 25
         R = rand(grid_size, grid_size)

         c_vals = range(10.0, 30.0, length = grid_size)
         β_vals = range(0.9, 0.99, length = grid_size)

         for (i, c) in enumerate(c_vals)
             for (j, β) in enumerate(β_vals)
                 R[i, j] = compute_reservation_wage(mcm(c=c, β=β)) # change from
 ↪defaults
             end
         end
```

```
In [11]: contour(c_vals, β_vals, R',
                 title = "Reservation Wage",
                 xlabel = "c",
                 ylabel = "beta",
                 fill = true)
```

```
Out[11]:
```



As expected, the reservation wage increases both with patience and with unemployment compensation.

25.5 Computing the Optimal Policy: Take 2

The approach to dynamic programming just described is very standard and broadly applicable.

For this particular problem, there's also an easier way, which circumvents the need to compute the value function.

Let ψ denote the value of not accepting a job in this period but then behaving optimally in all subsequent periods.

That is,

$$\psi = c + \beta \sum_{i=1}^{n} V(w_i) p_i \tag{6}$$

where V is the value function.

By the Bellman equation, we then have

$$V(w_i) = \max \left\{ \frac{w_i}{1-\beta}, \psi \right\}$$

Substituting this last equation into (6) gives

$$\psi = c + \beta \sum_{i=1}^{n} \max \left\{ \frac{w_i}{1-\beta}, \psi \right\} p_i \tag{7}$$

Which we could also write as $\psi = T_\psi(\psi)$ for the appropriate operator.

This is a nonlinear equation that we can solve for ψ.

One solution method for this kind of nonlinear equation is iterative.

That is,

Step 1: pick an initial guess ψ.

Step 2: compute the update ψ' via

$$\psi' = c + \beta \sum_{i=1}^{n} \max\left\{\frac{w_i}{1-\beta}, \psi\right\} p_i \tag{8}$$

Step 3: calculate the deviation $|\psi - \psi'|$.

Step 4: if the deviation is larger than some fixed tolerance, set $\psi = \psi'$ and go to step 2, else continue.

Step 5: return ψ.

Once again, one can use the Banach contraction mapping theorem to show that this process always converges.

The big difference here, however, is that we're iterating on a single number, rather than an n-vector.

Here's an implementation:

```
In [12]: function compute_reservation_wage_ψ(c, β; ψ_iv = E * w ./ (1 - β),
  ↪max_iter = 500,
                                                tol = 1e-5)
             T_ψ(ψ) = [c + β * E*max.((w ./ (1 - β)), ψ[1])] # (7)
             # using vectors since fixedpoint doesn't support scalar
             ψ_star = fixedpoint(T_ψ, [ψ_iv]).zero[1]
             return (1 - β) * ψ_star # (2)
         end
         compute_reservation_wage_ψ(c, β)
```

```
Out[12]: 47.31649976654629
```

You can use this code to solve the exercise below.

Another option is to solve for the root of the $T_\psi(\psi) - \psi$ equation

```
In [13]: function compute_reservation_wage_ψ2(c, β; ψ_iv = E * w ./ (1 - β),
  ↪max_iter = 500,
                                                tol = 1e-5)
             root_ψ(ψ) = c + β * E*max.((w ./ (1 - β)), ψ) - ψ # (7)
             ψ_star = find_zero(root_ψ, ψ_iv)
             return (1 - β) * ψ_star # (2)
         end
         compute_reservation_wage_ψ2(c, β)
```

```
Out[13]: 47.316499766546194
```

25.6 Exercises

25.6.1 Exercise 1

Compute the average duration of unemployment when $\beta = 0.99$ and c takes the following values

```
c_vals = range(10, 40, length = 25)
```

That is, start the agent off as unemployed, computed their reservation wage given the parameters, and then simulate to see how long it takes to accept.

Repeat a large number of times and take the average.

Plot mean unemployment duration as a function of c in `c_vals`.

25.7 Solutions

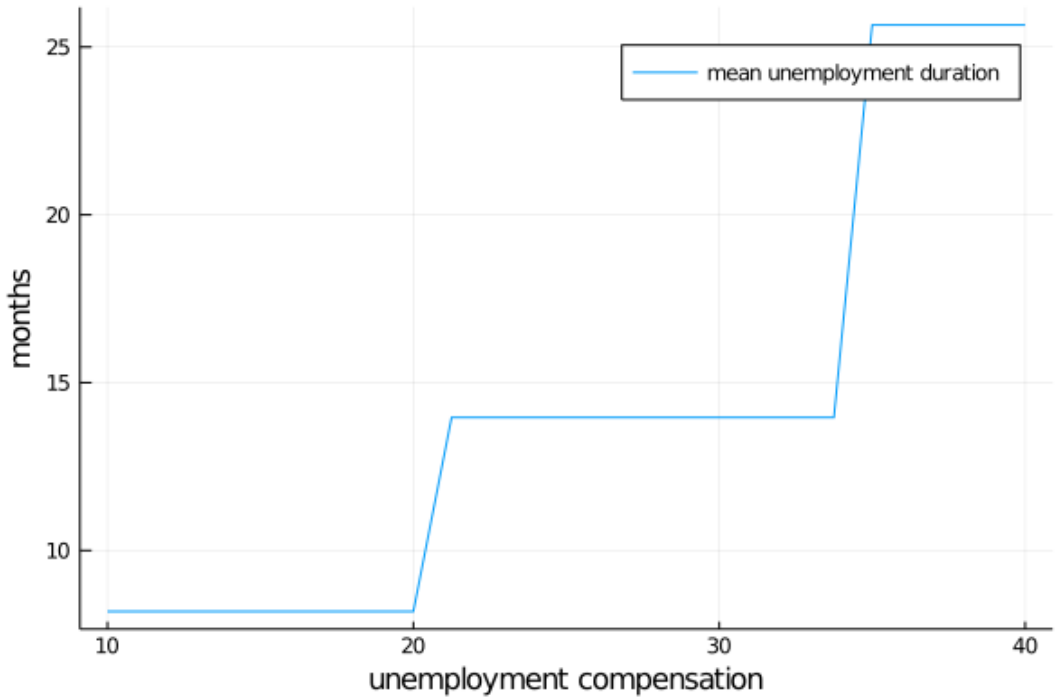
25.7.1 Exercise 1

Here's one solution

```
In [14]: function compute_stopping_time(w; seed=1234)
             Random.seed!(seed)
             stopping_time = 0
             t = 1
             # make sure the constraint is sometimes binding
             @assert length(w) - 1  support(dist) && w <= w[end]
             while true
                 # Generate a wage draw
                 w_val = w[rand(dist)] # the wage dist set up earlier
                 if w_val ≥ w
                     stopping_time = t
                     break
                 else
                     t += 1
                 end
             end
             return stopping_time
         end

         compute_mean_stopping_time(w, num_reps=10000) = mean(i ->
                                                              compute_stopping_time(w,
                                                                seed = i), 1:num_reps)
         c_vals = range(10,  40, length = 25)
         stop_times = similar(c_vals)

         beta = 0.99
         for (i, c) in enumerate(c_vals)
             w = compute_reservation_wage_ψ(c, beta)
             stop_times[i] = compute_mean_stopping_time(w)
```

```
    end

    plot(c_vals, stop_times, label = "mean unemployment duration",
         xlabel = "unemployment compensation", ylabel = "months")
```

Out[14]:



Chapter 26

Job Search II: Search and Separation

26.1 Contents

26.2 Overview

Previously we looked at the McCall job search model [76] as a way of understanding unemployment and worker decisions.

One unrealistic feature of the model is that every job is permanent.

In this lecture we extend the McCall model by introducing job separation.

Once separation enters the picture, the agent comes to view

- the loss of a job as a capital loss, and
- a spell of unemployment as an *investment* in searching for an acceptable job

26.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Expectations, Parameters, NLsolve, Plots
```

26.3 The Model

The model concerns the life of an infinitely lived worker and

- the opportunities he or she (let's say he to save one character) has to work at different wages
- exogenous events that destroy his current job
- his decision making process while unemployed

The worker can be in one of two states: employed or unemployed.

He wants to maximize

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t u(Y_t) \tag{1}$$

The only difference from the baseline model is that we've added some flexibility over preferences by introducing a utility function u.

It satisfies $u' > 0$ and $u'' < 0$.

26.3.1 Timing and Decisions

Here's what happens at the start of a given period in our model with search and separation.

If currently *employed*, the worker consumes his wage w, receiving utility $u(w)$.

If currently *unemployed*, he

- receives and consumes unemployment compensation c
- receives an offer to start work *next period* at a wage w' drawn from a known distribution $p_1, \ldots, p_n$

He can either accept or reject the offer.

If he accepts the offer, he enters next period employed with wage w'.

If he rejects the offer, he enters next period unemployed.

When employed, the agent faces a constant probability α of becoming unemployed at the end of the period.

(Note: we do not allow for job search while employed—this topic is taken up in a later lecture)

26.4 Solving the Model using Dynamic Programming

Let

- $V(w)$ be the total lifetime value accruing to a worker who enters the current period *employed* with wage w.
- U be the total lifetime value accruing to a worker who is *unemployed* this period.

Here *value* means the value of the objective function (1) when the worker makes optimal decisions at all future points in time.

Suppose for now that the worker can calculate the function V and the constant U and use them in his decision making.

Then V and U should satisfy

$$V(w) = u(w) + \beta[(1-\alpha)V(w) + \alpha U] \tag{2}$$

and

$$U = u(c) + \beta \sum_i \max\{U, V(w_i)\} p_i \tag{3}$$

Let's interpret these two equations in light of the fact that today's tomorrow is tomorrow's today.

- The left hand sides of equations (2) and (3) are the values of a worker in a particular situation *today*.
- The right hand sides of the equations are the discounted (by β) expected values of the possible situations that worker can be in *tomorrow*.
- But *tomorrow* the worker can be in only one of the situations whose values *today* are on the left sides of our two equations.

Equation (3) incorporates the fact that a currently unemployed worker will maximize his own welfare.

In particular, if his next period wage offer is w', he will choose to remain unemployed unless $U < V(w')$.

Equations (2) and (3) are the Bellman equations for this model.

Equations (2) and (3) provide enough information to solve out for both V and U.

Before discussing this, however, let's make a small extension to the model.

26.4.1 Stochastic Offers

Let's suppose now that unemployed workers don't always receive job offers.

Instead, let's suppose that unemployed workers only receive an offer with probability γ.

If our worker does receive an offer, the wage offer is drawn from p as before.

He either accepts or rejects the offer.

Otherwise the model is the same.

With some thought, you will be able to convince yourself that V and U should now satisfy

$$V(w) = u(w) + \beta[(1-\alpha)V(w) + \alpha U] \tag{4}$$

and

$$U = u(c) + \beta(1-\gamma)U + \beta\gamma \sum_i \max\{U, V(w_i)\} p_i \tag{5}$$

26.4.2 Solving the Bellman Equations

We'll use the same iterative approach to solving the Bellman equations that we adopted in the first job search lecture.

Here this amounts to

1. make guesses for U and V
2. plug these guesses into the right hand sides of (4) and (5)
3. update the left hand sides from this rule and then repeat

In other words, we are iterating using the rules

$$V_{n+1}(w_i) = u(w_i) + \beta[(1-\alpha)V_n(w_i) + \alpha U_n] \tag{6}$$

and

$$U_{n+1} = u(c) + \beta(1-\gamma)U_n + \beta\gamma \sum_i \max\{U_n, V_n(w_i)\}p_i \tag{7}$$

starting from some initial conditions U_0, V_0.

Formally, we can define a "Bellman operator" T which maps:

$$TV(\cdot) = u(\cdot) + \beta(1-\alpha)V(\cdot) + \alpha U \tag{8}$$

In which case we are searching for a fixed point

$$TV^* = V^* \tag{9}$$

As before, the system always converges to the true solutions—in this case, the V and U that solve (4) and (5).

A proof can be obtained via the Banach contraction mapping theorem.

26.5 Implementation

Let's implement this iterative process

```
In [3]: using Distributions, LinearAlgebra, Expectations, Parameters, NLsolve,
        Plots

        function solve_mccall_model(mcm; U_iv = 1.0, V_iv = ones(length(mcm.w)),
        tol = 1e-5,
                                    iter = 2_000)
            # α, β, σ, c, γ, w = mcm.α, mcm.β, mcm.σ, mcm.c, mcm.γ, mcm.w
            @unpack α, β, σ, c, γ, w, dist, u = mcm

            # parameter validation
```

```
        @assert c > 0.0
        @assert minimum(w) > 0.0 # perhaps not strictly necessary, but useful
↪here

        # necessary objects
        u_w = u.(w, σ)
        u_c = u(c, σ)
        E = expectation(dist) # expectation operator for wage distribution

        # Bellman operator T. Fixed point is x* s.t. T(x*) = x*
        function T(x)
            V = x[1:end-1]
            U = x[end]
            [u_w + β * ((1 - α) * V .+ α * U); u_c + β * (1 - γ) * U + β * γ * E
↪* max.(U,
        V)]
        end

        # value function iteration
        x_iv = [V_iv; U_iv] # initial x val
        xstar = fixedpoint(T, x_iv, iterations = iter, xtol = tol, m = 0).zero
        V = xstar[1:end-1]
        U = xstar[end]

        # compute the reservation wage
        wbarindex = searchsortedfirst(V .- U, 0.0)
        if wbarindex >= length(w) # if this is true, you never want to accept
            w̄ = Inf
        else
            w̄ = w[wbarindex] # otherwise, return the number
        end

        # return a NamedTuple, so we can select values by name
        return (V = V, U = U, w̄ = w̄)
    end
```

```
Out[3]: solve_mccall_model (generic function with 1 method)
```

The approach is to iterate until successive iterates are closer together than some small tolerance level.

We then return the current iterate as an approximate solution.

Let's plot the approximate solutions U and V to see what they look like.

We'll use the default parameterizations found in the code above.

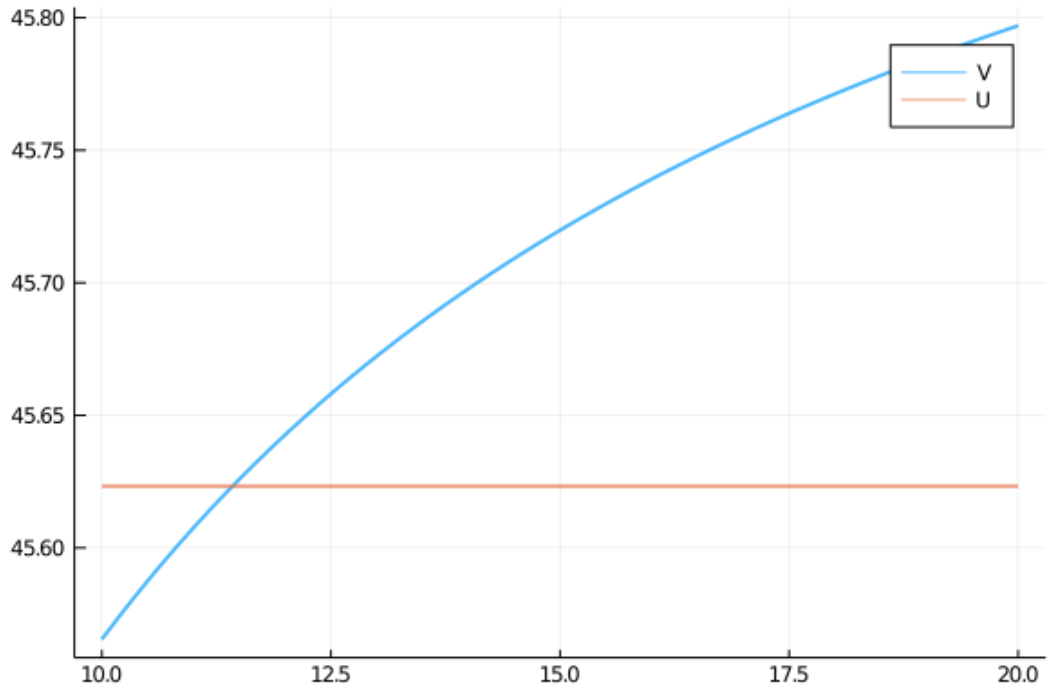
```
In [4]: # a default utility function
        u(c, σ) = (c^(1 - σ) - 1) / (1 - σ)

        # model constructor
        McCallModel = @with_kw (α = 0.2,
            β = 0.98, # discount rate
            γ = 0.7,
            c = 6.0, # unemployment compensation
            σ = 2.0,
```

```
    u = u, # utility function
    w = range(10, 20, length = 60), # wage values
    dist = BetaBinomial(59, 600, 400)) # distribution over wage values
```

```
Out[4]: ##NamedTuple_kw#254 (generic function with 2 methods)
```

```
In [5]: # plots setting
        gr(fmt=:png);

        mcm = McCallModel()
        @unpack V, U = solve_mccall_model(mcm)
        U_vec = fill(U, length(mcm.w))

        plot(mcm.w, [V U_vec], lw = 2, α = 0.7, label = ["V" "U"])
```

```
Out[5]:
```



The value V is increasing because higher w generates a higher wage flow conditional on staying employed.

At this point, it's natural to ask how the model would respond if we perturbed the parameters.

These calculations, called comparative statics, are performed in the next section.

26.6 The Reservation Wage

Once V and U are known, the agent can use them to make decisions in the face of a given wage offer.

If $V(w) > U$, then working at wage w is preferred to unemployment.

If $V(w) < U$, then remaining unemployed will generate greater lifetime value.

Suppose in particular that V crosses U (as it does in the preceding figure).

Then, since V is increasing, there is a unique smallest w in the set of possible wages such that $V(w) \geq U$.

We denote this wage $\bar{w}$ and call it the reservation wage.

Optimal behavior for the worker is characterized by $\bar{w}$

- if the wage offer w in hand is greater than or equal to $\bar{w}$, then the worker accepts
- if the wage offer w in hand is less than $\bar{w}$, then the worker rejects

If $V(w) < U$ for all w, then the function returns np.inf.

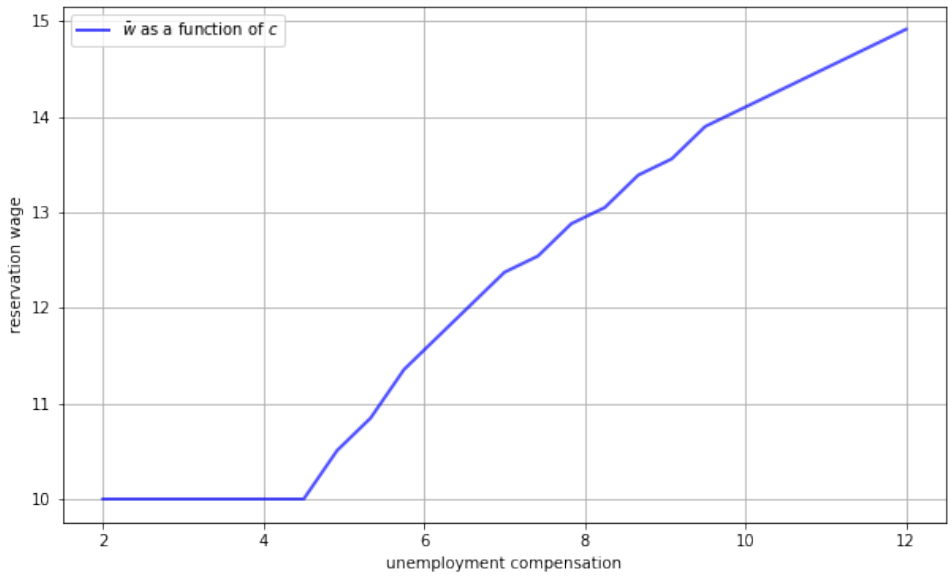
Let's use it to look at how the reservation wage varies with parameters.

In each instance below we'll show you a figure and then ask you to reproduce it in the exercises.

26.6.1 The Reservation Wage and Unemployment Compensation

First, let's look at how $\bar{w}$ varies with unemployment compensation.

In the figure below, we use the default parameters in the McCallModel tuple, apart from c (which takes the values given on the horizontal axis)



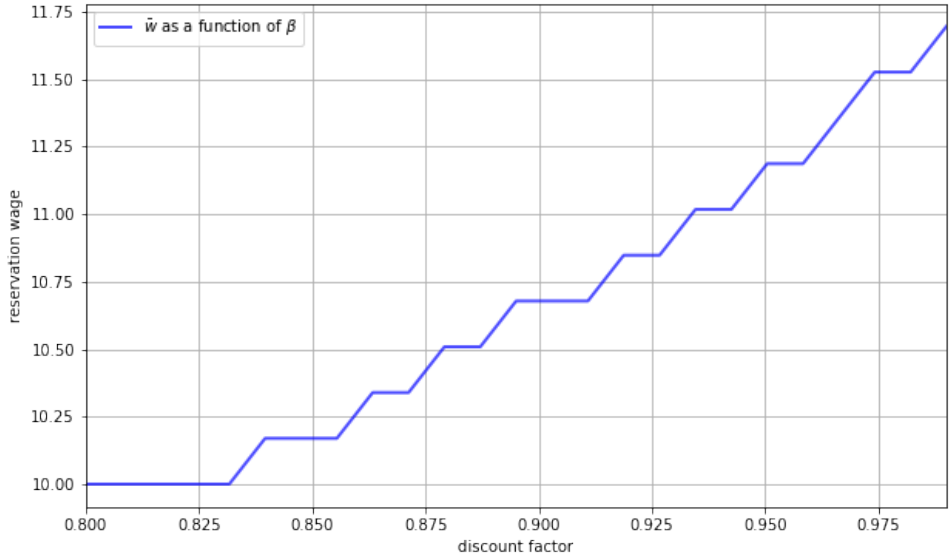
As expected, higher unemployment compensation causes the worker to hold out for higher wages.

In effect, the cost of continuing job search is reduced.

26.6.2 The Reservation Wage and Discounting

Next let's investigate how $\bar{w}$ varies with the discount rate.

The next figure plots the reservation wage associated with different values of β

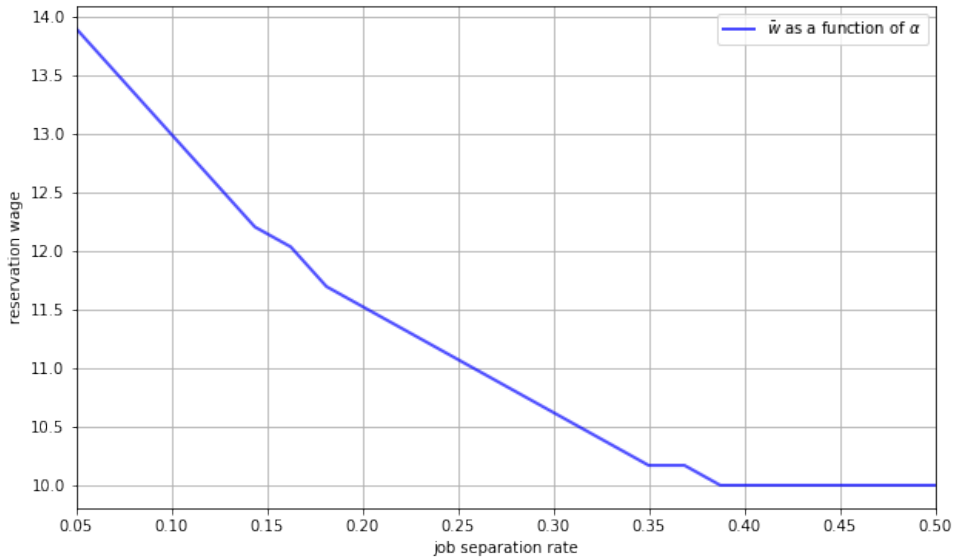


Again, the results are intuitive: More patient workers will hold out for higher wages.

26.6.3 The Reservation Wage and Job Destruction

Finally, let's look at how $\bar{w}$ varies with the job separation rate α.

Higher α translates to a greater chance that a worker will face termination in each period once employed.



Once more, the results are in line with our intuition.

If the separation rate is high, then the benefit of holding out for a higher wage falls.

Hence the reservation wage is lower.

26.7 Exercises

26.7.1 Exercise 1

Reproduce all the reservation wage figures shown above.

26.7.2 Exercise 2

Plot the reservation wage against the job offer rate γ.

Use

```
In [6]: γ_vals = range(0.05,  0.95, length = 25)
```

```
Out[6]: 0.05:0.0375:0.95
```

Interpret your results.

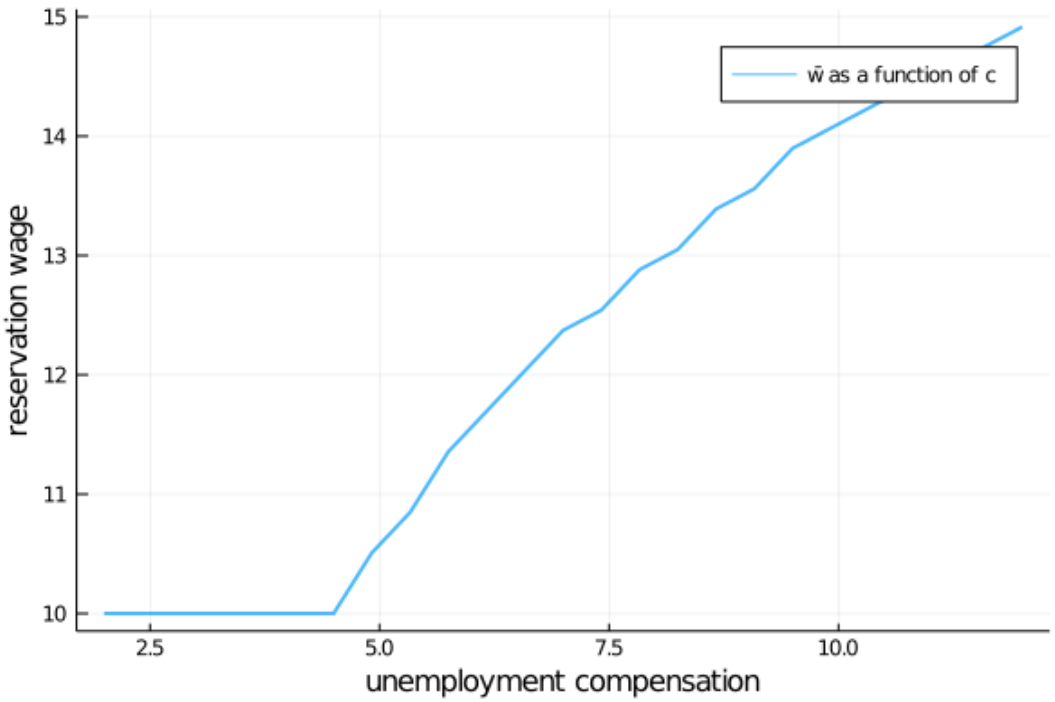
26.8 Solutions

26.8.1 Exercise 1

Using the solve_mccall_model function mentioned earlier in the lecture, we can create an array for reservation wages for different values of c, β and α and plot the results like so

```
In [7]: c_vals = range(2,  12, length = 25)

        models = [McCallModel(c = cval) for cval in c_vals]
        sols = solve_mccall_model.(models)
        w_vals = [sol.w for sol in sols]

        plot(c_vals,
            w_vals,
            lw = 2,
            α = 0.7,
            xlabel = "unemployment compensation",
            ylabel = "reservation wage",
            label = "w as a function of c")
```

```
Out[7]:
```



Note that we could've done the above in one pass (which would be important if, for example, the parameter space was quite large).

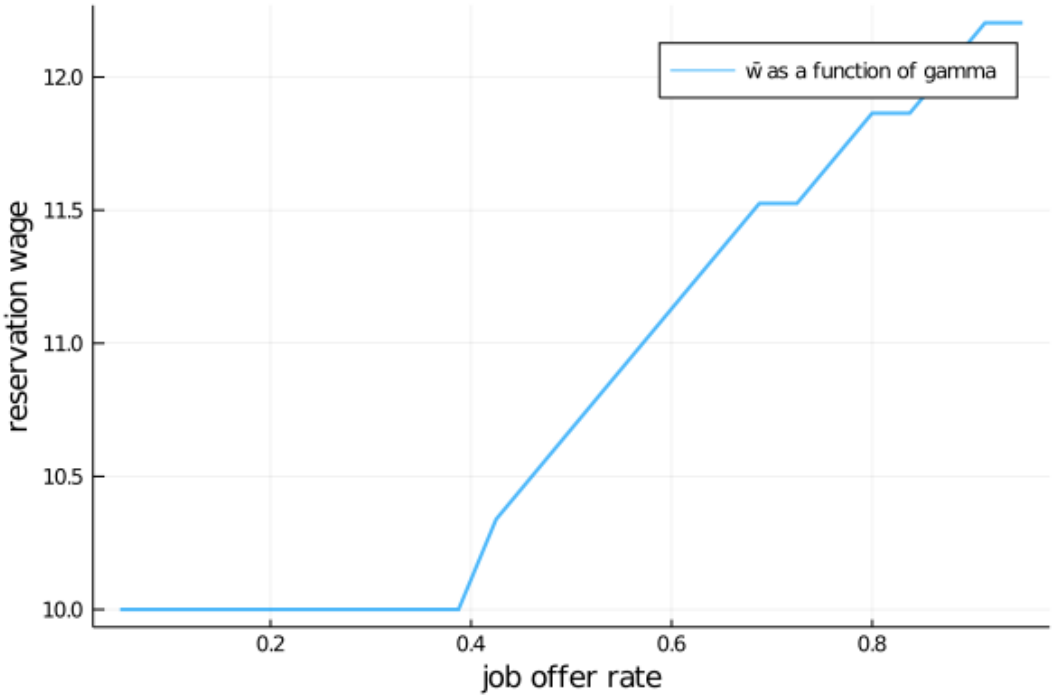
```
In [8]: w_vals = [solve_mccall_model(McCallModel(c = cval)).w for cval in c_vals];
        # doesn't allocate new arrays for models and solutions
```

26.8.2 Exercise 2

Similar to above, we can plot $\bar{w}$ against γ as follows

```
In [9]: γ_vals = range(0.05,  0.95, length = 25)

        models = [McCallModel(γ = γval) for γval in γ_vals]
        sols = solve_mccall_model.(models)
        w_vals = [sol.w for sol in sols]

        plot(γ_vals, w_vals, lw = 2, α = 0.7, xlabel = "job offer rate",
             ylabel = "reservation wage", label = "w as a function of gamma")
```

```
Out[9]:
```



As expected, the reservation wage increases in γ.

This is because higher γ translates to a more favorable job search environment.

Hence workers are less willing to accept lower offers.

Chapter 27

A Problem that Stumped Milton Friedman

(and that Abraham Wald solved by inventing sequential analysis)

27.1 Contents

Co-authored with Chase Coleman

27.2 Overview

This lecture describes a statistical decision problem encountered by Milton Friedman and W. Allen Wallis during World War II when they were analysts at the U.S. Government's Statistical Research Group at Columbia University.

This problem led Abraham Wald [106] to formulate **sequential analysis**, an approach to statistical decision problems intimately related to dynamic programming.

In this lecture, we apply dynamic programming algorithms to Friedman and Wallis and Wald's problem.

Key ideas in play will be:

- Bayes' Law
- Dynamic programming
- Type I and type II statistical errors
  - a type I error occurs when you reject a null hypothesis that is true
  - a type II error is when you accept a null hypothesis that is false
- Abraham Wald's **sequential probability ratio test**
- The **power** of a statistical test
- The **critical region** of a statistical test
- A **uniformly most powerful test**

27.3 Origin of the problem

On pages 137-139 of his 1998 book *Two Lucky People* with Rose Friedman [33], Milton Friedman described a problem presented to him and Allen Wallis during World War II, when they worked at the US Government's Statistical Research Group at Columbia University.

Let's listen to Milton Friedman tell us what happened.

"In order to understand the story, it is necessary to have an idea of a simple statistical problem, and of the standard procedure for dealing with it. The actual problem out of which sequential analysis grew will serve. The Navy has two alternative designs (say A and B) for a projectile. It wants to determine which is superior. To do so it undertakes a series of paired firings. On each round it assigns the value 1 or 0 to A accordingly as its performance is superior or inferior to that of B and conversely 0 or 1 to B. The Navy asks the statistician how to conduct the test and how to analyze the results.

"The standard statistical answer was to specify a number of firings (say 1,000) and a pair of percentages (e.g., 53% and 47%) and tell the client that if A receives a 1 in more than 53% of the firings, it can be regarded as superior; if it receives a 1 in fewer than 47%, B can be regarded as superior; if the percentage is between 47% and 53%, neither can be so regarded.

"When Allen Wallis was discussing such a problem with (Navy) Captain Garret L. Schyler, the captain objected that such a test, to quote from Allen's account, may prove wasteful. If a wise and seasoned ordnance officer like Schyler were on the premises, he would see after the first few thousand or even few hundred [rounds] that the experiment need not be completed either because the new method is obviously inferior or because it is obviously superior beyond what was hoped for ... ''

Friedman and Wallis struggled with the problem but, after realizing that they were not able to solve it, described the problem to Abraham Wald.

That started Wald on the path that led him to *Sequential Analysis* [106].

We'll formulate the problem using dynamic programming.

27.4 A dynamic programming approach

The following presentation of the problem closely follows Dmitri Berskekas's treatment in **Dynamic Programming and Stochastic Control** [11].

A decision maker observes iid draws of a random variable z.

He (or she) wants to know which of two probability distributions f_0 or f_1 governs z.

After a number of draws, also to be determined, he makes a decision as to which of the distributions is generating the draws he observers.

To help formalize the problem, let $x \in \{x_0, x_1\}$ be a hidden state that indexes the two distributions:

$$\mathbb{P}\{z = v \mid x\} = \begin{cases} f_0(v) & \text{if } x = x_0, \\ f_1(v) & \text{if } x = x_1 \end{cases}$$

Before observing any outcomes, the decision maker believes that the probability that $x = x_0$ is

$$p_{-1} = \mathbb{P}\{x = x_0 \mid \text{ no observations}\} \in (0, 1)$$

After observing $k+1$ observations $z_k, z_{k-1}, \ldots, z_0$, he updates this value to

$$p_k = \mathbb{P}\{x = x_0 \mid z_k, z_{k-1}, \ldots, z_0\},$$

which is calculated recursively by applying Bayes' law:

$$p_{k+1} = \frac{p_k f_0(z_{k+1})}{p_k f_0(z_{k+1}) + (1 - p_k) f_1(z_{k+1})}, \quad k = -1, 0, 1, \ldots$$

After observing $z_k, z_{k-1}, \ldots, z_0$, the decision maker believes that z_{k+1} has probability distribution

$$f(v) = p_k f_0(v) + (1 - p_k) f_1(v)$$

This is a mixture of distributions f_0 and f_1, with the weight on f_0 being the posterior probability that $x = x_0$ Section **??**.

To help illustrate this kind of distribution, let's inspect some mixtures of beta distributions.

The density of a beta probability distribution with parameters a and b is

$$f(z; a, b) = \frac{\Gamma(a+b) z^{a-1} (1-z)^{b-1}}{\Gamma(a)\Gamma(b)} \quad \text{where} \quad \Gamma(t) := \int_0^\infty x^{t-1} e^{-x} dx$$

We'll discretize this distribution to make it more straightforward to work with.

The next figure shows two discretized beta distributions in the top panel.

The bottom panel presents mixtures of these distributions, with various mixing probabilities p_k.

27.4.1 Setup

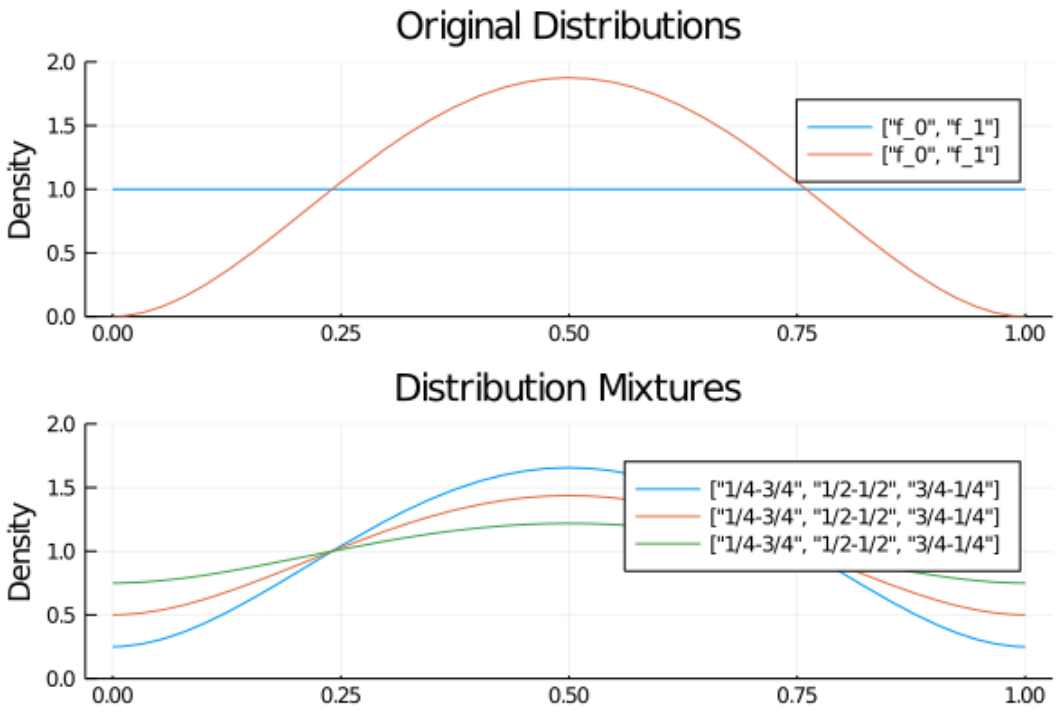
```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Parameters, Printf, Random, Roots, Plots
        gr(fmt = :png)
```

```
In [3]: using StatsPlots

        begin
            base_dist = [Beta(1, 1), Beta(3, 3)]
            mixed_dist = MixtureModel.(Ref(base_dist), (p -> [p, one(p) - p]).(0.
        25:0.25:0.75))
            plot(plot(base_dist, labels = ["f_0", "f_1"], title = "Original
        Distributions"),
```

```
        plot(mixed_dist, labels = ["1/4-3/4", "1/2-1/2", "3/4-1/4"],
             title = "Distribution Mixtures"),
        # Global settings across both plots
        ylab = "Density", ylim = (0, 2), layout = (2, 1)
        )
end
```

Out[3]:



27.4.2 Losses and costs

After observing $z_k, z_{k-1}, \ldots, z_0$, the decision maker chooses among three distinct actions:

- He decides that $x = x_0$ and draws no more z's.
- He decides that $x = x_1$ and draws no more z's.
- He postpones deciding now and instead chooses to draw a z_{k+1}.

Associated with these three actions, the decision maker can suffer three kinds of losses:

- A loss L_0 if he decides $x = x_0$ when actually $x = x_1$.
- A loss L_1 if he decides $x = x_1$ when actually $x = x_0$.
- A cost c if he postpones deciding and chooses instead to draw another z.

27.4.3 Digression on type I and type II errors

If we regard $x = x_0$ as a null hypothesis and $x = x_1$ as an alternative hypothesis, then L_1 and L_0 are losses associated with two types of statistical errors.

- a type I error is an incorrect rejection of a true null hypothesis (a "false positive")
- a type II error is a failure to reject a false null hypothesis (a "false negative")

So when we treat $x = x_0$ as the null hypothesis

- We can think of L_1 as the loss associated with a type I error.
- We can think of L_0 as the loss associated with a type II error.

27.4.4 Intuition

Let's try to guess what an optimal decision rule might look like before we go further.

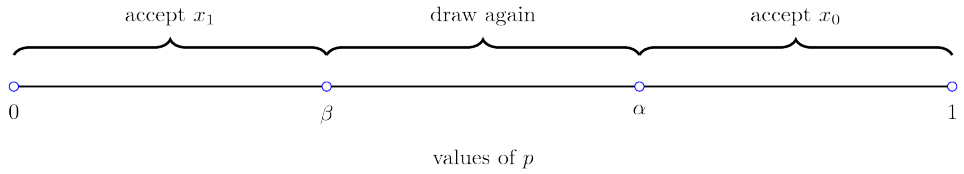
Suppose at some given point in time that p is close to 1.

Then our prior beliefs and the evidence so far point strongly to $x = x_0$.

If, on the other hand, p is close to 0, then $x = x_1$ is strongly favored.

Finally, if p is in the middle of the interval $[0, 1]$, then we have little information in either direction.

This reasoning suggests a decision rule such as the one shown in the figure



As we'll see, this is indeed the correct form of the decision rule.

The key problem is to determine the threshold values α, β, which will depend on the parameters listed above.

You might like to pause at this point and try to predict the impact of a parameter such as c or L_0 on α or β.

27.4.5 A Bellman equation

Let $J(p)$ be the total loss for a decision maker with current belief p who chooses optimally.

With some thought, you will agree that J should satisfy the Bellman equation

$$J(p) = \min \{(1-p)L_0,\ pL_1,\ c + \mathbb{E}[J(p')]\} \tag{1}$$

where p' is the random variable defined by

$$p' = \frac{pf_0(z)}{pf_0(z) + (1-p)f_1(z)} \tag{2}$$

when p is fixed and z is drawn from the current best guess, which is the distribution f defined by

$$f(v) = pf_0(v) + (1-p)f_1(v) \tag{3}$$

In the Bellman equation, minimization is over three actions:

1. accept x_0
2. accept x_1
3. postpone deciding and draw again

Let

$$A(p) := \mathbb{E}[J(p')] \tag{4}$$

Then we can represent the Bellman equation as

$$J(p) = \min\{(1-p)L_0,\ pL_1,\ c + A(p)\} \tag{5}$$

where $p \in [0, 1]$.

Here

- $(1-p)L_0$ is the expected loss associated with accepting x_0 (i.e., the cost of making a type II error).
- pL_1 is the expected loss associated with accepting x_1 (i.e., the cost of making a type I error).
- $c + A(p)$ is the expected cost associated with drawing one more z.

The optimal decision rule is characterized by two numbers $\alpha, \beta \in (0, 1) \times (0, 1)$ that satisfy

$$(1-p)L_0 < \min\{pL_1, c + A(p)\} \text{ if } p \geq \alpha \tag{6}$$

and

$$pL_1 < \min\{(1-p)L_0, c + A(p)\} \text{ if } p \leq \beta \tag{7}$$

The optimal decision rule is then

$$\begin{aligned} \text{accept } x = x_0 \text{ if } p \geq \alpha \\ \text{accept } x = x_1 \text{ if } p \leq \beta \\ \text{draw another } z \text{ if } \beta \leq p \leq \alpha \end{aligned} \tag{8}$$

Our aim is to compute the value function J, and from it the associated cutoffs α and β.

One sensible approach is to write the three components of J that appear on the right side of the Bellman equation as separate functions.

Later, doing this will help us obey **the don't repeat yourself (DRY)** golden rule of coding.

27.5 Implementation

Let's code this problem up and solve it.

We implement the cost functions for each choice considered in the Bellman equation (7).

First, consider the cost associated to accepting either distribution and compare the minimum of the two to the expected benefit of drawing again.

Drawing again will only be worthwhile if the expected marginal benefit of learning from an additional draw is greater than the explicit cost.

For every belief p, we can compute the difference between accepting a distribution and choosing to draw again.

The solution α, β occurs at indifference points.

Define the cost function be the minimum of the pairwise differences in cost among the choices.

Then we can find the indifference points when the cost function is zero.

We can use any roots finding algorithm to solve for the solutions in the interval [0, 1].

Lastly, verify which indifference points correspond to the definition of a permanent transition between the accept and reject space for each choice.

Here's the code

```
In [4]: accept_x0(p, L0) = (one(p) - p) * L0
        accept_x1(p, L1) = p * L1
        bayes_update(p, d0, d1) = p * pdf(d0, p) / pdf(MixtureModel([d0, d1], [p,
 ↪one(p) - p]),
        p)
        function draw_again(p, d0, d1, L0, L1, c, target)
            candidate = 0.0
            cost = 0.0
            while candidate < target
                p = bayes_update(p, d0, d1)
                cost += c
                candidate = min(accept_x0(p, L0), accept_x1(p, L1)) + cost
                if candidate >= target
                    break
                end
                target = candidate
            end
            return candidate
        end
        function choice(p, d0, d1, L0, L1, c)
            if isone(p)
                output = (1, 0)
            elseif iszero(p)
                output = (2, 0)
            elseif zero(p) < p < one(p)
                target, option = findmin([accept_x0(p, L0), accept_x1(p, L1)])
                candidate = draw_again(p, d0, d1, L0, L1, c, target)
                if candidate < target
                    target, option = (candidate, 3)
                end
                output = (option, target)
            else
                throw(ArgumentError("p must be  [0, 1]"))
            end
            return output
        end
```

```
Out[4]: choice (generic function with 1 method)
```

Next we solve a problem by finding the α, β values for the decision rule

```
In [5]: function decision_rule(d0, d1, L0, L1, c)
            function cost(p, d0, d1, L0, L1, c)
                if c < zero(c)
                    throw(ArgumentError("Cost must be non-negative"))
                end
                x0 = accept_x0(p, L0)
                x1 = accept_x1(p, L1)
                draw = draw_again(p, d0, d1, L0, L1, c, min(x0, x1))
                output = min(abs(draw - x0), abs(draw - x1), abs(x1 - x0))
                return output
            end
            # Find the indifference points
            roots = find_zeros(p -> cost(p, d0, d1, L0, L1, c), 0 + eps(), 1 - eps())
            # Compute the choice at both sides
            left = first.(choice.(roots .- eps(), d0, d1, L0, L1, c))
            right = first.(choice.(roots .+ eps(), d0, d1, L0, L1, c))
            # Find β by checking for a permanent transition from the area
        ↪accepting to
            # x to never again accepting x at the various indifference points
            # Find α by checking for a permanent transition from the area
        ↪accepting of
            # x to never again accepting x at the various indifference points
            β = findlast((left .== 2) .& (right .≠ 2)) |> (x -> isa(x, Int) ?
        ↪roots[x] : 0)
            α = findfirst((left .≠ 1) .& (right .== 1)) |> (x -> isa(x, Int) ?
        ↪roots[x] : 1)
            if β < α
                @printf("Accept x1 if p ≤ %.2f\nContinue to draw if %.2f ≤ p ≤ %.2f
                        \nAccept x0 if p ≥ %.2f", β, β, α, α)
            else
                x0 = accept_x0(β, L0)
                x1 = accept_x1(β, L1)
                draw = draw_again(β, d0, d1, L0, L1, c, min(x0, x1))
                if draw == min(x0, x1, draw)
                    @printf("Accept x1 if p ≤ %.2f\nContinue to draw if %.2f ≤ p ≤
        ↪%.2f
                                \nAccept x0 if p ≥ %.2f", β, β, α, α)
                else
                    @printf("Accept x1 if p ≤ %.2f\nAccept x0 if p ≥ %.2f", β, α)
                end
            end
            return (α, β)
        end
```

```
Out[5]: decision_rule (generic function with 1 method)
```

We can simulate an agent facing a problem and the outcome with the following function

```
In [6]: function simulation(problem)
            @unpack d0, d1, L0, L1, c, p, n, return_output = problem
            α, β = decision_rule(d0, d1, L0, L1, c)
```

```
        outcomes = fill(false, n)
        costs = fill(0.0, n)
        trials = fill(0, n)
        for trial in 1:n
            # Nature chooses
            truth = rand(1:2)
            # The true distribution and loss are defined based on the truth
            d = (d0, d1)[truth]
            l = (L0, L1)[truth]
            t = 0
            choice = 0
            while iszero(choice)
                t += 1
                outcome = rand(d)
                p = bayes_update(p, d0, d1)
                if p <= β
                    choice = 1
                elseif p >= α
                    choice = 2
                end
            end
            correct = choice == truth
            cost = t * c + (correct ? 0 : l)
            outcomes[trial] = correct
            costs[trial] = cost
            trials[trial] = t
        end
        @printf("\nCorrect: %.2f\nAverage Cost: %.2f\nAverage number of trials:
↪ %.2f",
                mean(outcomes), mean(costs), mean(trials))
        return return_output ? (α, β, outcomes, costs, trials) : nothing
    end

    Problem = @with_kw (d0 = Beta(1,1), d1 = Beta(9,9),
                        L0 = 2, L1 = 2,
                        c = 0.2, p = 0.5,
                        n = 100, return_output = false);
```

In [7]:
```
Random.seed!(0);
simulation(Problem());
```

```
   Accept x1 if p ≤ 0.35
Continue to draw if 0.35 ≤ p ≤ 0.57

Accept x0 if p ≥ 0.57
Correct: 0.43
Average Cost: 1.42
Average number of trials: 1.40
```

27.5.1 Comparative statics

Now let's consider the following exercise.

We double the cost of drawing an additional observation.

Before you look, think about what will happen:

- Will the decision maker be correct more or less often?

- Will he make decisions sooner or later?

```
In [8]: Random.seed!(0);
        simulation(Problem(c = 0.4));
```

```
    Accept x1 if p ≤ 0.41
Continue to draw if 0.41 ≤ p ≤ 0.54

Accept x0 if p ≥ 0.54
Correct: 0.45
Average Cost: 1.59
Average number of trials: 1.22
```

Notice what happens?

The average number of trials decreased.

Increased cost per draw has induced the decision maker to decide in 0.18 less trials on average.

Because he decides with less experience, the percentage of time he is correct drops.

This leads to him having a higher expected loss when he puts equal weight on both models.

27.6 Comparison with Neyman-Pearson formulation

For several reasons, it is useful to describe the theory underlying the test that Navy Captain G. S. Schuyler had been told to use and that led him to approach Milton Friedman and Allan Wallis to convey his conjecture that superior practical procedures existed.

Evidently, the Navy had told Captail Schuyler to use what it knew to be a state-of-the-art Neyman-Pearson test.

We'll rely on Abraham Wald's [106] elegant summary of Neyman-Pearson theory.

For our purposes, watch for there features of the setup:

- the assumption of a *fixed* sample size n
- the application of laws of large numbers, conditioned on alternative probability models, to interpret the probabilities α and β defined in the Neyman-Pearson theory

Recall that in the sequential analytic formulation above, that

- The sample size n is not fixed but rather an object to be chosen; technically n is a random variable.
- The parameters β and α characterize cut-off rules used to determine n as a random variable.
- Laws of large numbers make no appearances in the sequential construction.

In chapter 1 of **Sequential Analysis** [106] Abraham Wald summarizes the Neyman-Pearson approach to hypothesis testing.

Wald frames the problem as making a decision about a probability distribution that is partially known.

(You have to assume that *something* is already known in order to state a well posed problem. Usually, *something* means *a lot*.)

By limiting what is unknown, Wald uses the following simple structure to illustrate the main ideas.

- A decision maker wants to decide which of two distributions f_0, f_1 govern an i.i.d. random variable z.
- The null hypothesis H_0 is the statement that f_0 governs the data.
- The alternative hypothesis H_1 is the statement that f_1 governs the data.
- The problem is to devise and analyze a test of hypothesis H_0 against the alternative hypothesis H_1 on the basis of a sample of a fixed number n independent observations $z_1, z_2, \ldots, z_n$ of the random variable z.

To quote Abraham Wald,

- A test procedure leading to the acceptance or rejection of the hypothesis in question is simply a rule specifying, for each possible sample of size n, whether the hypothesis should be accepted or rejected on the basis of the sample. This may also be expressed as follows: A test procedure is simply a subdivision of the totality of all possible samples of size n into two mutually exclusive parts, say part 1 and part 2, together with the application of the rule that the hypothesis be accepted if the observed sample is contained in part 2. Part 1 is also called the critical region. Since part 2 is the totality of all samples of size 2 which are not included in part 1, part 2 is uniquely determined by part 1. Thus, choosing a test procedure is equivalent to determining a critical region.

Let's listen to Wald longer:

- As a basis for choosing among critical regions the following considerations have been advanced by Neyman and Pearson: In accepting or rejecting H_0 we may commit errors of two kinds. We commit an error of the first kind if we reject H_0 when it is true; we commit an error of the second kind if we accept H_0 when H_1 is true. After a particular critical region W has been chosen, the probability of committing an error of the first kind, as well as the probability of committing an error of the second kind is uniquely determined. The probability of committing an error of the first kind is equal to the probability, determined by the assumption that H_0 is true, that the observed sample will be included in the critical region W. The probability of committing an error of the second kind is equal to the probability, determined on the assumption that H_1 is true, that the probability will fall outside the critical region W. For any given critical region W we shall denote the probability of an error of the first kind by α and the probability of an error of the second kind by β.

Let's listen carefully to how Wald applies a law of large numbers to interpret α and β:

- The probabilities α and β have the following important practical interpretation: Suppose that we draw a large number of samples of size n. Let M be the number of such samples drawn. Suppose that for each of these M samples we reject H_0 if the sample is included in W and accept H_0 if the sample lies outside W. In this way we make M statements of rejection or acceptance. Some of these statements will in general be wrong. If H_0 is true and if M is large, the probability is nearly 1 (i.e., it is practically certain) that the proportion of wrong statements (i.e., the number of wrong statements divided by M) will be approximately α. If H_1 is true, the probability is nearly 1 that the proportion of wrong statements will be approximately β. Thus, we can say that in the long run [here Wald applies a law of large numbers by driving $M \to \infty$ (our comment, not Wald's)] the proportion of wrong statements will be α if $H_0$is true and β if H_1 is true.

The quantity α is called the *size* of the critical region, and the quantity $1 - \beta$ is called the

power of the critical region.

Wald notes that

- one critical region W is more desirable than another if it has smaller values of α and β. Although either α or β can be made arbitrarily small by a proper choice of the critical region W, it is possible to make both α and β arbitrarily small for a fixed value of n, i.e., a fixed sample size.

Wald summarizes Neyman and Pearson's setup as follows:

- Neyman and Pearson show that a region consisting of all samples $(z_1, z_2, ..., z_n)$ which satisfy the inequality

$$\frac{f_1(z_1) \cdots f_1(z_n)}{f_0(z_1) \cdots f_1(z_n)} \geq k$$

  is a most powerful critical region for testing the hypothesis H_0 against the alternative hypothesis H_1. The term k on the right side is a constant chosen so that the region will have the required size α.

Wald goes on to discuss Neyman and Pearson's concept of *uniformly most powerful* test.

Here is how Wald introduces the notion of a sequential test

- A rule is given for making one of the following three decisions at any stage of the experiment (at the m th trial for each integral value of m): (1) to accept the hypothesis H , (2) to reject the hypothesis H , (3) to continue the experiment by making an additional observation. Thus, such a test procedure is carried out sequentially. On the basis of the first observation one of the aforementioned decisions is made. If the first or second decision is made, the process is terminated. If the third decision is made, a second trial is performed. Again, on the basis of the first two observations one of the three decisions is made. If the third decision is made, a third trial is performed, and so on. The process is continued until either the first or the second decisions is made. The number n of observations required by such a test procedure is a random variable, since the value of n depends on the outcome of the observations.

Footnotes

[1] Because the decision maker believes that z_{k+1} is drawn from a mixture of two i.i.d. distributions, he does *not* believe that the sequence $[z_{k+1}, z_{k+2}, ...]$ is i.i.d. Instead, he believes that it is *exchangeable*. See [62] chapter 11, for a discussion of exchangeability.

Chapter 28

Job Search III: Search with Learning

28.1 Contents

28.2 Overview

In this lecture we consider an extension of the previously studied job search model of McCall [76].

In the McCall model, an unemployed worker decides when to accept a permanent position at a specified wage, given

- his or her discount rate
- the level of unemployment compensation
- the distribution from which wage offers are drawn

In the version considered below, the wage distribution is unknown and must be learned.

- The following is based on the presentation in [68], section 6.6.

28.2.1 Model features

- Infinite horizon dynamic programming with two states and one binary control.
- Bayesian updating to learn the unknown distribution.

28.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

28.3 Model

Let's first review the basic McCall model [76] and then add the variation we want to consider.

28.3.1 The Basic McCall Model

Recall that, in the baseline model, an unemployed worker is presented in each period with a permanent job offer at wage W_t.

At time t, our worker either

1. accepts the offer and works permanently at constant wage W_t
2. rejects the offer, receives unemployment compensation c and reconsiders next period

The wage sequence $\{W_t\}$ is iid and generated from known density h.

The worker aims to maximize the expected discounted sum of earnings $\mathbb{E}\sum_{t=0}^{\infty}\beta^t y_t$ The function V satisfies the recursion

$$V(w) = \max\left\{\frac{w}{1-\beta}, c + \beta\int V(w')h(w')dw'\right\} \tag{1}$$

The optimal policy has the form $\mathbf{1}\{w \geq \bar{w}\}$, where $\bar{w}$ is a constant depending called the *reservation wage*.

28.3.2 Offer Distribution Unknown

Now let's extend the model by considering the variation presented in [68], section 6.6.

The model is as above, apart from the fact that

- the density h is unknown
- the worker learns about h by starting with a prior and updating based on wage offers that he/she observes

The worker knows there are two possible distributions F and G — with densities f and g.

At the start of time, "nature" selects h to be either f or g — the wage distribution from which the entire sequence $\{W_t\}$ will be drawn.

This choice is not observed by the worker, who puts prior probability π_0 on f being chosen.

Update rule: worker's time t estimate of the distribution is $\pi_t f + (1-\pi_t)g$, where π_t updates via

$$\pi_{t+1} = \frac{\pi_t f(w_{t+1})}{\pi_t f(w_{t+1}) + (1-\pi_t) g(w_{t+1})} \tag{2}$$

This last expression follows from Bayes' rule, which tells us that

$$\mathbb{P}\{h = f \,|\, W = w\} = \frac{\mathbb{P}\{W = w \,|\, h = f\}\mathbb{P}\{h = f\}}{\mathbb{P}\{W = w\}} \quad \text{and} \quad \mathbb{P}\{W = w\} = \sum_{\psi \in \{f,g\}} \mathbb{P}\{W = w \,|\, h = \psi\}\mathbb{P}\{h = \psi\}$$

The fact that (2) is recursive allows us to progress to a recursive solution method.

Letting

$$h_\pi(w) := \pi f(w) + (1-\pi) g(w) \quad \text{and} \quad q(w, \pi) := \frac{\pi f(w)}{\pi f(w) + (1-\pi) g(w)}$$

we can express the value function for the unemployed worker recursively as follows

$$V(w, \pi) = \max \left\{ \frac{w}{1-\beta}, \, c + \beta \int V(w', \pi') \, h_\pi(w') \, dw' \right\} \quad \text{where} \quad \pi' = q(w', \pi) \tag{3}$$

Notice that the current guess π is a state variable, since it affects the worker's perception of probabilities for future rewards.

28.3.3 Parameterization

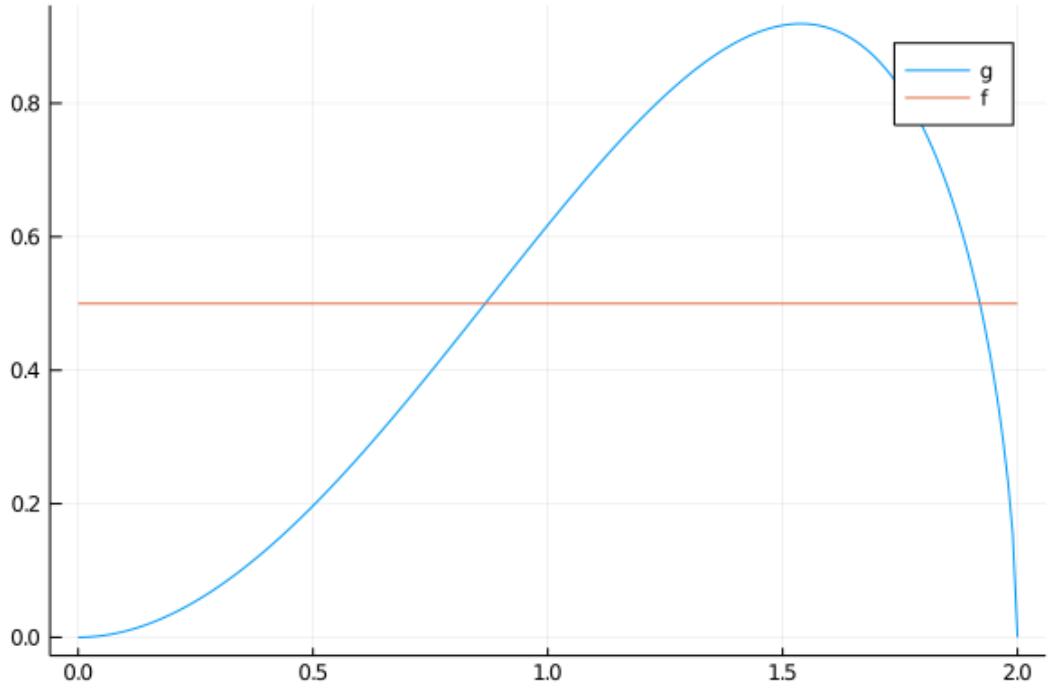
Following section 6.6 of [68], our baseline parameterization will be

- f is Beta$(1, 1)$ scaled (i.e., draws are multiplied by) some factor w_m
- g is Beta$(3, 1.2)$ scaled (i.e., draws are multiplied by) the same factor w_m
- $\beta = 0.95$ and $c = 0.6$

With $w_m = 2$, the densities f and g have the following shape

In [2]:
```
using LinearAlgebra, Statistics
using Distributions, Plots, QuantEcon, Interpolations, Parameters

gr(fmt=:png);

w_max = 2
x = range(0,  w_max, length = 200)

G = Beta(3, 1.6)
F = Beta(1, 1)
plot(x, pdf.(G, x/w_max)/w_max, label="g")
plot!(x, pdf.(F, x/w_max)/w_max, label="f")
```

Out[2]:



28.3.4 Looking Forward

What kind of optimal policy might result from (3) and the parameterization specified above?

Intuitively, if we accept at w_a and $w_a \leq w_b$, then — all other things being given — we should also accept at w_b.

This suggests a policy of accepting whenever w exceeds some threshold value $\bar{w}$.

But $\bar{w}$ should depend on π — in fact it should be decreasing in π because

- f is a less attractive offer distribution than g
- larger π means more weight on f and less on g

Thus larger π depresses the worker's assessment of her future prospects, and relatively low current offers become more attractive.

Summary: We conjecture that the optimal policy is of the form $\mathbb{1}\{w \geq \bar{w}(\pi)\}$ for some decreasing function $\bar{w}$.

28.4 Take 1: Solution by VFI

Let's set about solving the model and see how our results match with our intuition.

We begin by solving via value function iteration (VFI), which is natural but ultimately turns out to be second best.

The code is as follows.

```
In [3]: # use key word argment
        function SearchProblem(;β = 0.95, c = 0.6, F_a = 1, F_b = 1,
                                G_a = 3, G_b = 1.2, w_max = 2.0,
                                w_grid_size = 40, π_grid_size = 40)
```

```
    F = Beta(F_a, F_b)
    G = Beta(G_a, G_b)

    # scaled pdfs
    f(x) = pdf.(F, x/w_max)/w_max
    g(x) = pdf.(G, x/w_max)/w_max

    π_min = 1e-3  # avoids instability
    π_max = 1 - π_min

    w_grid = range(0,  w_max, length = w_grid_size)
    π_grid = range(π_min,  π_max, length = π_grid_size)

    nodes, weights = qnwlege(21, 0.0, w_max)

    return (β = β, c = c, F = F, G = G, f = f,
            g = g, n_w = w_grid_size, w_max = w_max,
            w_grid = w_grid, n_π = π_grid_size, π_min = π_min,
            π_max = π_max, π_grid = π_grid, quad_nodes = nodes,
            quad_weights = weights)
end

function q(sp, w, π_val)
    new_π = 1.0 / (1 + ((1 - π_val) * sp.g(w)) / (π_val * sp.f(w)))

    # Return new_π when in [π_min, π_max] and else end points
    return clamp(new_π, sp.π_min, sp.π_max)
end

function T!(sp, v, out;
                            ret_policy = false)
    # simplify names
    @unpack f, g, β, c = sp
    nodes, weights = sp.quad_nodes, sp.quad_weights

    vf = extrapolate(interpolate((sp.w_grid, sp.π_grid), v,
                    Gridded(Linear())), Flat())

    # set up quadrature nodes/weights
    # q_nodes, q_weights = qnwlege(21, 0.0, sp.w_max)

    for (w_i, w) in enumerate(sp.w_grid)
        # calculate v1
        v1 = w / (1 - β)

        for (π_j, _π) in enumerate(sp.π_grid)
            # calculate v2
            integrand(m) = [vf(m[i], q.(Ref(sp), m[i], _π)) *
                            (_π * f(m[i]) + (1 - _π) * g(m[i])) for i in 1:
↪length(m)]
            integral = do_quad(integrand, nodes, weights)
            # integral = do_quad(integrand, q_nodes, q_weights)
            v2 = c + β * integral

            # return policy if asked for, otherwise return max of values
            out[w_i, π_j] = ret_policy ? v1 > v2 : max(v1, v2)
        end
```

```
        end
        return out
    end

    function T(sp, v;
                               ret_policy = false)
        out_type = ret_policy ? Bool : Float64
        out = zeros(out_type, sp.n_w, sp.n_π)
        T!(sp, v, out, ret_policy=ret_policy)
    end


    get_greedy!(sp, v, out) = T!(sp, v, out, ret_policy = true)

    get_greedy(sp, v) = T(sp, v, ret_policy = true)

    function res_wage_operator!(sp, ϕ, out)
        # simplify name
        @unpack f, g, β, c = sp

        # Construct interpolator over π_grid, given ⊠
        ϕ_f = LinearInterpolation(sp.π_grid, ϕ, extrapolation_bc = Line())

        # set up quadrature nodes/weights
        q_nodes, q_weights = qnwlege(7, 0.0, sp.w_max)

        for (i, _π) in enumerate(sp.π_grid)
            integrand(x) = max.(x, ϕ_f.(q.(Ref(sp), x, _π))) .* (_π * f(x) + (1
↪- _π) *
    g(x))
             integral = do_quad(integrand, q_nodes, q_weights)
             out[i] = (1 - β) * c + β * integral
        end
    end

    function res_wage_operator(sp, ϕ)
        out = similar(ϕ)
        res_wage_operator!(sp, ϕ, out)
        return out
    end
```

```
Out[3]: res_wage_operator (generic function with 1 method)
```

The type `SearchProblem` is used to store parameters and methods needed to compute optimal actions.

The Bellman operator is implemented as the method `T()`, while `get_greedy()` computes an approximate optimal policy from a guess `v` of the value function.

We will omit a detailed discussion of the code because there is a more efficient solution method.

These ideas are implemented in the `.res_wage_operator()` method.

Before explaining it let's look at solutions computed from value function iteration.

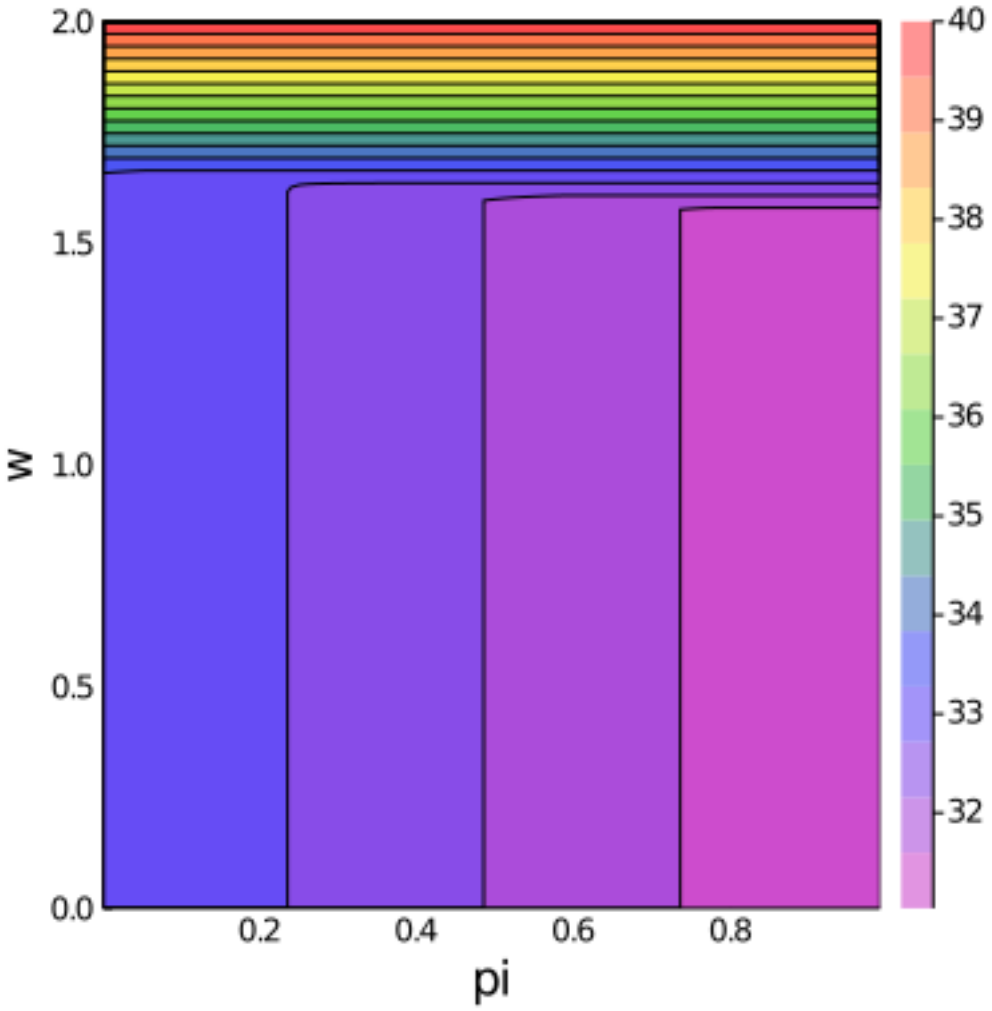
Here's the value function:

```
In [4]: # Set up the problem and initial guess, solve by VFI
```

```
sp = SearchProblem(;w_grid_size=100, π_grid_size=100)
v_init = fill(sp.c / (1 - sp.β), sp.n_w, sp.n_π)
f(x) = T(sp, x)
v = compute_fixed_point(f, v_init)
policy = get_greedy(sp, v)

# Make functions for the linear interpolants of these
vf = extrapolate(interpolate((sp.w_grid, sp.π_grid), v, Gridded(Linear())),
                 Flat())
pf = extrapolate(interpolate((sp.w_grid, sp.π_grid), policy,
                 Gridded(Linear())), Flat())

function plot_value_function(;w_plot_grid_size = 100,
                             π_plot_grid_size = 100)
  π_plot_grid = range(0.001,  0.99, length =  π_plot_grid_size)
  w_plot_grid = range(0,  sp.w_max, length = w_plot_grid_size)
  Z = [vf(w_plot_grid[j], π_plot_grid[i])
          for j in 1:w_plot_grid_size, i in 1:π_plot_grid_size]
  p = contour(π_plot_grid, w_plot_grid, Z, levels=15, alpha=0.6,
              fill=true, size=(400, 400), c=:lightrainbow)
  plot!(xlabel="pi", ylabel="w", xguidefont=font(12))
  return p
end

plot_value_function()
```

```
   Compute iterate 10 with error 0.19801710153283736
Compute iterate 20 with error 0.007608221868107279
Compute iterate 30 with error 0.0002901698734376623
Converged in 34 steps
```

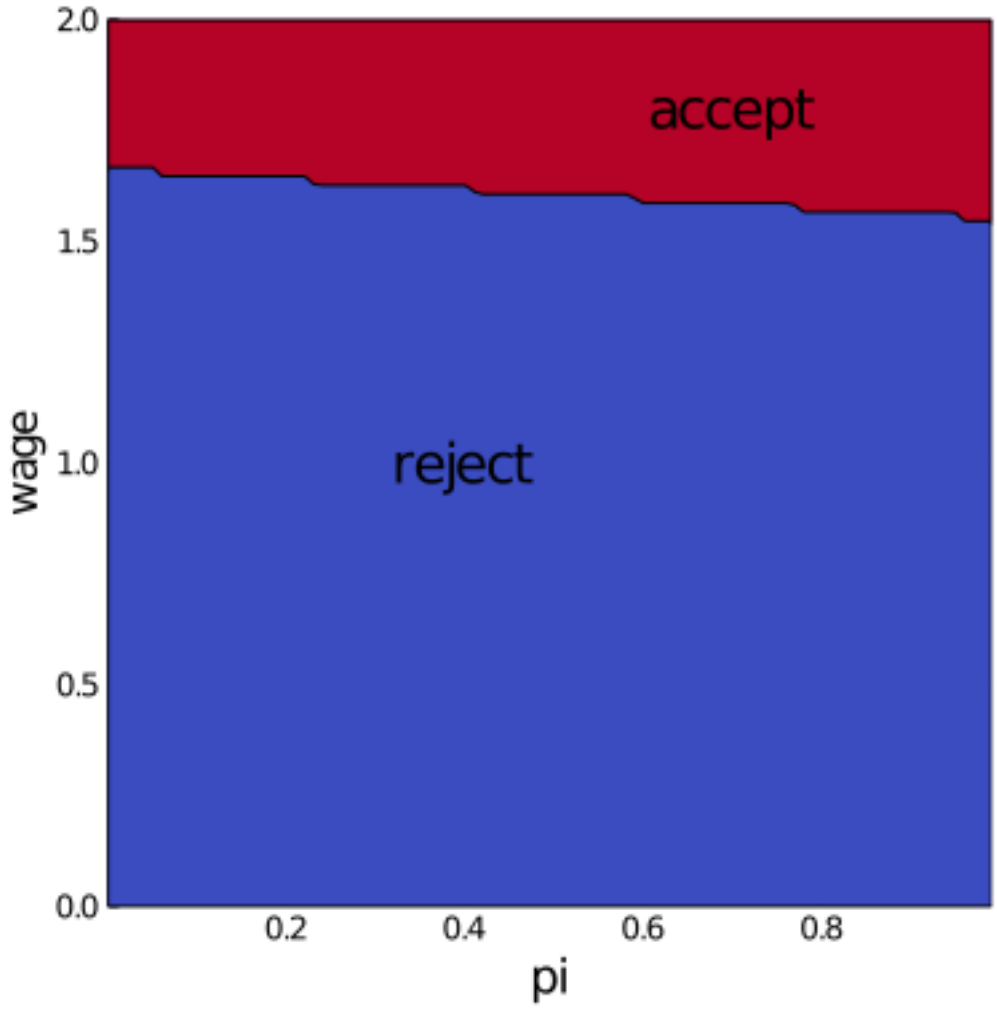
Out[4]:



The optimal policy:

```
In [5]: function plot_policy_function(;w_plot_grid_size = 100,
                                      π_plot_grid_size = 100)
            π_plot_grid = range(0.001,  0.99, length = π_plot_grid_size)
            w_plot_grid = range(0,  sp.w_max, length = w_plot_grid_size)
            Z = [pf(w_plot_grid[j], π_plot_grid[i])
                    for j in 1:w_plot_grid_size, i in 1:π_plot_grid_size]
           p = contour(π_plot_grid, w_plot_grid, Z, levels=1, alpha=0.6, fill=true,
                       size=(400, 400), c=:coolwarm)
            plot!(xlabel="pi", ylabel="wage", xguidefont=font(12), cbar=false)
            annotate!(0.4, 1.0, "reject")
            annotate!(0.7, 1.8, "accept")
            return p
        end

        plot_policy_function()
```

Out[5]:



The code takes several minutes to run.

The results fit well with our intuition from section looking forward.

- The black line in the figure above corresponds to the function $\bar{w}(\pi)$ introduced there.
- It is decreasing as expected.

28.5 Take 2: A More Efficient Method

Our implementation of VFI can be optimized to some degree.

But instead of pursuing that, let's consider another method to solve for the optimal policy.

We will use iteration with an operator that has the same contraction rate as the Bellman operator, but

- one dimensional rather than two dimensional
- no maximization step

As a consequence, the algorithm is orders of magnitude faster than VFI.

This section illustrates the point that when it comes to programming, a bit of mathematical analysis goes a long way.

28.5.1 Another Functional Equation

To begin, note that when $w = \bar{w}(\pi)$, the worker is indifferent between accepting and rejecting.

Hence the two choices on the right-hand side of (3) have equal value:

$$\frac{\bar{w}(\pi)}{1-\beta} = c + \beta \int V(w', \pi') \, h_\pi(w') \, dw' \tag{4}$$

Together, (3) and (4) give

$$V(w, \pi) = \max \left\{ \frac{w}{1-\beta}, \frac{\bar{w}(\pi)}{1-\beta} \right\} \tag{5}$$

Combining (4) and (5), we obtain

$$\frac{\bar{w}(\pi)}{1-\beta} = c + \beta \int \max \left\{ \frac{w'}{1-\beta}, \frac{\bar{w}(\pi')}{1-\beta} \right\} h_\pi(w') \, dw'$$

Multiplying by $1-\beta$, substituting in $\pi' = q(w', \pi)$ and using $\circ$ for composition of functions yields

$$\bar{w}(\pi) = (1-\beta)c + \beta \int \max \{w', \bar{w} \circ q(w', \pi)\} \; h_\pi(w') \, dw' \tag{6}$$

Equation (6) can be understood as a functional equation, where $\bar{w}$ is the unknown function.

- Let's call it the *reservation wage functional equation* (RWFE).
- The solution $\bar{w}$ to the RWFE is the object that we wish to compute.

28.5.2 Solving the RWFE

To solve the RWFE, we will first show that its solution is the fixed point of a contraction mapping.

To this end, let

- $b[0, 1]$ be the bounded real-valued functions on $[0, 1]$
- $\|\psi\| := \sup_{x \in [0,1]} |\psi(x)|$

Consider the operator Q mapping $\psi \in b[0, 1]$ into $Q\psi \in b[0, 1]$ via

$$(Q\psi)(\pi) = (1-\beta)c + \beta \int \max \{w', \psi \circ q(w', \pi)\} \; h_\pi(w') \, dw' \tag{7}$$

Comparing (6) and (7), we see that the set of fixed points of Q exactly coincides with the set of solutions to the RWFE.

- If $Q\bar{w} = \bar{w}$ then $\bar{w}$ solves (6) and vice versa.

Moreover, for any $\psi, \phi \in b[0, 1]$, basic algebra and the triangle inequality for integrals tells us that

$$|(Q\psi)(\pi) - (Q\phi)(\pi)| \leq \beta \int |\max \{w', \psi \circ q(w', \pi)\} - \max \{w', \phi \circ q(w', \pi)\}| \; h_\pi(w') \, dw' \tag{8}$$

Working case by case, it is easy to check that for real numbers a, b, c we always have

$$|\max\{a, b\} - \max\{a, c\}| \leq |b - c| \tag{9}$$

Combining (8) and (9) yields

$$|(Q\psi)(\pi) - (Q\phi)(\pi)| \leq \beta \int |\psi \circ q(w', \pi) - \phi \circ q(w', \pi)| \; h_\pi(w') \, dw' \leq \beta \|\psi - \phi\| \tag{10}$$

Taking the supremum over π now gives us

$$\|Q\psi - Q\phi\| \leq \beta \|\psi - \phi\| \tag{11}$$

In other words, Q is a contraction of modulus β on the complete metric space $(b[0, 1], \|\cdot\|)$.

Hence

- A unique solution $\bar{w}$ to the RWFE exists in $b[0, 1]$.
- $Q^k \psi \to \bar{w}$ uniformly as $k \to \infty$, for any $\psi \in b[0, 1]$.

Implementation

These ideas are implemented in the `.res_wage_operator()` method from `odu.jl` as shown above.

The method corresponds to action of the operator Q.

The following exercise asks you to exploit these facts to compute an approximation to $\bar{w}$.

28.6 Exercises

28.6.1 Exercise 1

Use the default parameters and the `.res_wage_operator()` method to compute an optimal policy.

Your result should coincide closely with the figure for the optimal policy shown above.

Try experimenting with different parameters, and confirm that the change in the optimal policy coincides with your intuition.

28.7 Solutions

28.7.1 Exercise 1

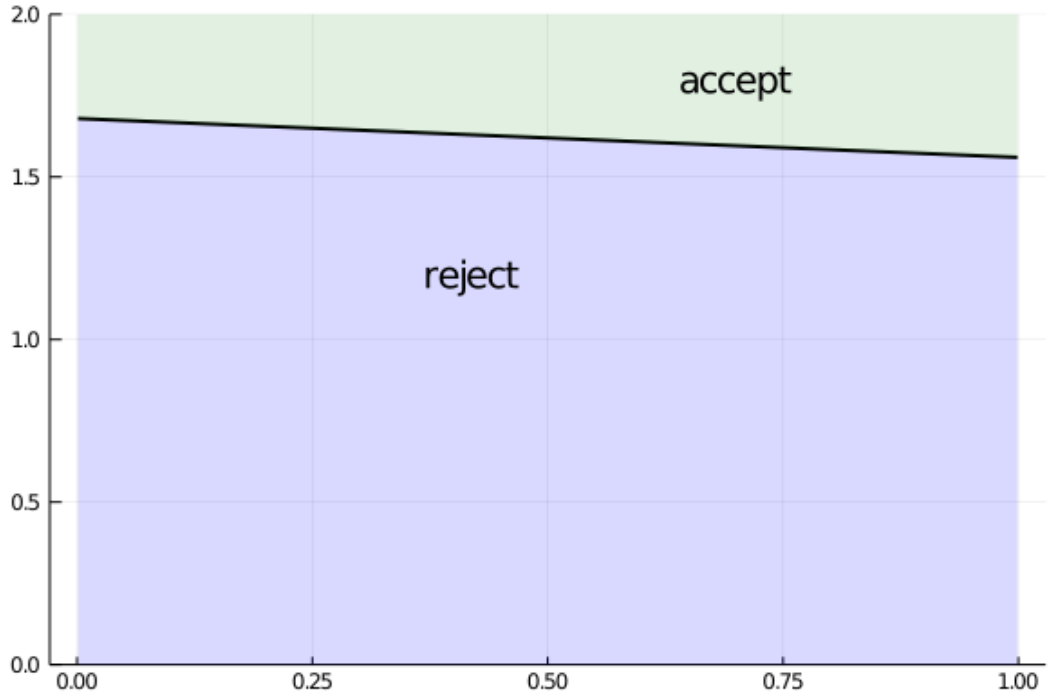
This code solves the "Offer Distribution Unknown" model by iterating on a guess of the reservation wage function. You should find that the run time is much shorter than that of the value function approach in `examples/odu_vfi_plots.jl`.

```
In [6]: sp = SearchProblem(π_grid_size = 50)
```

```
ϕ_init = ones(sp.n_π)
f_ex1(x) = res_wage_operator(sp, x)
w = compute_fixed_point(f_ex1, ϕ_init)

plot(sp.π_grid, w, linewidth = 2, color=:black,
     fillrange = 0, fillalpha = 0.15, fillcolor = :blue)
plot!(sp.π_grid, 2 * ones(length(w)), linewidth = 0, fillrange = w,
      fillalpha = 0.12, fillcolor = :green, legend = :none)
plot!(ylims = (0, 2), annotations = [(0.42, 1.2, "reject"),
                                     (0.7, 1.8, "accept")])
```

```
   Compute iterate 10 with error 0.007194437603255555
Compute iterate 20 with error 0.0004348703417873523
Converged in 26 steps
```

Out[6]:



The next piece of code is not one of the exercises from QuantEcon – it's just a fun simulation to see what the effect of a change in the underlying distribution on the unemployment rate is.

At a point in the simulation, the distribution becomes significantly worse. It takes a while for agents to learn this, and in the meantime they are too optimistic, and turn down too many jobs. As a result, the unemployment rate spikes.

The code takes a few minutes to run.

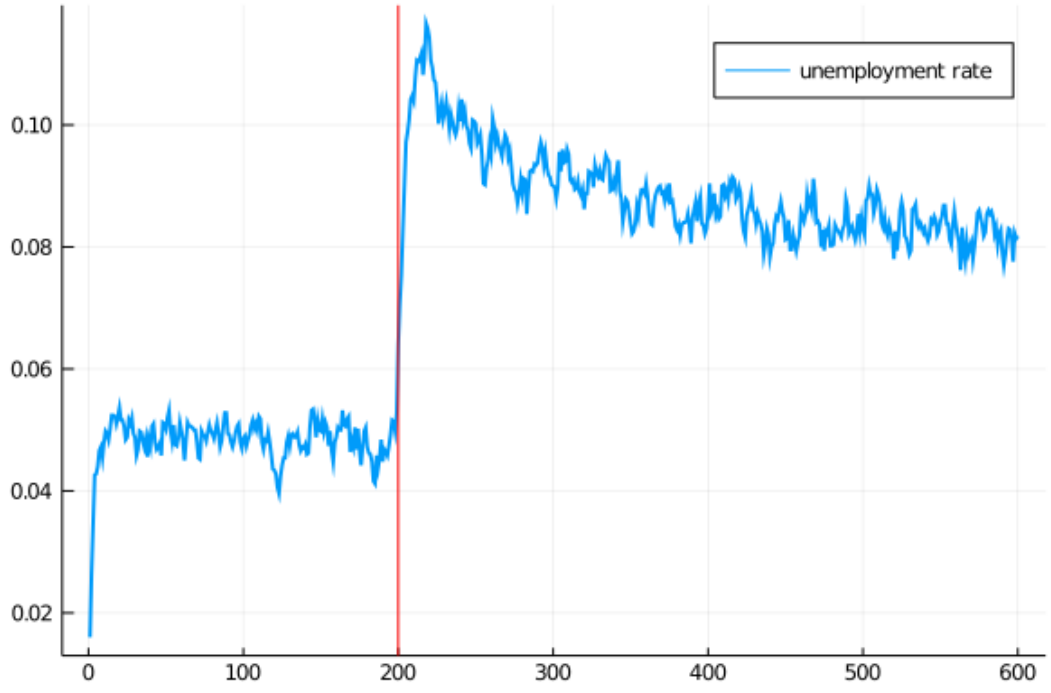
In [7]:
```
# Determinism and random objects.
using Random
Random.seed!(42)
```

```
# Set up model and compute the function w
sp = SearchProblem(π_grid_size = 50, F_a = 1, F_b = 1)
ϕ_init = ones(sp.n_π)
g(x) = res_wage_operator(sp, x)
w_vals = compute_fixed_point(g, ϕ_init)
w = extrapolate(interpolate((sp.π_grid, ), w_vals,
                    Gridded(Linear())), Flat())

# Holds the employment state and beliefs of an individual agent.
mutable struct Agent{TF <: AbstractFloat, TI <: Integer}
    _π::TF
    employed::TI
end

Agent(_π=1e-3) = Agent(_π, 1)

function update!(ag, H)
    if ag.employed == 0
        w = rand(H) * 2   # account for scale in julia
        if w ≥ w(ag._π)
            ag.employed = 1
        else
          ag._π = 1.0 ./ (1 .+ ((1 - ag._π) .* sp.g(w)) ./ (ag._π * sp.f(w)))
        end
    end
    nothing
end

num_agents = 5000
separation_rate = 0.025  # Fraction of jobs that end in each period
separation_num = round(Int, num_agents * separation_rate)
agent_indices = collect(1:num_agents)
agents = [Agent() for i=1:num_agents]
sim_length = 600
H = sp.G                 # Start with distribution G
change_date = 200        # Change to F after this many periods
unempl_rate = zeros(sim_length)

for i in 1:sim_length
    if i % 20 == 0
        println("date = $i")
    end

    if i == change_date
        H = sp.F
    end

    # Randomly select separation_num agents and set employment status to 0
    shuffle!(agent_indices)
    separation_list = agent_indices[1:separation_num]

    for agent in agents[separation_list]
        agent.employed = 0
    end

    # update agents
    for agent in agents
```

```
            update!(agent, H)
        end
        employed = Int[agent.employed for agent in agents]
        unempl_rate[i] = 1.0 - mean(employed)
    end

    plot(unempl_rate, linewidth = 2, label = "unemployment rate")
    vline!([change_date], color = :red, label = "")
```

```
    Compute iterate 10 with error 0.007194437603255555
Compute iterate 20 with error 0.0004348703417873523
Converged in 26 steps
date = 20
date = 40
date = 60
date = 80
date = 100
date = 120
date = 140
date = 160
date = 180
date = 200
date = 220
date = 240
date = 260
date = 280
date = 300
date = 320
date = 340
date = 360
date = 380
date = 400
date = 420
date = 440
date = 460
date = 480
date = 500
date = 520
date = 540
date = 560
date = 580
date = 600
```

Out[7]:


unemployment rate
0.10
0.08
0.06
0.04
0.02
0
100
200
300
400
500
600

Chapter 29

Job Search IV: Modeling Career Choice

29.1 Contents

29.2 Overview

Next we study a computational problem concerning career and job choices.

The model is originally due to Derek Neal [81].

This exposition draws on the presentation in [68], section 6.5.

29.2.1 Model features

- Career and job within career both chosen to maximize expected discounted wage flow.
- Infinite horizon dynamic programming with two state variables.

29.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")

In [2]: using LinearAlgebra, Statistics
```

29.3 Model

In what follows we distinguish between a career and a job, where

- a *career* is understood to be a general field encompassing many possible jobs, and
- a *job* is understood to be a position with a particular firm

For workers, wages can be decomposed into the contribution of job and career

- $w_t = \theta_t + \epsilon_t$, where
  - θ_t is contribution of career at time t
  - ϵ_t is contribution of job at time t

At the start of time t, a worker has the following options

- retain a current (career, job) pair (θ_t, ϵ_t) — referred to hereafter as "stay put"
- retain a current career θ_t but redraw a job ϵ_t — referred to hereafter as "new job"
- redraw both a career θ_t and a job ϵ_t — referred to hereafter as "new life"

Draws of θ and ϵ are independent of each other and past values, with

- $\theta_t \sim F$
- $\epsilon_t \sim G$

Notice that the worker does not have the option to retain a job but redraw a career — starting a new career always requires starting a new job.

A young worker aims to maximize the expected sum of discounted wages.

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t w_t \tag{1}$$

subject to the choice restrictions specified above.

Let $V(\theta, \epsilon)$ denote the value function, which is the maximum of (1) over all feasible (career, job) policies, given the initial state (θ, ϵ).

The value function obeys

$$V(\theta, \epsilon) = \max\{I, II, III\},$$

where

$$\begin{aligned} I &= \theta + \epsilon + \beta V(\theta, \epsilon) \\ II &= \theta + \int \epsilon' G(d\epsilon') + \beta \int V(\theta, \epsilon') G(d\epsilon') \\ III &= \int \theta' F(d\theta') + \int \epsilon' G(d\epsilon') + \beta \int \int V(\theta', \epsilon') G(d\epsilon') F(d\theta') \end{aligned} \tag{2}$$

Evidently I, II and III correspond to "stay put", "new job" and "new life", respectively.

29.3.1 Parameterization

As in [68], section 6.5, we will focus on a discrete version of the model, parameterized as follows:

- both θ and ϵ take values in the set `linspace(0, B, N)` — an even grid of N points between 0 and B inclusive
- $N = 50$

- $B = 5$
- $\beta = 0.95$

The distributions F and G are discrete distributions generating draws from the grid points `linspace(0, B, N)`.

A very useful family of discrete distributions is the Beta-binomial family, with probability mass function

$$p(k \mid n, a, b) = \binom{n}{k} \frac{B(k + a, n - k + b)}{B(a, b)}, \qquad k = 0, \ldots, n$$

Interpretation:

- draw q from a β distribution with shape parameters (a, b)
- run n independent binary trials, each with success probability q
- $p(k \mid n, a, b)$ is the probability of k successes in these n trials

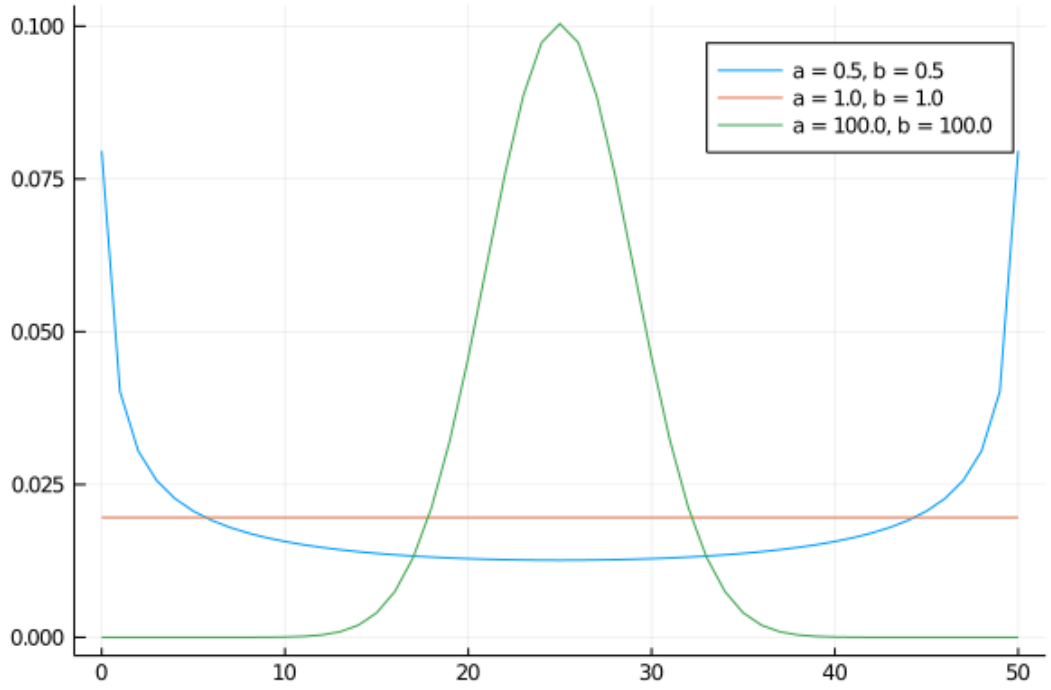
Nice properties:

- very flexible class of distributions, including uniform, symmetric unimodal, etc.
- only three parameters

Here's a figure showing the effect of different shape parameters when $n = 50$.

In [3]:
```
using Plots, QuantEcon, Distributions
gr(fmt=:png);

n = 50
a_vals = [0.5, 1, 100]
b_vals = [0.5, 1, 100]

plt = plot()
for (a, b) in zip(a_vals, b_vals)
    ab_label = "a = $a, b = $b"
    dist = BetaBinomial(n, a, b)
    plot!(plt, 0:n, pdf.(dist, support(dist)), label = ab_label)
end
plt
```

Out[3]:



Implementation:

The code for solving the DP problem described above is found below:

```
In [4]: function CareerWorkerProblem(;β = 0.95,
                                      B = 5.0,
                                      N = 50,
                                      F_a = 1.0,
                                      F_b = 1.0,
                                      G_a = 1.0,
                                      G_b = 1.0)
            θ = range(0, B, length = N)
            ϵ = copy(θ)
            dist_F = BetaBinomial(N-1, F_a, F_b)
            dist_G = BetaBinomial(N-1, G_a, G_b)
            F_probs = pdf.(dist_F, support(dist_F))
            G_probs = pdf.(dist_G, support(dist_G))
            F_mean = sum(θ .* F_probs)
            G_mean = sum(ϵ .* G_probs)
            return (β = β, N = N, B = B, θ = θ, ϵ = ϵ,
                    F_probs = F_probs, G_probs = G_probs,
                    F_mean = F_mean, G_mean = G_mean)
        end

        function update_bellman!(cp, v, out; ret_policy = false)

            # new life. This is a function of the distribution parameters and is
            # always constant. No need to recompute it in the loop
            v3 = (cp.G_mean + cp.F_mean .+ cp.β .*
                  cp.F_probs' * v * cp.G_probs)[1] # do not need 1 element array

            for j in 1:cp.N
                for i in 1:cp.N
                    # stay put
```

```
                v1 = cp.θ[i] + cp.ϵ[j] + cp.β * v[i, j]

                # new job
                v2 = (cp.θ[i] .+ cp.G_mean .+ cp.β .*
                      v[i, :]' * cp.G_probs)[1] # do not need a single element
↪array

                if ret_policy
                    if v1 > max(v2, v3)
                        action = 1
                    elseif v2 > max(v1, v3)
                        action = 2
                    else
                        action = 3
                    end
                    out[i, j] = action
                else
                    out[i, j] = max(v1, v2, v3)
                end
            end
        end
    end


    function update_bellman(cp, v; ret_policy = false)
        out = similar(v)
        update_bellman!(cp, v, out, ret_policy = ret_policy)
        return out
    end

    function get_greedy!(cp, v, out)
        update_bellman!(cp, v, out, ret_policy = true)
    end

    function get_greedy(cp, v)
        update_bellman(cp, v, ret_policy = true)
    end
```

```
Out[4]: get_greedy (generic function with 1 method)
```

The code defines

- a named tuple `CareerWorkerProblem` that
  - encapsulates all the details of a particular parameterization
  - implements the Bellman operator T

In this model, T is defined by $Tv(\theta, \epsilon) = \max\{I, II, III\}$, where I, II and III are as given in (2), replacing V with v.

The default probability distributions in `CareerWorkerProblem` correspond to discrete uniform distributions (see the Beta-binomial figure).

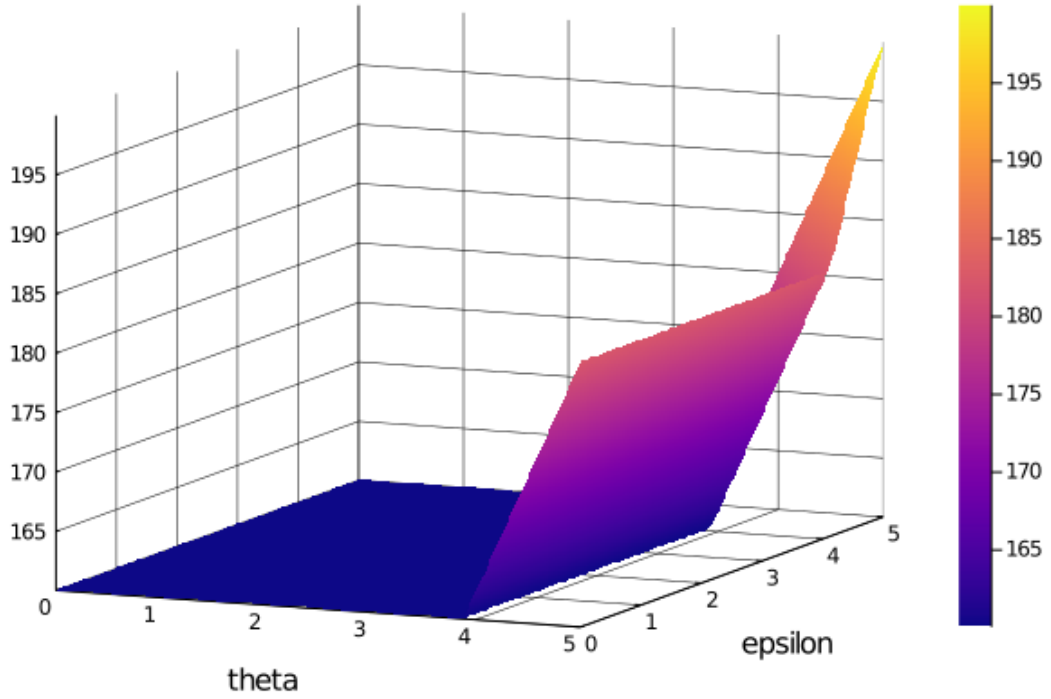
In fact all our default settings correspond to the version studied in [68], section 6.5.

Hence we can reproduce figures 6.5.1 and 6.5.2 shown there, which exhibit the value function and optimal policy respectively.

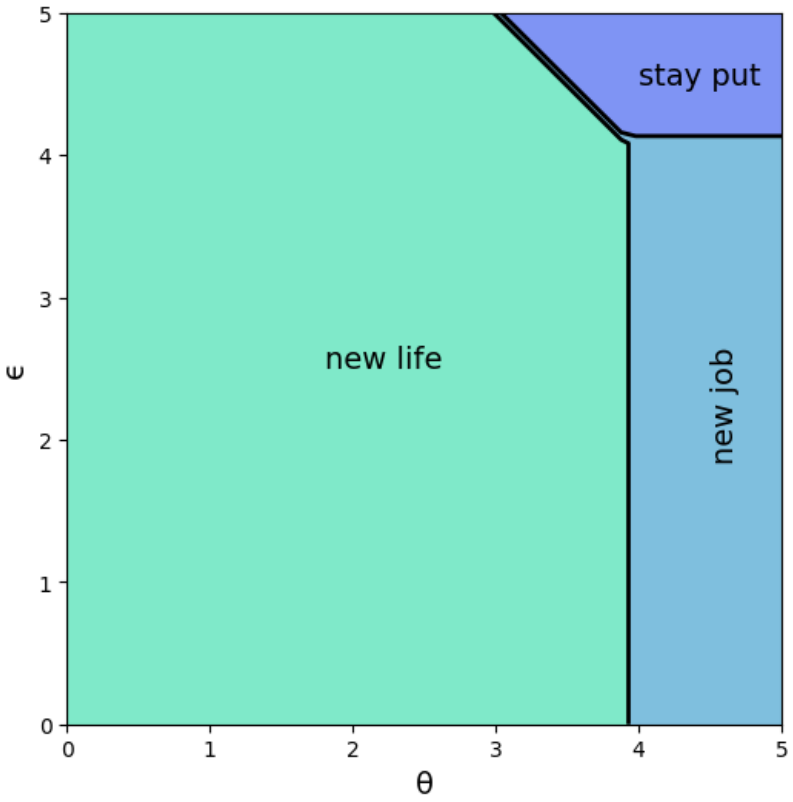
Here's the value function

```
In [5]: wp = CareerWorkerProblem()
        v_init = fill(100.0, wp.N, wp.N)
        func(x) = update_bellman(wp, x)
        v = compute_fixed_point(func, v_init, max_iter = 500, verbose = false)

        plot(linetype = :surface, wp.θ, wp.ϵ, transpose(v), xlabel="theta",
  ↪ylabel="epsilon",
             seriescolor=:plasma, gridalpha = 1)
```

Out[5]:



The optimal policy can be represented as follows (see Exercise 3 for code).



Interpretation:

- If both job and career are poor or mediocre, the worker will experiment with new job and new career.
- If career is sufficiently good, the worker will hold it and experiment with new jobs until a sufficiently good one is found.
- If both job and career are good, the worker will stay put.

Notice that the worker will always hold on to a sufficiently good career, but not necessarily hold on to even the best paying job.

The reason is that high lifetime wages require both variables to be large, and the worker cannot change careers without changing jobs.

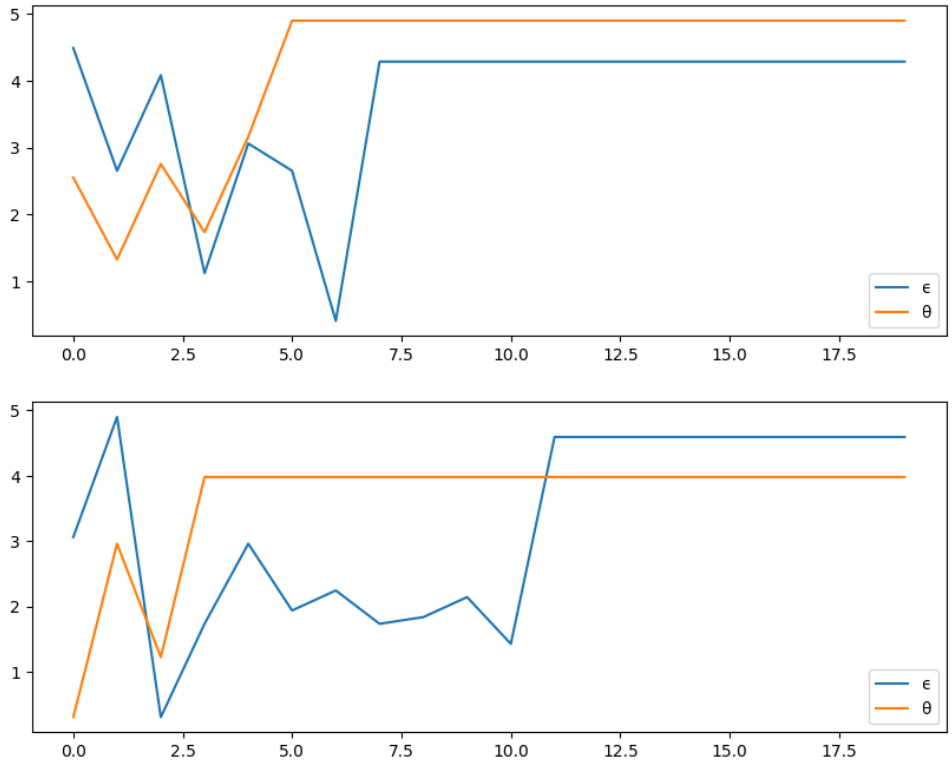
- Sometimes a good job must be sacrificed in order to change to a better career.

29.4 Exercises

29.4.1 Exercise 1

Using the default parameterization in the `CareerWorkerProblem`, generate and plot typical sample paths for θ and ϵ when the worker follows the optimal policy.

In particular, modulo randomness, reproduce the following figure (where the horizontal axis represents time)



Hint: To generate the draws from the distributions F and G, use the type DiscreteRV.

29.4.2 Exercise 2

Let's now consider how long it takes for the worker to settle down to a permanent job, given a starting point of $(\theta, \epsilon) = (0, 0)$.

In other words, we want to study the distribution of the random variable

$$T^* := \text{the first point in time from which the worker's job no longer changes}$$

Evidently, the worker's job becomes permanent if and only if (θ_t, ϵ_t) enters the "stay put" region of (θ, ϵ) space.

Letting S denote this region, T^* can be expressed as the first passage time to S under the optimal policy:

$$T^* := \inf\{t \geq 0 \,|\, (\theta_t, \epsilon_t) \in S\}$$

Collect 25,000 draws of this random variable and compute the median (which should be about 7).

Repeat the exercise with $\beta = 0.99$ and interpret the change.

29.4.3 Exercise 3

As best you can, reproduce the figure showing the optimal policy.

Hint: The `get_greedy()` method returns a representation of the optimal policy where values 1, 2 and 3 correspond to "stay put", "new job" and "new life" respectively. Use this and the plots functions (e.g., `contour, contour!`) to produce the different shadings.

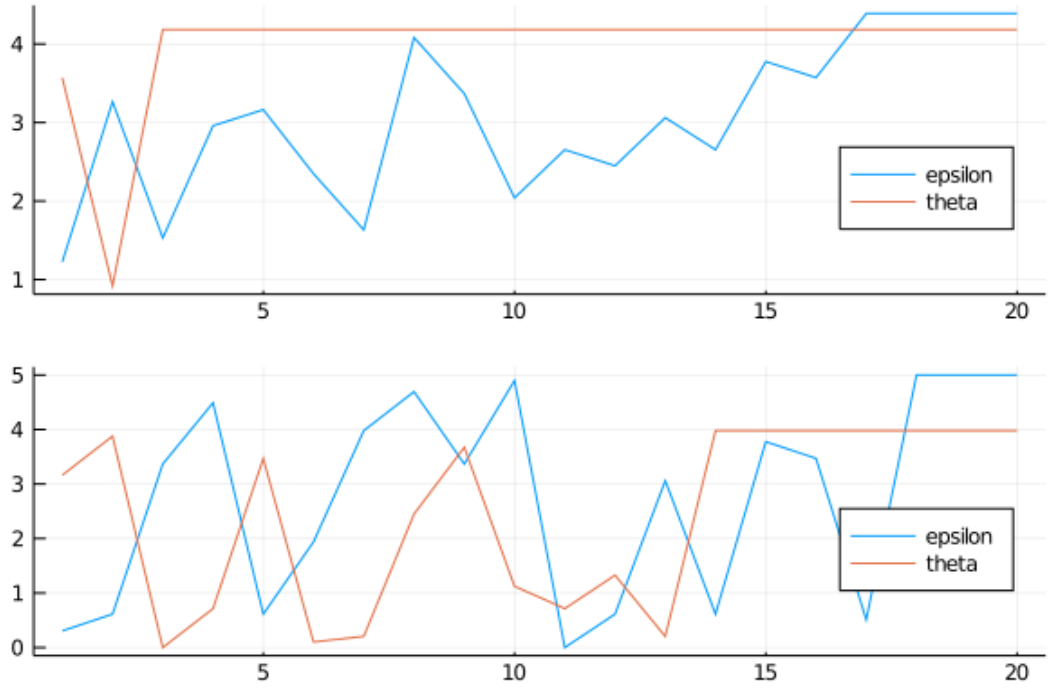
Now set `G_a = G_b = 100` and generate a new figure with these parameters. Interpret.

29.5 Solutions

29.5.1 Exercise 1

In [6]:
```
wp = CareerWorkerProblem()

function solve_wp(wp)
    v_init = fill(100.0, wp.N, wp.N)
    func(x) = update_bellman(wp, x)
    v = compute_fixed_point(func, v_init, max_iter = 500, verbose = false)
    optimal_policy = get_greedy(wp, v)
    return v, optimal_policy
end

v, optimal_policy = solve_wp(wp)

F = DiscreteRV(wp.F_probs)
G = DiscreteRV(wp.G_probs)

function gen_path(T = 20)
    i = j = 1
    θ_ind = Int[]
    ϵ_ind = Int[]

    for t=1:T
        # do nothing if stay put
        if optimal_policy[i, j] == 2 # new job
            j = rand(G)[1]
        elseif optimal_policy[i, j] == 3 # new life
            i, j = rand(F)[1], rand(G)[1]
        end
        push!(θ_ind, i)
        push!(ϵ_ind, j)
    end
    return wp.θ[θ_ind], wp.ϵ[ϵ_ind]
end

plot_array = Any[]
for i in 1:2
    θ_path, ϵ_path = gen_path()
    plt = plot(ϵ_path, label="epsilon")
    plot!(plt, θ_path, label="theta")
    plot!(plt, legend=:bottomright)
    push!(plot_array, plt)
end
plot(plot_array..., layout = (2,1))
```

Out[6]:



29.5.2 Exercise 2

The median for the original parameterization can be computed as follows

```
In [7]: function gen_first_passage_time(optimal_policy)
            t = 0
            i = j = 1
            while true
                if optimal_policy[i, j] == 1 # Stay put
                    return t
                elseif optimal_policy[i, j] == 2 # New job
                    j = rand(G)[1]
                else # New life
                    i, j = rand(F)[1], rand(G)[1]
                end
                t += 1
            end
        end


        M = 25000
        samples = zeros(M)
        for i in 1:M
            samples[i] = gen_first_passage_time(optimal_policy)
        end
        print(median(samples))
```

```
   7.0
```

To compute the median with $\beta = 0.99$ instead of the default value $\beta = 0.95$, replace `wp=CareerWorkerProblem()` with `wp=CareerWorkerProblem(β=0.99)`.

The medians are subject to randomness, but should be about 7 and 14 respectively. Not surprisingly, more patient workers will wait longer to settle down to their final job.

```
In [8]: wp2 = CareerWorkerProblem(β=0.99)

        v2, optimal_policy2 = solve_wp(wp2)

        samples2 = zeros(M)
        for i in 1:M
            samples2[i] = gen_first_passage_time(optimal_policy2)
        end
        print(median(samples2))
```

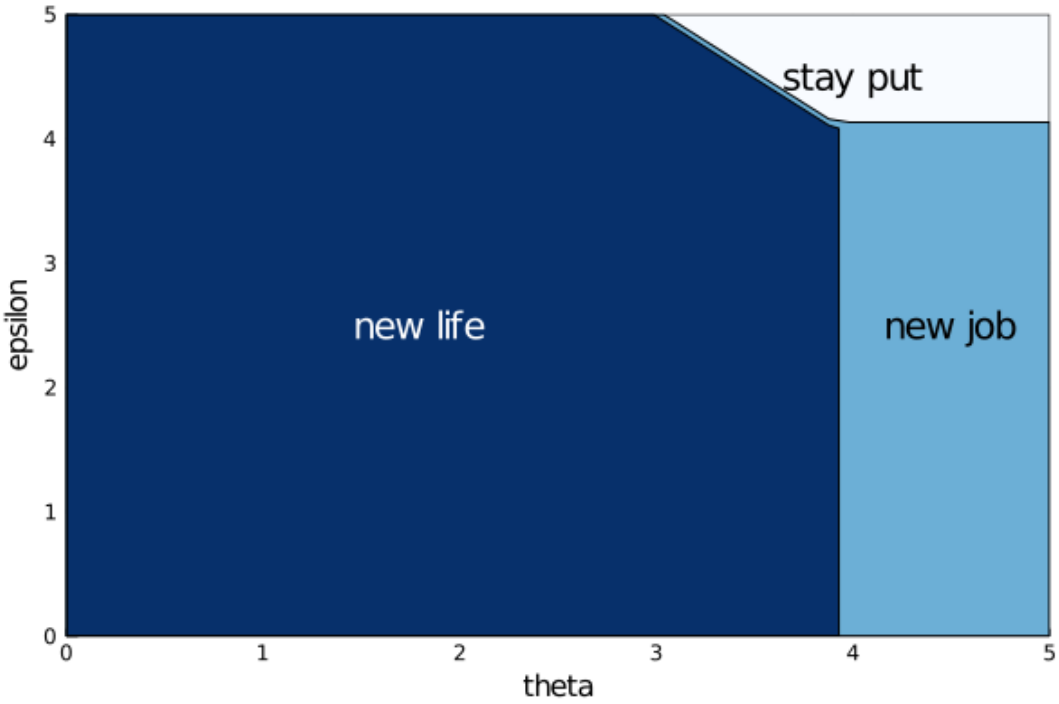
```
14.0
```

29.5.3 Exercise 3

Here's the code to reproduce the original figure

```
In [9]: wp = CareerWorkerProblem();
        v, optimal_policy = solve_wp(wp)

        lvls = [0.5, 1.5, 2.5, 3.5]
        x_grid = range(0, 5, length = 50)
        y_grid = range(0, 5, length = 50)

        contour(x_grid, y_grid, optimal_policy', fill=true, levels=lvls,color = :
↪Blues,
                fillalpha=1, cbar = false)
        contour!(xlabel="theta", ylabel="epsilon")
        annotate!([(1.8,2.5, text("new life", 14, :white, :center))])
        annotate!([(4.5,2.5, text("new job", 14, :center))])
        annotate!([(4.0,4.5, text("stay put", 14, :center))])
```

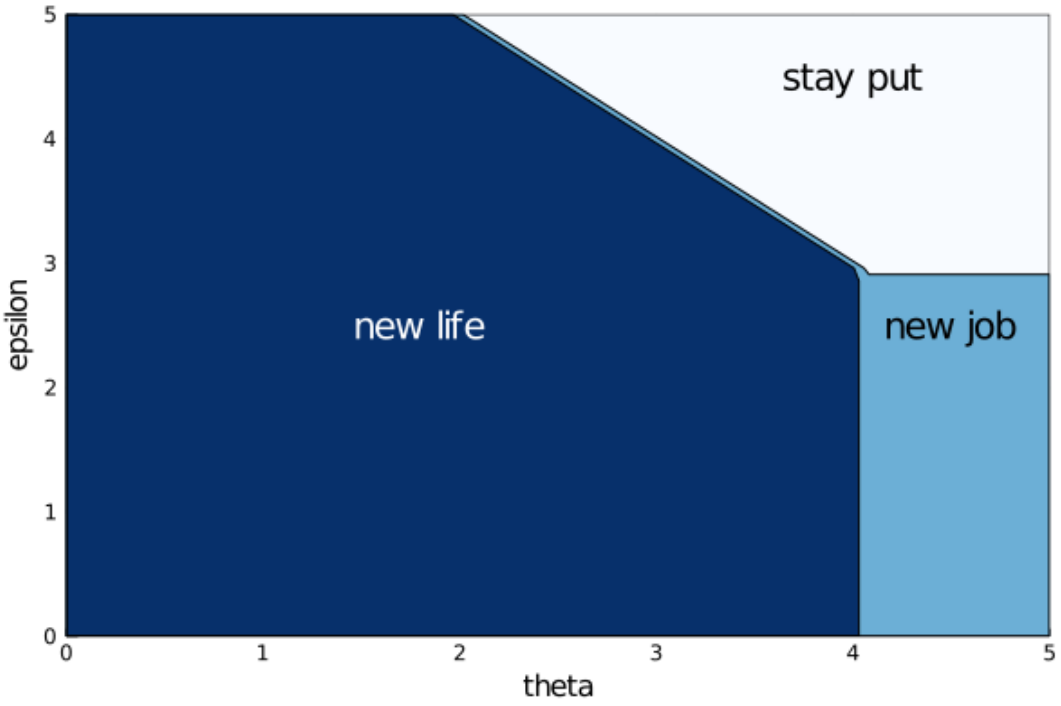
```
Out[9]:
```



Now, we need only swap out for the new parameters

```
In [10]: wp = CareerWorkerProblem(G_a=100.0, G_b=100.0); # use new params
         v, optimal_policy = solve_wp(wp)

         lvls = [0.5, 1.5, 2.5, 3.5]
         x_grid = range(0, 5, length = 50)
         y_grid = range(0, 5, length = 50)

         contour(x_grid, y_grid, optimal_policy', fill=true, levels=lvls,color = :
 ↪Blues,
                 fillalpha=1, cbar = false)
         contour!(xlabel="theta", ylabel="epsilon")
         annotate!([(1.8,2.5, text("new life", 14, :white, :center))])
         annotate!([(4.5,2.5, text("new job", 14, :center))])
         annotate!([(4.0,4.5, text("stay put", 14, :center))])
```

Out[10]:



You will see that the region for which the worker will stay put has grown because the distribution for ϵ has become more concentrated around the mean, making high-paying jobs less realistic.

Chapter 30

Job Search V: On-the-Job Search

30.1 Contents

30.2 Overview

30.2.1 Model features

- job-specific human capital accumulation combined with on-the-job search
- infinite horizon dynamic programming with one state variable and two controls

30.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, QuantEcon, Interpolations, Expectations, Parameters
        using Plots, NLsolve, Random
        gr(fmt = :png);
```

30.3 Model

Let

- x_t denote the time-t job-specific human capital of a worker employed at a given firm
- w_t denote current wages

Let $w_t = x_t(1 - s_t - \phi_t)$, where

- ϕ_t is investment in job-specific human capital for the current role
- s_t is search effort, devoted to obtaining new offers from other firms

For as long as the worker remains in the current job, evolution of $\{x_t\}$ is given by $x_{t+1} = G(x_t, \phi_t)$.

When search effort at t is s_t, the worker receives a new job offer with probability $\pi(s_t) \in [0, 1]$.

Value of offer is U_{t+1}, where $\{U_t\}$ is iid with common distribution F.

Worker has the right to reject the current offer and continue with existing job.

In particular, $x_{t+1} = U_{t+1}$ if accepts and $x_{t+1} = G(x_t, \phi_t)$ if rejects.

Letting $b_{t+1} \in \{0, 1\}$ be binary with $b_{t+1} = 1$ indicating an offer, we can write

$$x_{t+1} = (1 - b_{t+1})G(x_t, \phi_t) + b_{t+1} \max\{G(x_t, \phi_t), U_{t+1}\} \tag{1}$$

Agent's objective: maximize expected discounted sum of wages via controls $\{s_t\}$ and $\{\phi_t\}$.

Taking the expectation of $V(x_{t+1})$ and using (1), the Bellman equation for this problem can be written as

$$V(x) = \max_{s+\phi \leq 1} \left\{ x(1 - s - \phi) + \beta(1 - \pi(s))V[G(x, \phi)] + \beta\pi(s) \int V[G(x, \phi) \vee u]F(du) \right\}. \tag{2}$$

Here nonnegativity of s and ϕ is understood, while $a \vee b := \max\{a, b\}$.

30.3.1 Parameterization

In the implementation below, we will focus on the parameterization.

$$G(x, \phi) = A(x\phi)^\alpha, \quad \pi(s) = \sqrt{s} \quad \text{and} \quad F = \text{Beta}(2, 2)$$

with default parameter values

- $A = 1.4$
- $\alpha = 0.6$
- $\beta = 0.96$

The Beta(2,2) distribution is supported on $(0, 1)$. It has a unimodal, symmetric density peaked at 0.5.

30.3.2 Back-of-the-Envelope Calculations

Before we solve the model, let's make some quick calculations that provide intuition on what the solution should look like.

To begin, observe that the worker has two instruments to build capital and hence wages:

1. invest in capital specific to the current job via ϕ

2. search for a new job with better job-specific capital match via s

Since wages are $x(1-s-\phi)$, marginal cost of investment via either ϕ or s is identical.

Our risk neutral worker should focus on whatever instrument has the highest expected return.

The relative expected return will depend on x.

For example, suppose first that $x = 0.05$

- If $s = 1$ and $\phi = 0$, then since $G(x, \phi) = 0$, taking expectations of (1) gives expected next period capital equal to $\pi(s)\mathbb{E}U = \mathbb{E}U = 0.5$.
- If $s = 0$ and $\phi = 1$, then next period capital is $G(x, \phi) = G(0.05, 1) \approx 0.23$.

Both rates of return are good, but the return from search is better.

Next suppose that $x = 0.4$

- If $s = 1$ and $\phi = 0$, then expected next period capital is again 0.5
- If $s = 0$ and $\phi = 1$, then $G(x, \phi) = G(0.4, 1) \approx 0.8$

Return from investment via ϕ dominates expected return from search.

Combining these observations gives us two informal predictions:

1. At any given state x, the two controls ϕ and s will function primarily as substitutes — worker will focus on whichever instrument has the higher expected return.
2. For sufficiently small x, search will be preferable to investment in job-specific human capital. For larger x, the reverse will be true.

Now let's turn to implementation, and see if we can match our predictions.

30.4 Implementation

The following code solves the DP problem described above

In [3]:
```
using Distributions, QuantEcon, Interpolations, Expectations, Parameters

    # model object
    function JvWorker(;A = 1.4,
                      α = 0.6,
                      β = 0.96,
                      grid_size = 50,
                      ϵ = 1e-4)

        G(x, ϕ) = A .* (x .* ϕ).^α
        π_func = sqrt
        F = Beta(2, 2)

        # expectation operator
        E = expectation(F)

        # Set up grid over the state space for DP
        # Max of grid is the max of a large quantile value for F and the
        # fixed point y = G(y, 1).
```

```
    grid_max = max(A^(1.0 / (1.0 - α)), quantile(F, 1 - ϵ))

    # range for range(ϵ, grid_max, grid_size). Needed for
    # CoordInterpGrid below
    x_grid = range(ϵ, grid_max, length = grid_size)

    return (A = A, α = α, β = β, x_grid = x_grid, G = G,
            π_func = π_func, F = F, E = E, ϵ = ϵ)
end

function T!(jv,
                          V,
                          new_V::AbstractVector)

    # simplify notation
    @unpack G, π_func, F, β, E, ϵ = jv

    # prepare interpoland of value function
    Vf = LinearInterpolation(jv.x_grid, V, extrapolation_bc=Line())

    # instantiate the linesearch variables
    max_val = -1.0
    cur_val = 0.0
    max_s = 1.0
    max_ϕ = 1.0
    search_grid = range(ϵ, 1.0, length = 15)

    for (i, x) in enumerate(jv.x_grid)

        function w(z)
            s, ϕ = z
            h(u) = Vf(max(G(x, ϕ), u))
            integral = E(h)
            q = π_func(s) * integral + (1.0 - π_func(s)) * Vf(G(x, ϕ))

            return - x * (1.0 - ϕ - s) - β * q
        end

        for s in search_grid
            for ϕ in search_grid
                cur_val = ifelse(s + ϕ <= 1.0, -w((s, ϕ)), -1.0)
                if cur_val > max_val
                    max_val, max_s, max_ϕ = cur_val, s, ϕ
                end
            end
        end

        new_V[i] = max_val
    end
end

function T!(jv,
                          V,
                          out::Tuple{AbstractVector, AbstractVector})

    # simplify notation
    @unpack G, π_func, F, β, E, ϵ = jv
```

```
    # prepare interpoland of value function
    Vf = LinearInterpolation(jv.x_grid, V, extrapolation_bc=Line())

    # instantiate variables
    s_policy, ϕ_policy = out[1], out[2]

    # instantiate the linesearch variables
    max_val = -1.0
    cur_val = 0.0
    max_s = 1.0
    max_ϕ = 1.0
    search_grid = range(ϵ, 1.0, length = 15)

    for (i, x) in enumerate(jv.x_grid)

        function w(z)
            s, ϕ = z
            h(u) = Vf(max(G(x, ϕ), u))
            integral = E(h)
            q = π_func(s) * integral + (1.0 - π_func(s)) * Vf(G(x, ϕ))

            return - x * (1.0 - ϕ - s) - β * q
        end

        for s in search_grid
            for ϕ in search_grid
                cur_val = ifelse(s + ϕ <= 1.0, -w((s, ϕ)), -1.0)
                if cur_val > max_val
                    max_val, max_s, max_ϕ = cur_val, s, ϕ
                end
            end
        end

    s_policy[i], ϕ_policy[i] = max_s, max_ϕ
end
end

function T(jv, V; ret_policies = false)
    out = ifelse(ret_policies, (similar(V), similar(V)), similar(V))
    T!(jv, V, out)
    return out
end
```

```
Out[3]: T (generic function with 1 method)
```

The code is written to be relatively generic—and hence reusable.

- For example, we use generic $G(x, \phi)$ instead of specific $A(x\phi)^\alpha$.

Regarding the imports

- `fixed_quad` is a simple non-adaptive integration routine
- `fmin_slsqp` is a minimization routine that permits inequality constraints

Next we write a constructor called `JvWorker` that

- packages all the parameters and other basic attributes of a given model
- implements the method `T` for value function iteration

The `T` method takes a candidate value function V and updates it to TV via

$$TV(x) = -\min_{s+\phi \leq 1} w(s, \phi)$$

where

$$w(s, \phi) := -\left\{ x(1-s-\phi) + \beta(1-\pi(s))V[G(x,\phi)] + \beta\pi(s) \int V[G(x,\phi) \vee u]F(du) \right\} \tag{3}$$

Here we are minimizing instead of maximizing to fit with optimization routines.

When we represent V, it will be with a Julia array `V` giving values on grid `x_grid`.

But to evaluate the right-hand side of (3), we need a function, so we replace the arrays `V` and `x_grid` with a function `Vf` that gives linear interpolation of `V` on `x_grid`.

Hence in the preliminaries of `T`

- from the array `V` we define a linear interpolation `Vf` of its values
  - `c1` is used to implement the constraint $s + \phi \leq 1$
  - `c2` is used to implement $s \geq \epsilon$, a numerically stable alternative to the true constraint $s \geq 0$
  - `c3` does the same for ϕ

Inside the `for` loop, for each `x` in the grid over the state space, we set up the function $w(z) = w(s, \phi)$ defined in (3).

The function is minimized over all feasible (s, ϕ) pairs, either by brute-force search over a grid, or specialized solver routines.

The latter is much faster, but convergence to the global optimum is not guaranteed. Grid search is a simple way to check results.

30.5 Solving for Policies

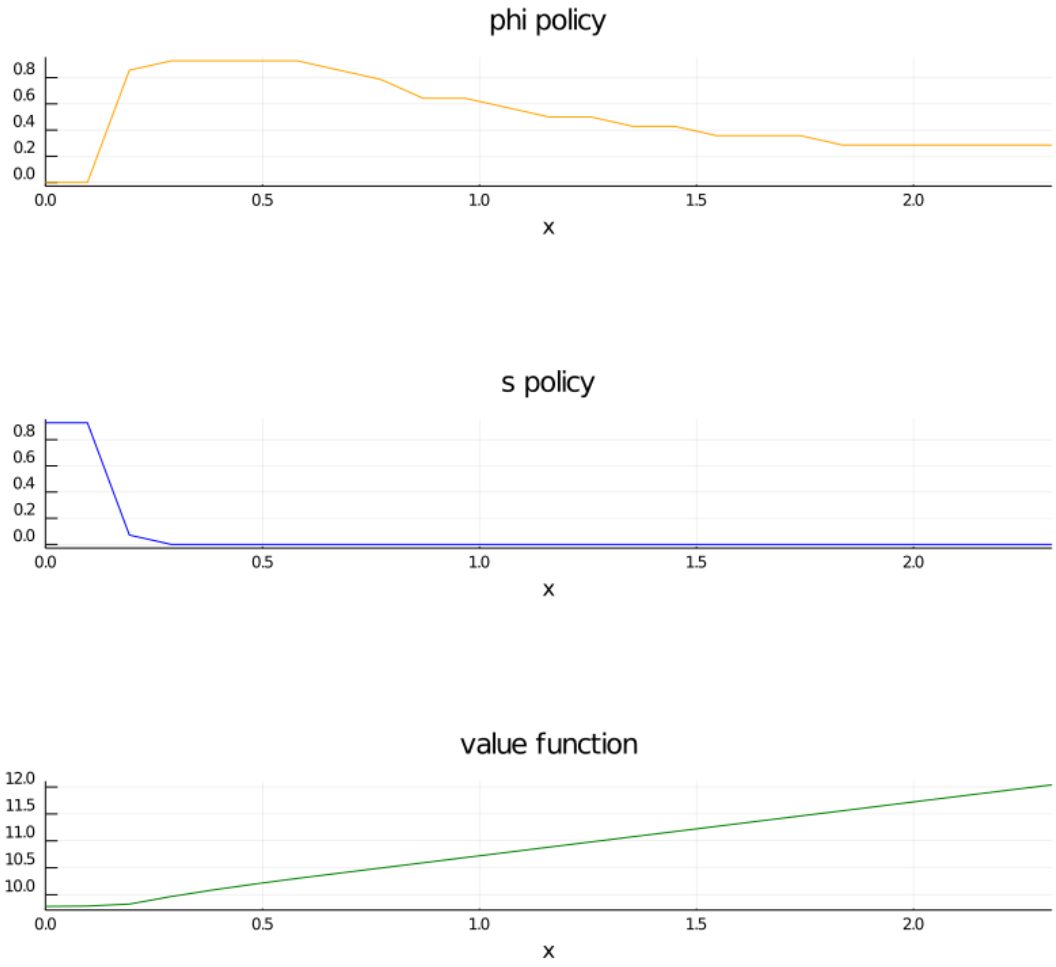
Let's plot the optimal policies and see what they look like.

The code is as follows

```
In [4]: wp = JvWorker(grid_size=25)
        v_init = collect(wp.x_grid) .* 0.5

        f(x) = T(wp, x)
        V = fixedpoint(f, v_init)
        sol_V = V.zero

        s_policy, ϕ_policy = T(wp, sol_V, ret_policies = true)

        # plot solution
        p = plot(wp.x_grid, [ϕ_policy s_policy sol_V],
                 title = ["phi policy" "s policy" "value function"],
                 color = [:orange :blue :green],
                 xaxis = ("x", (0.0, maximum(wp.x_grid))),
                 yaxis = ((-0.1, 1.1)), size = (800, 800),
```

```
        legend = false, layout = (3, 1),
        bottom_margin = Plots.PlotMeasures.Length(:mm, 20))
```

Out[4]:



The horizontal axis is the state x, while the vertical axis gives $s(x)$ and $\phi(x)$.

Overall, the policies match well with our predictions from section.

- Worker switches from one investment strategy to the other depending on relative return.
- For low values of x, the best option is to search for a new job.
- Once x is larger, worker does better by investing in human capital specific to the current position.

30.6 Exercises

30.6.1 Exercise 1

Let's look at the dynamics for the state process $\{x_t\}$ associated with these policies.

The dynamics are given by (1) when ϕ_t and s_t are chosen according to the optimal policies, and $\mathbb{P}\{b_{t+1} = 1\} = \pi(s_t)$.

Since the dynamics are random, analysis is a bit subtle.

One way to do it is to plot, for each x in a relatively fine grid called `plot_grid`, a large number K of realizations of x_{t+1} given $x_t = x$. Plot this with one dot for each realization, in the form of a 45 degree diagram. Set

```
K = 50
plot_grid_max, plot_grid_size = 1.2, 100
plot_grid = range(0, plot_grid_max, length = plot_grid_size)
plot(plot_grid, plot_grid, color = :black, linestyle = :dash,
     lims = (0, plot_grid_max), legend = :none)
```

By examining the plot, argue that under the optimal policies, the state x_t will converge to a constant value $\bar{x}$ close to unity.

Argue that at the steady state, $s_t \approx 0$ and $\phi_t \approx 0.6$.

30.6.2 Exercise 2

In the preceding exercise we found that s_t converges to zero and ϕ_t converges to about 0.6.

Since these results were calculated at a value of β close to one, let's compare them to the best choice for an *infinitely* patient worker.

Intuitively, an infinitely patient worker would like to maximize steady state wages, which are a function of steady state capital.

You can take it as given—it's certainly true—that the infinitely patient worker does not search in the long run (i.e., $s_t = 0$ for large t).

Thus, given ϕ, steady state capital is the positive fixed point $x^*(\phi)$ of the map $x \mapsto G(x, \phi)$.

Steady state wages can be written as $w^*(\phi) = x^*(\phi)(1 - \phi)$.

Graph $w^*(\phi)$ with respect to ϕ, and examine the best choice of ϕ.

Can you give a rough interpretation for the value that you see?

30.7 Solutions

30.7.1 Exercise 1

Here's code to produce the 45 degree diagram

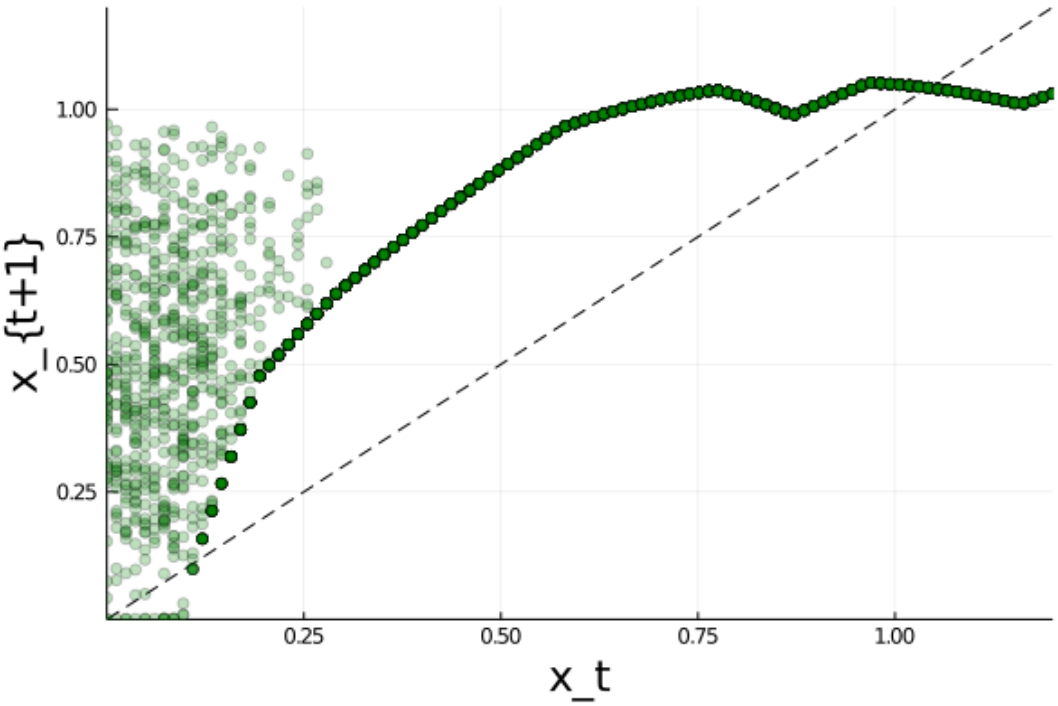
```
In [5]: wp = JvWorker(grid_size=25)
        # simplify notation
        @unpack G, π_func, F = wp

        v_init = collect(wp.x_grid) * 0.5
        f2(x) = T(wp, x)
        V2 = fixedpoint(f2, v_init)
        sol_V2 = V2.zero
```

```
        s_policy, ϕ_policy = T(wp, sol_V2, ret_policies=true)

        # Turn the policy function arrays into CoordInterpGrid objects for
↪interpolation
        s = LinearInterpolation(wp.x_grid, s_policy, extrapolation_bc=Line())
        ϕ = LinearInterpolation(wp.x_grid, ϕ_policy, extrapolation_bc=Line())

        h_func(x, b, U) = (1 - b) * G(x, ϕ(x)) + b * max(G(x, ϕ(x)), U)
```

Out[5]: h_func (generic function with 1 method)

In [6]:
```
using Random
Random.seed!(42)
K = 50

plot_grid_max, plot_grid_size = 1.2, 100
plot_grid = range(0, plot_grid_max, length = plot_grid_size)
ticks = [0.25, 0.5, 0.75, 1.0]

xs = []
ys = []
for x in plot_grid
    for i=1:K
        b = rand() < π_func(s(x)) ? 1 : 0
        U = rand(wp.F)
        y = h_func(x, b, U)
        push!(xs, x)
        push!(ys, y)
    end
end

plot(plot_grid, plot_grid, color=:black, linestyle=:dash, legend=:none)
scatter!(xs, ys, alpha=0.25, color=:green, lims=(0, plot_grid_max),
↪ticks=ticks)
plot!(xlabel="x_t", ylabel="x_{t+1}", guidefont=font(16))
```

Out[6]:



Looking at the dynamics, we can see that

- If x_t is below about 0.2 the dynamics are random, but $x_{t+1} > x_t$ is very likely
- As x_t increases the dynamics become deterministic, and x_t converges to a steady state value close to 1

Referring back to the figure here.

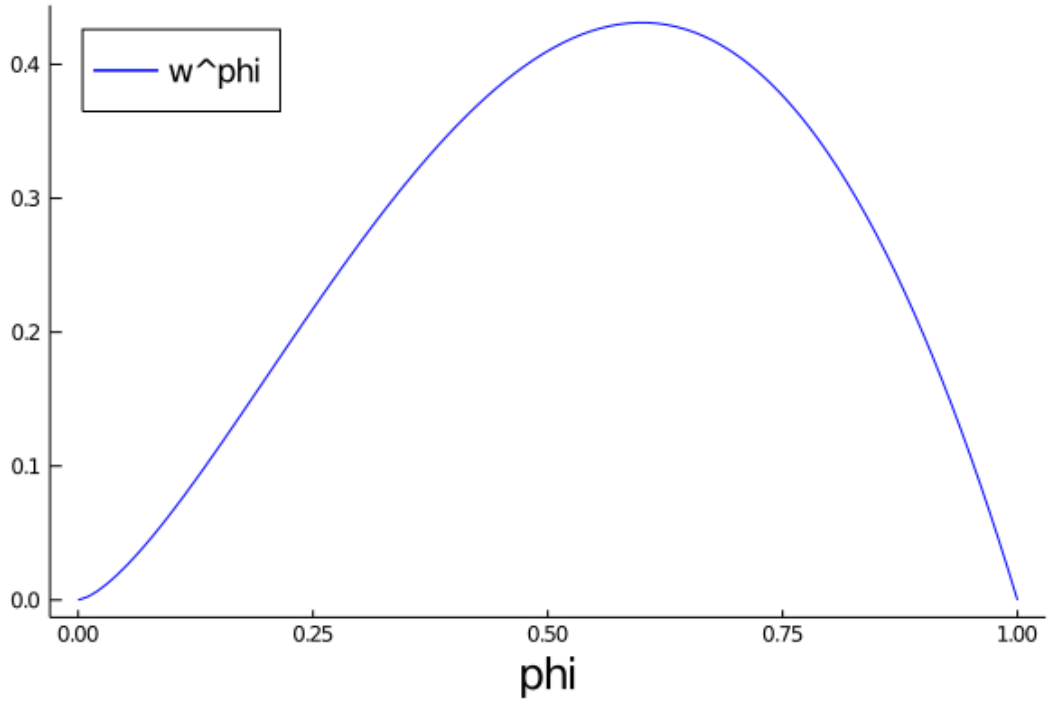
https://julia.quantecon.org/dynamic_programming/jv.html#Solving-for-Policies

we see that $x_t \approx 1$ means that $s_t = s(x_t) \approx 0$ and $\phi_t = \phi(x_t) \approx 0.6$.

30.7.2 Exercise 2

In [7]:
```
wp = JvWorker(grid_size=25)

xbar(ϕ) = (wp.A * ϕ^wp.α)^(1.0 / (1.0 - wp.α))

ϕ_grid = range(0, 1, length = 100)

plot(ϕ_grid, [xbar(ϕ) * (1 - ϕ) for ϕ in ϕ_grid], color = :blue,
     label = "w^phi", legendfont = font(12), xlabel = "phi",
     guidefont = font(16), grid = false, legend = :topleft)
```

Out[7]:



Observe that the maximizer is around 0.6.

This this is similar to the long run value for ϕ obtained in exercise 1.

Hence the behaviour of the infinitely patent worker is similar to that of the worker with $\beta = 0.96$.

This seems reasonable, and helps us confirm that our dynamic programming solutions are probably correct.

Chapter 31

Optimal Growth I: The Stochastic Optimal Growth Model

31.1 Contents

31.2 Overview

In this lecture we're going to study a simple optimal growth model with one agent.

The model is a version of the standard one sector infinite horizon growth model studied in

- [100], chapter 2
- [68], section 3.1
- EDTC, chapter 1
- [102], chapter 12

The technique we use to solve the model is dynamic programming.

Our treatment of dynamic programming follows on from earlier treatments in our lectures on shortest paths and job search.

We'll discuss some of the technical details of dynamic programming as we go along.

31.3 The Model

Consider an agent who owns an amount $y_t \in \mathbb{R}_+ := [0, \infty)$ of a consumption good at time t.

This output can either be consumed or invested.

When the good is invested it is transformed one-for-one into capital.

The resulting capital stock, denoted here by k_{t+1}, will then be used for production.

Production is stochastic, in that it also depends on a shock ξ_{t+1} realized at the end of the current period.

Next period output is

$$y_{t+1} := f(k_{t+1})\xi_{t+1}$$

where $f \colon \mathbb{R}_+ \to \mathbb{R}_+$ is called the production function.

The resource constraint is

$$k_{t+1} + c_t \leq y_t \tag{1}$$

and all variables are required to be nonnegative.

31.3.1 Assumptions and Comments

In what follows,

- The sequence $\{\xi_t\}$ is assumed to be IID.
- The common distribution of each ξ_t will be denoted ϕ.
- The production function f is assumed to be increasing and continuous.
- Depreciation of capital is not made explicit but can be incorporated into the production function.

While many other treatments of the stochastic growth model use k_t as the state variable, we will use y_t.

This will allow us to treat a stochastic model while maintaining only one state variable.

We consider alternative states and timing specifications in some of our other lectures.

31.3.2 Optimization

Taking y_0 as given, the agent wishes to maximize

$$\mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t u(c_t)\right] \tag{2}$$

subject to

$$y_{t+1} = f(y_t - c_t)\xi_{t+1} \quad \text{and} \quad 0 \leq c_t \leq y_t \quad \text{for all } t \tag{3}$$

where

- u is a bounded, continuous and strictly increasing utility function and
- $\beta \in (0, 1)$ is a discount factor

In (3) we are assuming that the resource constraint (1) holds with equality — which is reasonable because u is strictly increasing and no output will be wasted at the optimum.

In summary, the agent's aim is to select a path $c_0, c_1, c_2, \ldots$ for consumption that is

1. nonnegative,
2. feasible in the sense of (1),
3. optimal, in the sense that it maximizes (2) relative to all other feasible consumption sequences, and
4. *adapted*, in the sense that the action c_t depends only on observable outcomes, not future outcomes such as ξ_{t+1}

In the present context

- y_t is called the *state* variable — it summarizes the "state of the world" at the start of each period.
- c_t is called the *control* variable — a value chosen by the agent each period after observing the state.

31.3.3 The Policy Function Approach

One way to think about solving this problem is to look for the best **policy function**.

A policy function is a map from past and present observables into current action.

We'll be particularly interested in **Markov policies**, which are maps from the current state y_t into a current action c_t.

For dynamic programming problems such as this one (in fact for any Markov decision process), the optimal policy is always a Markov policy.

In other words, the current state y_t provides a sufficient statistic for the history in terms of making an optimal decision today.

This is quite intuitive but if you wish you can find proofs in texts such as [100] (section 4.1).

Hereafter we focus on finding the best Markov policy.

In our context, a Markov policy is a function $\sigma : \mathbb{R}_+ \to \mathbb{R}_+$, with the understanding that states are mapped to actions via

$$c_t = \sigma(y_t) \quad \text{for all } t$$

In what follows, we will call σ a *feasible consumption policy* if it satisfies

$$0 \leq \sigma(y) \leq y \quad \text{for all} \quad y \in \mathbb{R}_+ \tag{4}$$

In other words, a feasible consumption policy is a Markov policy that respects the resource constraint.

The set of all feasible consumption policies will be denoted by Σ.

Each $\sigma \in \Sigma$ determines a continuous state Markov process $\{y_t\}$ for output via

$$y_{t+1} = f(y_t - \sigma(y_t))\xi_{t+1}, \quad y_0 \text{ given} \tag{5}$$

This is the time path for output when we choose and stick with the policy σ.

We insert this process into the objective function to get

$$\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t u(c_t)\right] = \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t u(\sigma(y_t))\right] \tag{6}$$

This is the total expected present value of following policy σ forever, given initial income y_0.

The aim is to select a policy that makes this number as large as possible.

The next section covers these ideas more formally.

31.3.4 Optimality

The **policy value function** v_σ associated with a given policy σ is the mapping defined by

$$v_\sigma(y) = \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t u(\sigma(y_t))\right] \tag{7}$$

when $\{y_t\}$ is given by (5) with $y_0 = y$.

In other words, it is the lifetime value of following policy σ starting at initial condition y.

The **value function** is then defined as

$$v^*(y) := \sup_{\sigma\in\Sigma} v_\sigma(y) \tag{8}$$

The value function gives the maximal value that can be obtained from state y, after considering all feasible policies.

A policy $\sigma \in \Sigma$ is called **optimal** if it attains the supremum in (8) for all $y \in \mathbb{R}_+$.

31.3.5 The Bellman Equation

With our assumptions on utility and production function, the value function as defined in (8) also satisfies a **Bellman equation**.

For this problem, the Bellman equation takes the form

$$w(y) = \max_{0\le c\le y}\left\{u(c) + \beta\int w(f(y-c)z)\phi(dz)\right\} \qquad (y \in \mathbb{R}_+) \tag{9}$$

This is a *functional equation in* w.

The term $\int w(f(y-c)z)\phi(dz)$ can be understood as the expected next period value when

- w is used to measure value
- the state is y
- consumption is set to c

As shown in EDTC, theorem 10.1.11 and a range of other texts.

The value function v^* satisfies the Bellman equation

In other words, (9) holds when $w = v^*$.

The intuition is that maximal value from a given state can be obtained by optimally trading off

- current reward from a given action, vs
- expected discounted future value of the state resulting from that action

The Bellman equation is important because it gives us more information about the value function.

It also suggests a way of computing the value function, which we discuss below.

31.3.6 Greedy policies

The primary importance of the value function is that we can use it to compute optimal policies.

The details are as follows.

Given a continuous function w on $\mathbb{R}_+$, we say that $\sigma \in \Sigma$ is w-**greedy** if $\sigma(y)$ is a solution to

$$\max_{0 \leq c \leq y} \left\{ u(c) + \beta \int w(f(y-c)z)\phi(dz) \right\} \tag{10}$$

for every $y \in \mathbb{R}_+$.

In other words, $\sigma \in \Sigma$ is w-greedy if it optimally trades off current and future rewards when w is taken to be the value function.

In our setting, we have the following key result

> *A feasible consumption policy is optimal if and only if it is v^*-greedy*

The intuition is similar to the intuition for the Bellman equation, which was provided after (9).

See, for example, theorem 10.1.11 of EDTC.

Hence, once we have a good approximation to v^*, we can compute the (approximately) optimal policy by computing the corresponding greedy policy.

The advantage is that we are now solving a much lower dimensional optimization problem.

31.3.7 The Bellman Operator

How, then, should we compute the value function?

One way is to use the so-called **Bellman operator**.

(An operator is a map that sends functions into functions)

The Bellman operator is denoted by T and defined by

$$Tw(y) := \max_{0 \leq c \leq y} \left\{ u(c) + \beta \int w(f(y-c)z)\phi(dz) \right\} \qquad (y \in \mathbb{R}_+) \tag{11}$$

In other words, T sends the function w into the new function Tw defined (11).

By construction, the set of solutions to the Bellman equation (9) *exactly coincides with* the set of fixed points of T.

For example, if $Tw = w$, then, for any $y \geq 0$,

$$w(y) = Tw(y) = \max_{0 \leq c \leq y} \left\{ u(c) + \beta \int v^*(f(y-c)z)\phi(dz) \right\}$$

which says precisely that w is a solution to the Bellman equation.

It follows that v^* is a fixed point of T.

31.3.8 Review of Theoretical Results

One can also show that T is a contraction mapping on the set of continuous bounded functions on $\mathbb{R}_+$ under the supremum distance

$$\rho(g, h) = \sup_{y \geq 0} |g(y) - h(y)|$$

See EDTC, lemma 10.1.18.

Hence it has exactly one fixed point in this set, which we know is equal to the value function.

It follows that

- The value function v^* is bounded and continuous.
- Starting from any bounded and continuous w, the sequence $w, Tw, T^2w, \ldots$ generated by iteratively applying T converges uniformly to v^*.

This iterative method is called **value function iteration**.

We also know that a feasible policy is optimal if and only if it is v^*-greedy.

It's not too hard to show that a v^*-greedy policy exists (see EDTC, theorem 10.1.11 if you get stuck).

Hence at least one optimal policy exists.

Our problem now is how to compute it.

31.3.9 Unbounded Utility

The results stated above assume that the utility function is bounded.

In practice economists often work with unbounded utility functions — and so will we.

In the unbounded setting, various optimality theories exist.

Unfortunately, they tend to be case specific, as opposed to valid for a large range of applications.

Nevertheless, their main conclusions are usually in line with those stated for the bounded case just above (as long as we drop the word "bounded").

Consult, for example, section 12.2 of EDTC, [61] or [74].

31.4 Computation

Let's now look at computing the value function and the optimal policy.

31.4.1 Fitted Value Iteration

The first step is to compute the value function by value function iteration.

In theory, the algorithm is as follows

1. Begin with a function w — an initial condition.
2. Solving (11), obtain the function Tw.
3. Unless some stopping condition is satisfied, set $w = Tw$ and go to step 2.

This generates the sequence $w, Tw, T^2w, \ldots$.

However, there is a problem we must confront before we implement this procedure: The iterates can neither be calculated exactly nor stored on a computer.

To see the issue, consider (11).

Even if w is a known function, unless Tw can be shown to have some special structure, the only way to store it is to record the value $Tw(y)$ for every $y \in \mathbb{R}_+$.

Clearly this is impossible.

What we will do instead is use **fitted value function iteration**.

The procedure is to record the value of the function Tw at only finitely many "grid" points $y_1 < y_2 < \cdots < y_I$ and reconstruct it from this information when required.

More precisely, the algorithm will be

1. Begin with an array of values $\{w_1, \ldots, w_I\}$ representing the values of some initial function w on the grid points $\{y_1, \ldots, y_I\}$.
2. Build a function $\hat{w}$ on the state space $\mathbb{R}_+$ by interpolation or approximation, based on these data points.
3. Obtain and record the value $T\hat{w}(y_i)$ on each grid point y_i by repeatedly solving (11).
4. Unless some stopping condition is satisfied, set $\{w_1, \ldots, w_I\} = \{T\hat{w}(y_1), \ldots, T\hat{w}(y_I)\}$ and go to step 2.

How should we go about step 2?

This is a problem of function approximation, and there are many ways to approach it.

What's important here is that the function approximation scheme must not only produce a good approximation to Tw, but also combine well with the broader iteration algorithm described above.

One good choice from both respects is continuous piecewise linear interpolation (see this paper for further discussion).

The next figure illustrates piecewise linear interpolation of an arbitrary function on grid points $0, 0.2, 0.4, 0.6, 0.8, 1$.

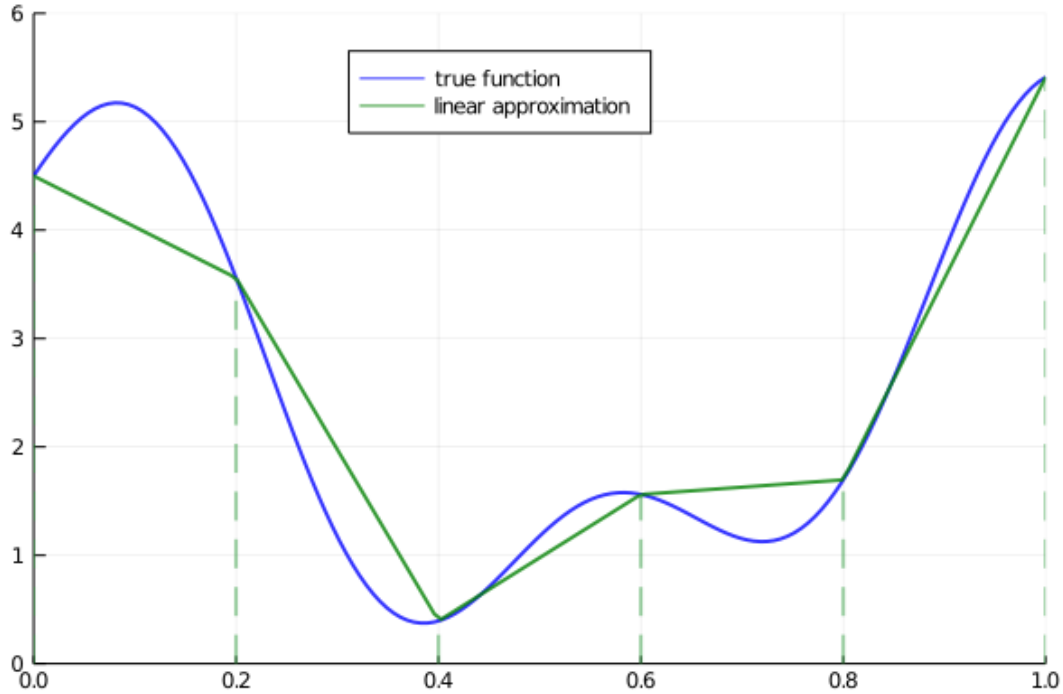
31.4.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Plots, QuantEcon, Interpolations, NLsolve, Optim, Random
        gr(fmt = :png);
```

```
In [3]: f(x) = 2 .* cos.(6x) .+ sin.(14x) .+ 2.5
        c_grid = 0:.2:1
        f_grid = range(0,  1, length = 150)

        Af = LinearInterpolation(c_grid, f(c_grid))

        plt = plot(xlim = (0,1), ylim = (0,6))
        plot!(plt, f, f_grid, color = :blue, lw = 2, alpha = 0.8, label = "true
        function")
        plot!(plt, f_grid, Af.(f_grid), color = :green, lw = 2, alpha = 0.8,
              label = "linear approximation")
        plot!(plt, f, c_grid, seriestype = :sticks, linestyle = :dash, linewidth =
        2, alpha =
        0.5,
              label = "")
        plot!(plt, legend = :top)
```

Out[3]:



Another advantage of piecewise linear interpolation is that it preserves useful shape properties such as monotonicity and concavity / convexity.

31.4.3 The Bellman Operator

Here's a function that implements the Bellman operator using linear interpolation

```
In [4]: using Optim

        function T(w, grid, β, u, f, shocks; compute_policy = false)
            w_func = LinearInterpolation(grid, w)
            # objective for each grid point
            objectives = (c -> u(c) + β * mean(w_func.(f(y - c) .* shocks)) for y
 ↪in grid)
            results = maximize.(objectives, 1e-10, grid) # solver result for each
 ↪grid point

            Tw = Optim.maximum.(results)
            if compute_policy
                σ = Optim.maximizer.(results)
                return Tw, σ
            end

            return Tw
        end
```

```
Out[4]: T (generic function with 1 method)
```

Notice that the expectation in (11) is computed via Monte Carlo, using the approximation

$$\int w(f(y-c)z)\phi(dz) \approx \frac{1}{n}\sum_{i=1}^{n} w(f(y-c)\xi_i)$$

where $\{\xi_i\}_{i=1}^n$ are IID draws from ϕ.

Monte Carlo is not always the most efficient way to compute integrals numerically but it does have some theoretical advantages in the present setting.

(For example, it preserves the contraction mapping property of the Bellman operator — see, e.g., [83])

31.4.4 An Example

Let's test out our operator when

- $f(k) = k^\alpha$
- $u(c) = \ln c$
- ϕ is the distribution of $\exp(\mu + \sigma\zeta)$ when ζ is standard normal

As is well-known (see [68], section 3.1.2), for this particular problem an exact analytical solution is available, with

$$v^*(y) = \frac{\ln(1-\alpha\beta)}{1-\beta} + \frac{(\mu + \alpha\ln(\alpha\beta))}{1-\alpha}\left[\frac{1}{1-\beta} - \frac{1}{1-\alpha\beta}\right] + \frac{1}{1-\alpha\beta}\ln y \tag{12}$$

The optimal consumption policy is

$$\sigma^*(y) = (1 - \alpha\beta)y$$

Let's code this up now so we can test against it below

In [5]:
```
α = 0.4
β = 0.96
μ = 0
s = 0.1

c1 = log(1 - α * β) / (1 - β)
c2 = (μ + α * log(α * β)) / (1 - α)
c3 = 1 / (1 - β)
c4 = 1 / (1 - α * β)

# Utility
u(c) = log(c)

∂u∂c(c) = 1 / c

# Deterministic part of production function
f(k) = k^α

f'(k) = α * k^(α - 1)

# True optimal policy
c_star(y) = (1 - α * β) * y

# True value function
v_star(y) = c1 + c2 * (c3 - c4) + c4 * log(y)
```

Out[5]:
```
v_star (generic function with 1 method)
```

31.4.5 A First Test

To test our code, we want to see if we can replicate the analytical solution numerically, using fitted value function iteration.

We need a grid and some shock draws for Monte Carlo integration.

In [6]:
```
using Random
Random.seed!(42) # For reproducible results.

grid_max = 4         # Largest grid point
grid_size = 200      # Number of grid points
shock_size = 250     # Number of shock draws in Monte Carlo integral

grid_y = range(1e-5,  grid_max, length = grid_size)
shocks = exp.(μ .+ s * randn(shock_size))
```

Now let's do some tests.

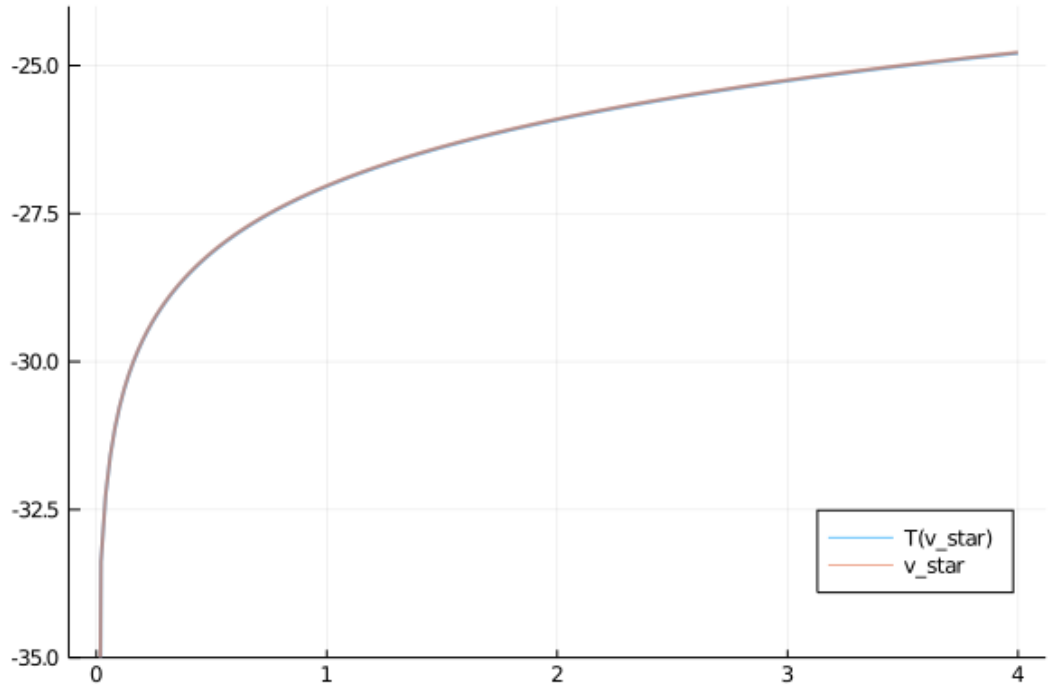
As one preliminary test, let's see what happens when we apply our Bellman operator to the exact solution v^*.

In theory, the resulting function should again be v^*.

In practice we expect some small numerical error.

In [7]:
```
w = T(v_star.(grid_y), grid_y, β, log, k -> k^α, shocks)

plt = plot(ylim = (-35,-24))
plot!(plt, grid_y, w, linewidth = 2, alpha = 0.6, label = "T(v_star)")
plot!(plt, v_star, grid_y, linewidth = 2, alpha=0.6, label = "v_star")
plot!(plt, legend = :bottomright)
```

Out[7]:



The two functions are essentially indistinguishable, so we are off to a good start.

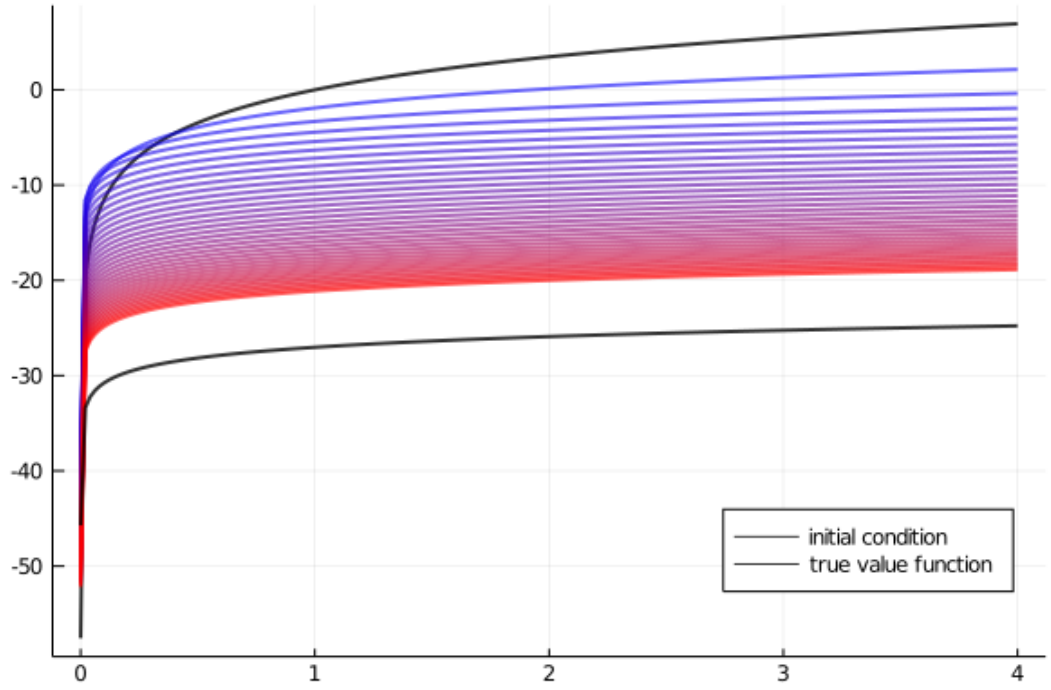
Now let's have a look at iterating with the Bellman operator, starting off from an arbitrary initial condition.

The initial condition we'll start with is $w(y) = 5 \ln(y)$

In [8]:
```
w = 5 * log.(grid_y)  # An initial condition -- fairly arbitrary
n = 35

plot(xlim = (extrema(grid_y)), ylim = (-50, 10))
lb = "initial condition"
plt = plot(grid_y, w, color = :black, linewidth = 2, alpha = 0.8, label = lb)
for i in 1:n
    w = T(w, grid_y, β, log, k -> k^α, shocks)
    plot!(grid_y, w, color = RGBA(i/n, 0, 1 - i/n, 0.8), linewidth = 2,
↪alpha = 0.6,
          label = "")
end

lb = "true value function"
```

```
        plot!(plt, v_star, grid_y, color = :black, linewidth = 2, alpha = 0.8,
↪label = lb)
        plot!(plt, legend = :bottomright)
```

Out[8]:



The figure shows

1. the first 36 functions generated by the fitted value function iteration algorithm, with hotter colors given to higher iterates
2. the true value function v^* drawn in black

The sequence of iterates converges towards v^*.

We are clearly getting closer.

We can write a function that computes the exact fixed point

In [9]:
```
function solve_optgrowth(initial_w; tol = 1e-6, max_iter = 500)
    fixedpoint(w -> T(w, grid_y, β, u, f, shocks), initial_w).zero # gets
↪returned
end
```

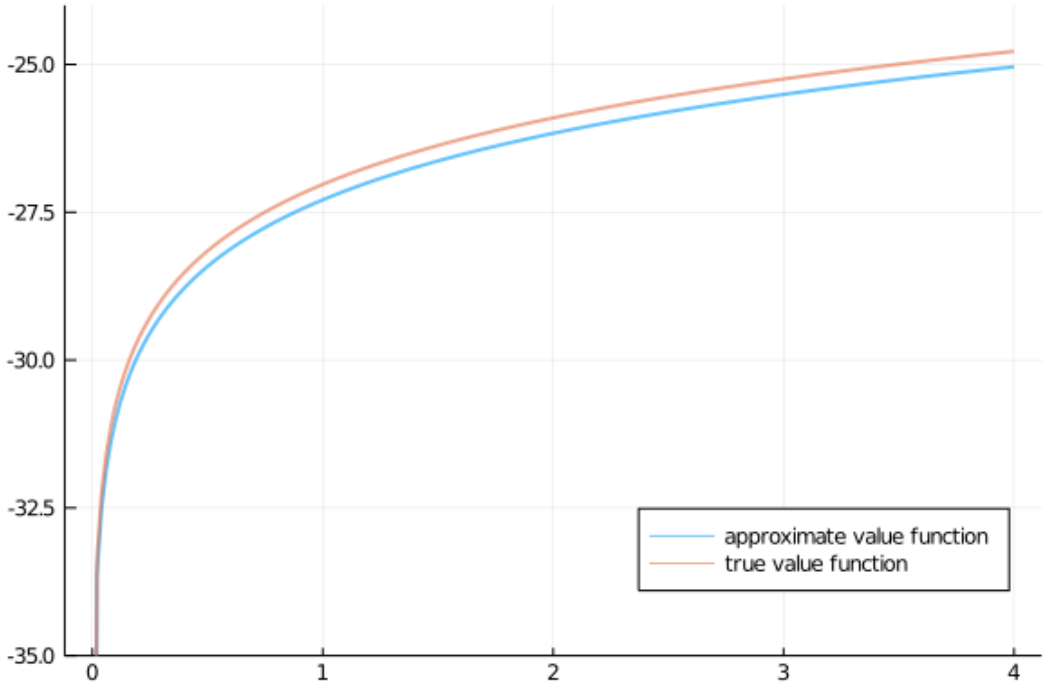
Out[9]:
```
solve_optgrowth (generic function with 1 method)
```

We can check our result by plotting it against the true value

In [10]:
```
initial_w = 5 * log.(grid_y)
v_star_approx = solve_optgrowth(initial_w)
```

```
        plt = plot(ylim = (-35, -24))
        plot!(plt, grid_y, v_star_approx, linewidth = 2, alpha = 0.6,
              label = "approximate value function")
        plot!(plt, v_star, grid_y, linewidth = 2, alpha = 0.6, label = "true
↪value function")
        plot!(plt, legend = :bottomright)
```

Out[10]:



The figure shows that we are pretty much on the money.

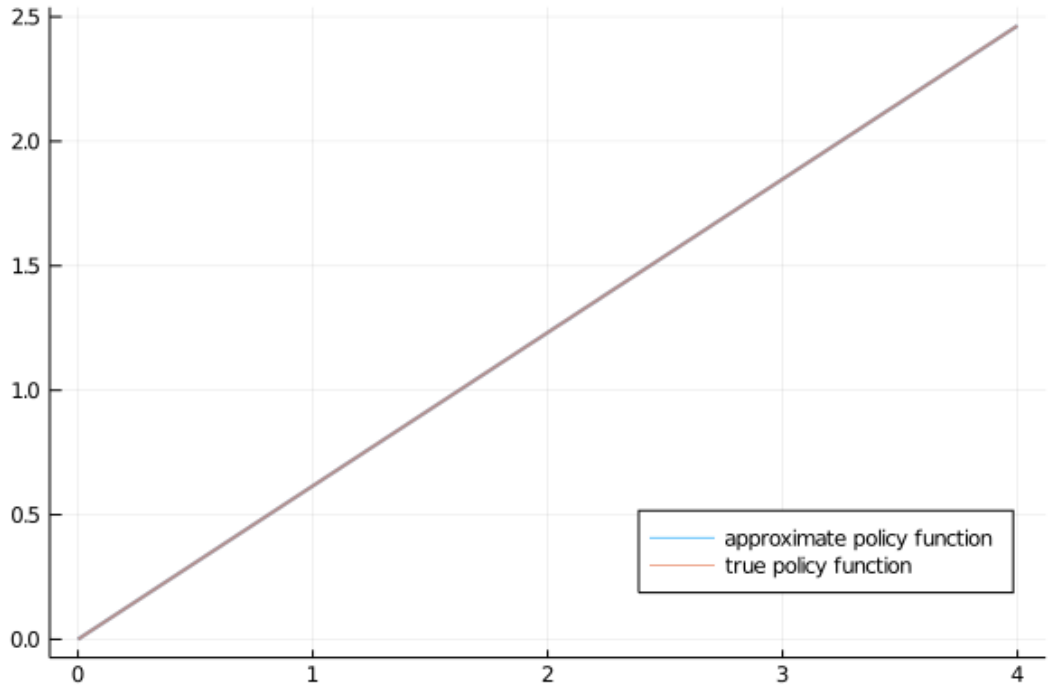
31.4.6 The Policy Function

To compute an approximate optimal policy, we take the approximate value function we just calculated and then compute the corresponding greedy policy.

The next figure compares the result to the exact solution, which, as mentioned above, is $\sigma(y) = (1 - \alpha\beta)y$.

```
In [11]: Tw, σ = T(v_star_approx, grid_y, β, log, k -> k^α, shocks;
                                  compute_policy = true)
         cstar = (1 - α * β) * grid_y

         plt = plot(grid_y, σ, lw=2, alpha=0.6, label = "approximate policy
↪function")
         plot!(plt, grid_y, cstar, lw = 2, alpha = 0.6, label = "true policy
↪function")
         plot!(plt, legend = :bottomright)
```

Out[11]:



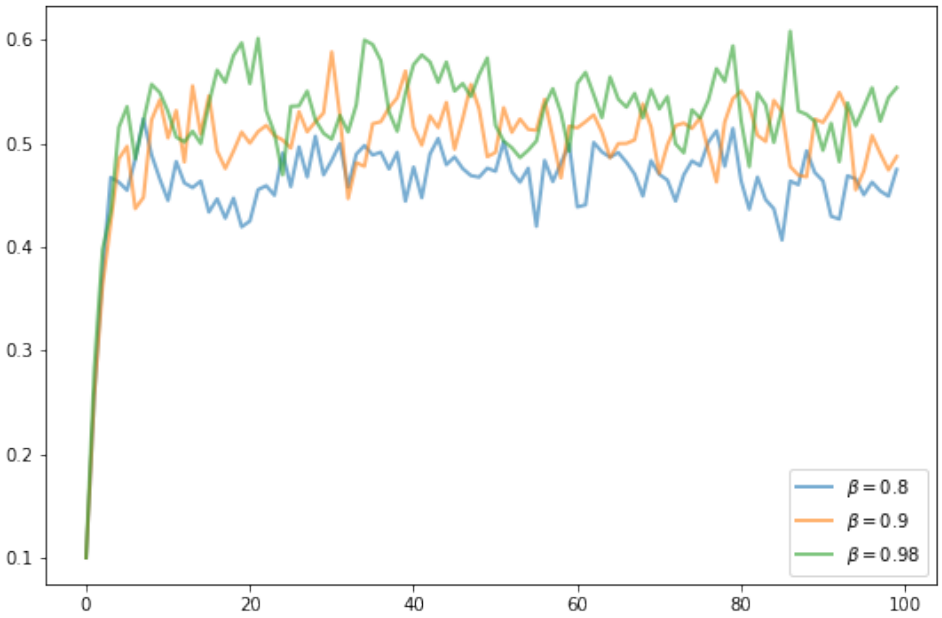
The figure shows that we've done a good job in this instance of approximating the true policy.

31.5 Exercises

31.5.1 Exercise 1

Once an optimal consumption policy σ is given, income follows (5).

The next figure shows a simulation of 100 elements of this sequence for three different discount factors (and hence three different policies).



In each sequence, the initial condition is $y_0 = 0.1$.

The discount factors are `discount_factors = (0.8, 0.9, 0.98)`.

We have also dialed down the shocks a bit.

```
In [12]: s = 0.05
         shocks = exp.(μ .+ s * randn(shock_size))
```

Otherwise, the parameters and primitives are the same as the log linear model discussed earlier in the lecture.

Notice that more patient agents typically have higher wealth.

Replicate the figure modulo randomness.

31.6 Solutions

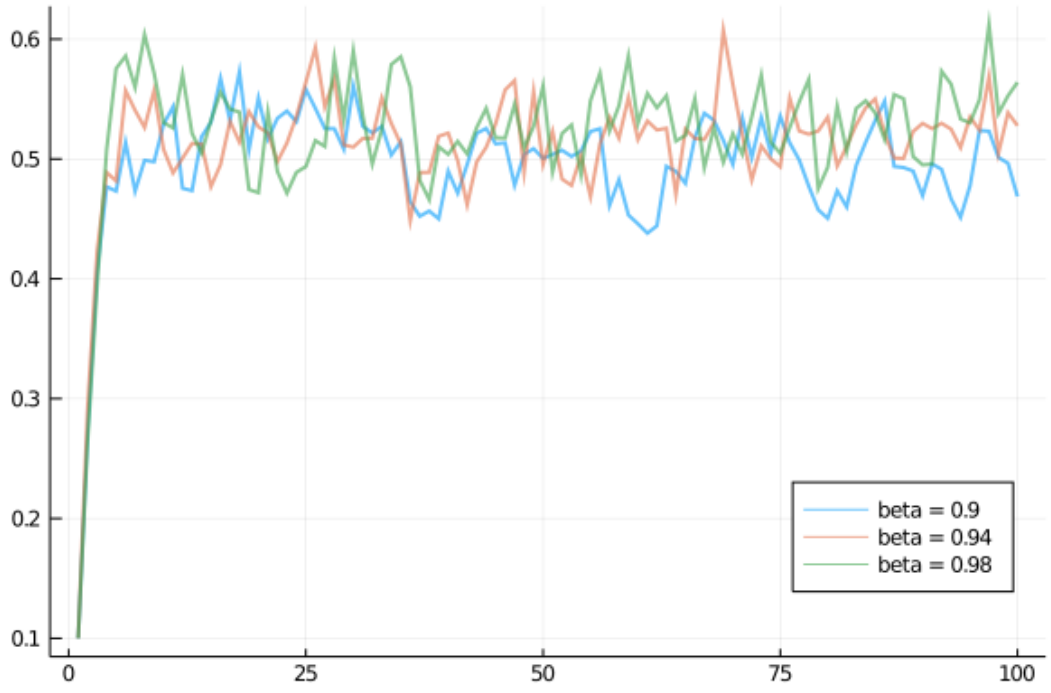
31.6.1 Exercise 1

Here's one solution (assuming as usual that you've executed everything above)

```
In [13]: function simulate_og(σ, y0 = 0.1, ts_length=100)
             y = zeros(ts_length)
             ξ = randn(ts_length-1)
             y[1] = y0
             for t in 1:(ts_length-1)
                 y[t+1] = (y[t] - σ(y[t]))^α * exp(μ + s * ξ[t])
             end
             return y
         end

         plt = plot()
```

```
for β in (0.9, 0.94, 0.98)
    Tw = similar(grid_y)
    initial_w = 5 * log.(grid_y)

    v_star_approx = fixedpoint(w -> T(w, grid_y, β, u, f, shocks),
                               initial_w).zero
    Tw, σ = T(v_star_approx, grid_y, β, log, k -> k^α, shocks,
                             compute_policy = true)
    σ_func = LinearInterpolation(grid_y, σ)
    y = simulate_og(σ_func)

    plot!(plt, y, lw = 2, alpha = 0.6, label = label = "beta = $β")
end

plot!(plt, legend = :bottomright)
```

Out[13]:



Chapter 32

Optimal Growth II: Time Iteration

32.1 Contents

32.2 Overview

In this lecture we'll continue our earlier study of the stochastic optimal growth model.

In that lecture we solved the associated discounted dynamic programming problem using value function iteration.

The beauty of this technique is its broad applicability.

With numerical problems, however, we can often attain higher efficiency in specific applications by deriving methods that are carefully tailored to the application at hand.

The stochastic optimal growth model has plenty of structure to exploit for this purpose, especially when we adopt some concavity and smoothness assumptions over primitives.

We'll use this structure to obtain an **Euler equation** based method that's more efficient than value function iteration for this and some other closely related applications.

In a subsequent lecture we'll see that the numerical implementation part of the Euler equation method can be further adjusted to obtain even more efficiency.

32.3 The Euler Equation

Let's take the model set out in the stochastic growth model lecture and add the assumptions that

1. u and f are continuously differentiable and strictly concave

2. $f(0) = 0$
3. $\lim_{c \to 0} u'(c) = \infty$ and $\lim_{c \to \infty} u'(c) = 0$
4. $\lim_{k \to 0} f'(k) = \infty$ and $\lim_{k \to \infty} f'(k) = 0$

The last two conditions are usually called **Inada conditions**.

Recall the Bellman equation

$$v^*(y) = \max_{0 \leq c \leq y} \left\{ u(c) + \beta \int v^*(f(y-c)z)\phi(dz) \right\} \quad \text{for all} \quad y \in \mathbb{R}_+ \tag{1}$$

Let the optimal consumption policy be denoted by c^*.

We know that c^* is a v^* greedy policy, so that $c^*(y)$ is the maximizer in (1).

The conditions above imply that

- c^* is the unique optimal policy for the stochastic optimal growth model
- the optimal policy is continuous, strictly increasing and also **interior**, in the sense that $0 < c^*(y) < y$ for all strictly positive y, and
- the value function is strictly concave and continuously differentiable, with

$$(v^*)'(y) = u'(c^*(y)) := (u' \circ c^*)(y) \tag{2}$$

The last result is called the **envelope condition** due to its relationship with the envelope theorem.

To see why (2) might be valid, write the Bellman equation in the equivalent form

$$v^*(y) = \max_{0 \leq k \leq y} \left\{ u(y-k) + \beta \int v^*(f(k)z)\phi(dz) \right\},$$

differentiate naively with respect to y, and then evaluate at the optimum.

Section 12.1 of EDTC contains full proofs of these results, and closely related discussions can be found in many other texts.

Differentiability of the value function and iteriority of the optimal policy imply that optimal consumption satisfies the first order condition associated with (1), which is

$$u'(c^*(y)) = \beta \int (v^*)'(f(y - c^*(y))z) f'(y - c^*(y)) z \phi(dz) \tag{3}$$

Combining (2) and the first-order condition (3) gives the famous **Euler equation**

$$(u' \circ c^*)(y) = \beta \int (u' \circ c^*)(f(y - c^*(y))z) f'(y - c^*(y)) z \phi(dz) \tag{4}$$

We can think of the Euler equation as a functional equation

$$(u' \circ \sigma)(y) = \beta \int (u' \circ \sigma)(f(y - \sigma(y))z) f'(y - \sigma(y)) z \phi(dz) \tag{5}$$

over interior consumption policies σ, one solution of which is the optimal policy c^*.

Our aim is to solve the functional equation (5) and hence obtain c^*.

32.3.1 The Coleman Operator

Recall the Bellman operator

$$Tw(y) := \max_{0 \leq c \leq y} \left\{ u(c) + \beta \int w(f(y-c)z)\phi(dz) \right\} \tag{6}$$

Just as we introduced the Bellman operator to solve the Bellman equation, we will now introduce an operator over policies to help us solve the Euler equation.

This operator K will act on the set of all $\sigma \in \Sigma$ that are continuous, strictly increasing and interior (i.e., $0 < \sigma(y) < y$ for all strictly positive y).

Henceforth we denote this set of policies by $\mathcal{P}$

1. The operator K takes as its argument a $\sigma \in \mathcal{P}$ and
2. returns a new function $K\sigma$, where $K\sigma(y)$ is the $c \in (0, y)$ that solves

$$u'(c) = \beta \int (u' \circ \sigma)(f(y-c)z) f'(y-c) z \phi(dz) \tag{7}$$

We call this operator the **Coleman operator** to acknowledge the work of [17] (although many people have studied this and other closely related iterative techniques).

In essence, $K\sigma$ is the consumption policy that the Euler equation tells you to choose today when your future consumption policy is σ.

The important thing to note about K is that, by construction, its fixed points coincide with solutions to the functional equation (5).

In particular, the optimal policy c^* is a fixed point.

Indeed, for fixed y, the value $Kc^*(y)$ is the c that solves

$$u'(c) = \beta \int (u' \circ c^*)(f(y-c)z) f'(y-c) z \phi(dz)$$

In view of the Euler equation, this is exactly $c^*(y)$.

32.3.2 Is the Coleman Operator Well Defined?

In particular, is there always a unique $c \in (0, y)$ that solves (7)?

The answer is yes, under our assumptions.

For any $\sigma \in \mathcal{P}$, the right side of (7)

- is continuous and strictly increasing in c on $(0, y)$
- diverges to $+\infty$ as $c \uparrow y$

The left side of (7)

- is continuous and strictly decreasing in c on $(0, y)$
- diverges to $+\infty$ as $c \downarrow 0$

Sketching these curves and using the information above will convince you that they cross exactly once as c ranges over $(0, y)$.

With a bit more analysis, one can show in addition that $K\sigma \in \mathcal{P}$ whenever $\sigma \in \mathcal{P}$.

32.4 Comparison with Value Function Iteration

How does Euler equation time iteration compare with value function iteration?

Both can be used to compute the optimal policy, but is one faster or more accurate?

There are two parts to this story.

First, on a theoretical level, the two methods are essentially isomorphic.

In particular, they converge at the same rate.

We'll prove this in just a moment.

The other side to the story is the speed of the numerical implementation.

It turns out that, once we actually implement these two routines, time iteration is faster and more accurate than value function iteration.

More on this below.

32.4.1 Equivalent Dynamics

Let's talk about the theory first.

To explain the connection between the two algorithms, it helps to understand the notion of equivalent dynamics.

(This concept is very helpful in many other contexts as well).

Suppose that we have a function $g \colon X \to X$ where X is a given set.

The pair (X, g) is sometimes called a **dynamical system** and we associate it with trajectories of the form

$$x_{t+1} = g(x_t), \qquad x_0 \text{ given}$$

Equivalently, $x_t = g^t(x_0)$, where g is the t-th composition of g with itself.

Here's the picture

$$x_0 \xrightarrow{g} g(x_0) \xrightarrow{g} g^2(x_0) \xrightarrow{g} g^3(x_0) \xrightarrow{g} \cdots$$

Now let another function $h \colon Y \to Y$ where Y is another set.

Suppose further that

- there exists a bijection τ from X to Y

- the two functions **commute** under τ, which is to say that $\tau(g(x)) = h(\tau(x))$ for all $x \in X$

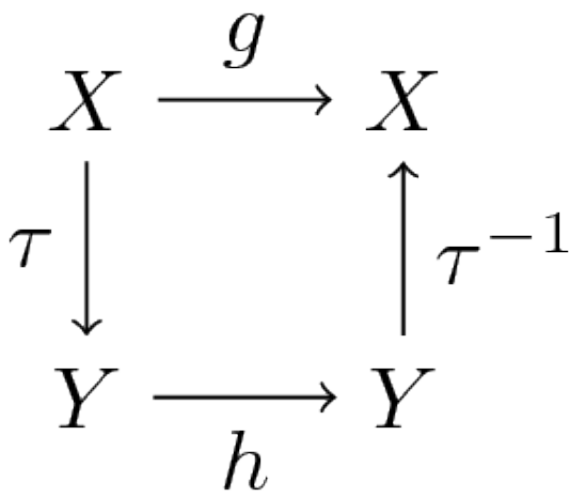
The last statement can be written more simply as

$$\tau \circ g = h \circ \tau$$

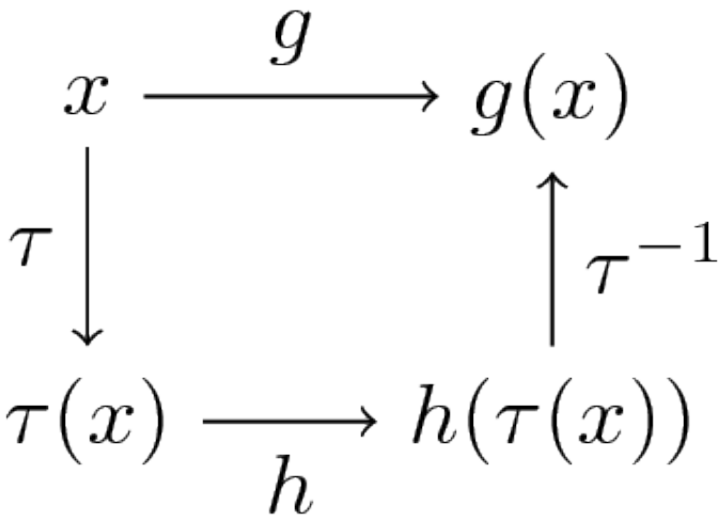
or, by applying τ^{-1} to both sides

$$g = \tau^{-1} \circ h \circ \tau \tag{8}$$

Here's a commutative diagram that illustrates



Here's a similar figure that traces out the action of the maps on a point $x \in X$



Now, it's easy to check from (8) that $g^2 = \tau^{-1} \circ h^2 \circ \tau$ holds.

In fact, if you like proofs by induction, you won't have trouble showing that

$$g^n = \tau^{-1} \circ h^n \circ \tau$$

is valid for all n.

What does this tell us?

It tells us that the following are equivalent

- iterate n times with g, starting at x
- shift x to Y using τ, iterate n times with h starting at $\tau(x)$, and shift the result $h^n(\tau(x))$ back to X using τ^{-1}

We end up with exactly the same object.

32.4.2 Back to Economics

Have you guessed where this is leading?

What we're going to show now is that the operators T and K commute under a certain bijection.

The implication is that they have exactly the same rate of convergence.

To make life a little easier, we'll assume in the following analysis (although not always in our applications) that $u(0) = 0$.

A Bijection

Let $\mathcal{V}$ be all strictly concave, continuously differentiable functions v mapping $\mathbb{R}_+$ to itself and satisfying $v(0) = 0$ and $v'(y) > u'(y)$ for all positive y.

For $v \in \mathcal{V}$ let

$$Mv := h \circ v' \qquad \text{where } h := (u')^{-1}$$

Although we omit details, $\sigma := Mv$ is actually the unique v-greedy policy.

- See proposition 12.1.18 of EDTC

It turns out that M is a bijection from $\mathcal{V}$ to $\mathcal{P}$.

A (solved) exercise below asks you to confirm this.

Commutative Operators

It is an additional solved exercise (see below) to show that T and K commute under M, in the sense that

$$M \circ T = K \circ M \tag{9}$$

In view of the preceding discussion, this implies that

$$T^n = M^{-1} \circ K^n \circ M$$

Hence, T and K converge at exactly the same rate!

32.5 Implementation

We've just shown that the operators T and K have the same rate of convergence.

However, it turns out that, once numerical approximation is taken into account, significant differences arises.

In particular, the image of policy functions under K can be calculated faster and with greater accuracy than the image of value functions under T.

Our intuition for this result is that

- the Coleman operator exploits more information because it uses first order and envelope conditions
- policy functions generally have less curvature than value functions, and hence admit more accurate approximations based on grid point information

32.5.1 The Operator

Here's some code that implements the Coleman operator.

32.5.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")

In [2]: using LinearAlgebra, Statistics
        using BenchmarkTools, Interpolations, Parameters, Plots, QuantEcon, Roots
        using Optim, Random

In [3]: using BenchmarkTools, Interpolations, Parameters, Plots, QuantEcon, Roots

        gr(fmt = :png);

In [4]: function K!(Kg, g, grid, β, ∂u∂c, f, f', shocks)
        # This function requires the container of the output value as argument Kg

            # Construct linear interpolation object
            g_func = LinearInterpolation(grid, g, extrapolation_bc=Line())

            # solve for updated consumption value
            for (i, y) in enumerate(grid)
                function h(c)
                    vals = ∂u∂c.(g_func.(f(y - c) * shocks)) .* f'(y - c) .* shocks
                    return ∂u∂c(c) - β * mean(vals)
                end
```

```
            Kg[i] = find_zero(h, (1e-10, y - 1e-10))
        end
        return Kg
    end

    # The following function does NOT require the container of the output
↪value as argument
    K(g, grid, β, ∂u∂c, f, f', shocks) =
        K!(similar(g), g, grid, β, ∂u∂c, f, f', shocks)
```

```
Out[4]: K (generic function with 1 method)
```

It has some similarities to the code for the Bellman operator in our optimal growth lecture.

For example, it evaluates integrals by Monte Carlo and approximates functions using linear interpolation.

Here's that Bellman operator code again, which needs to be executed because we'll use it in some tests below

```
In [5]: using Optim

    function T(w, grid, β, u, f, shocks, Tw = similar(w);
                               compute_policy = false)

        # apply linear interpolation to w
        w_func = LinearInterpolation(grid, w, extrapolation_bc=Line())

        if compute_policy
            σ = similar(w)
        end

        # set Tw[i] = max_c { u(c) + β E w(f(y  - c) z)}
        for (i, y) in enumerate(grid)
            objective(c) =  u(c) + β * mean(w_func.(f(y - c) .* shocks))
            res = maximize(objective, 1e-10, y)

            if compute_policy
                σ[i] = Optim.maximizer(res)
            end
            Tw[i] = Optim.maximum(res)
        end

        if compute_policy
            return Tw, σ
        else
            return Tw
        end
    end
```

```
Out[5]: T (generic function with 2 methods)
```

32.5.3 Testing on the Log / Cobb–Douglas case

As we did for value function iteration, let's start by testing our method in the presence of a model that does have an analytical solution.

Here's an object containing data from the log-linear growth model we used in the value function iteration lecture

```
In [6]: isoelastic(c, γ) = isone(γ) ? log(c) : (c^(1 - γ) - 1) / (1 - γ)
        Model = @with_kw (α = 0.65,                              # Productivity parameter
                          β = 0.95,                                # Discount factor
                          γ = 1.0,                                 # Risk aversion
                          μ = 0.0,                                # First parameter in
 ↪lognorm(μ,
        σ)
                          s = 0.1,                                # Second parameter in
 ↪lognorm(μ,
        σ)
                           grid = range(1e-6, 4, length = 200), # Grid
                          grid_min = 1e-6,                         # Smallest grid point
                           grid_max = 4.0,                          # Largest grid point
                         grid_size = 200,                         # Number of grid points
                           u = (c, γ = γ) -> isoelastic(c, γ),   # utility function
                           ∂u∂c = c -> c^(-γ),                      # u'
                          f = k -> k^α,                           # production function
                           f' = k -> α * k^(α - 1),                 # f'
                           )
```

```
Out[6]: ##NamedTuple_kw#253 (generic function with 2 methods)
```

Next we generate an instance

```
In [7]: m = Model();
```

We also need some shock draws for Monte Carlo integration

```
In [8]: using Random
        Random.seed!(42) # for reproducible results.

        shock_size = 250 # number of shock draws in Monte Carlo integral
        shocks = collect(exp.(m.μ .+ m.s * randn(shock_size))); # generate shocks
```

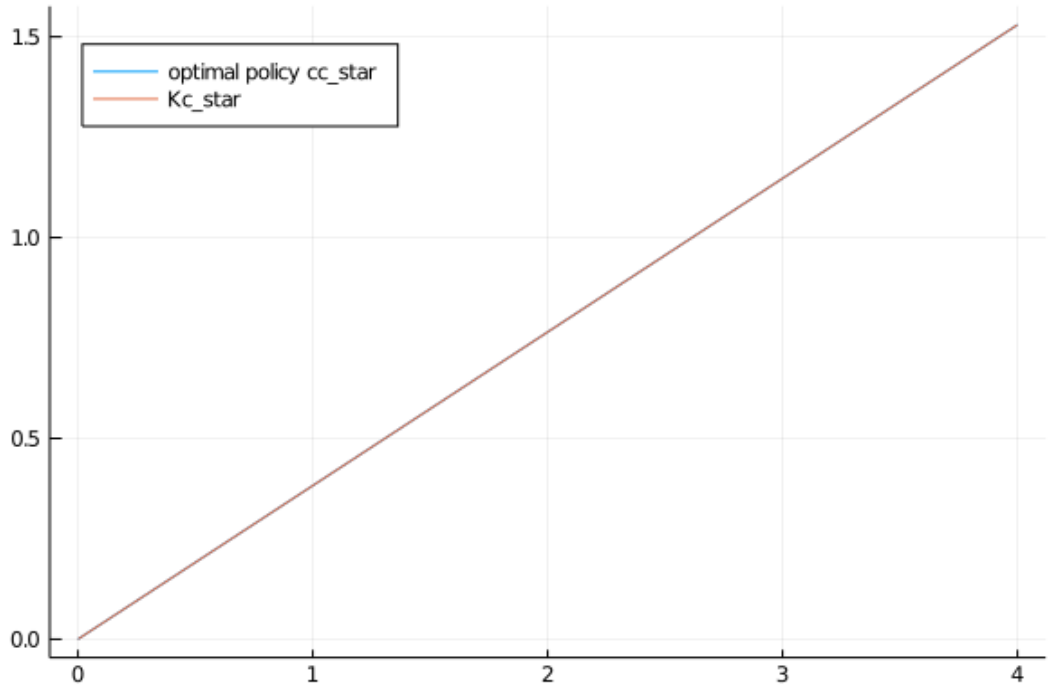
As a preliminary test, let's see if $Kc^* = c^*$, as implied by the theory

```
In [9]: function verify_true_policy(m, shocks, c_star)
            # compute (Kc_star)
            @unpack grid, β, ∂u∂c, f, f' = m
            c_star_new = K(c_star, grid, β, ∂u∂c, f, f', shocks)

            # plot c_star and Kc_star
            plot(grid, c_star, label = "optimal policy cc_star")
            plot!(grid, c_star_new, label = "Kc_star")
            plot!(legend = :topleft)
        end
```

```
Out[9]: verify_true_policy (generic function with 1 method)
```

```
In [10]: c_star = (1 - m.α * m.β) * m.grid # true policy (c_star)
         verify_true_policy(m, shocks, c_star)
```

Out[10]:



We can't really distinguish the two plots, so we are looking good, at least for this test.

Next let's try iterating from an arbitrary initial condition and see if we converge towards c^*.

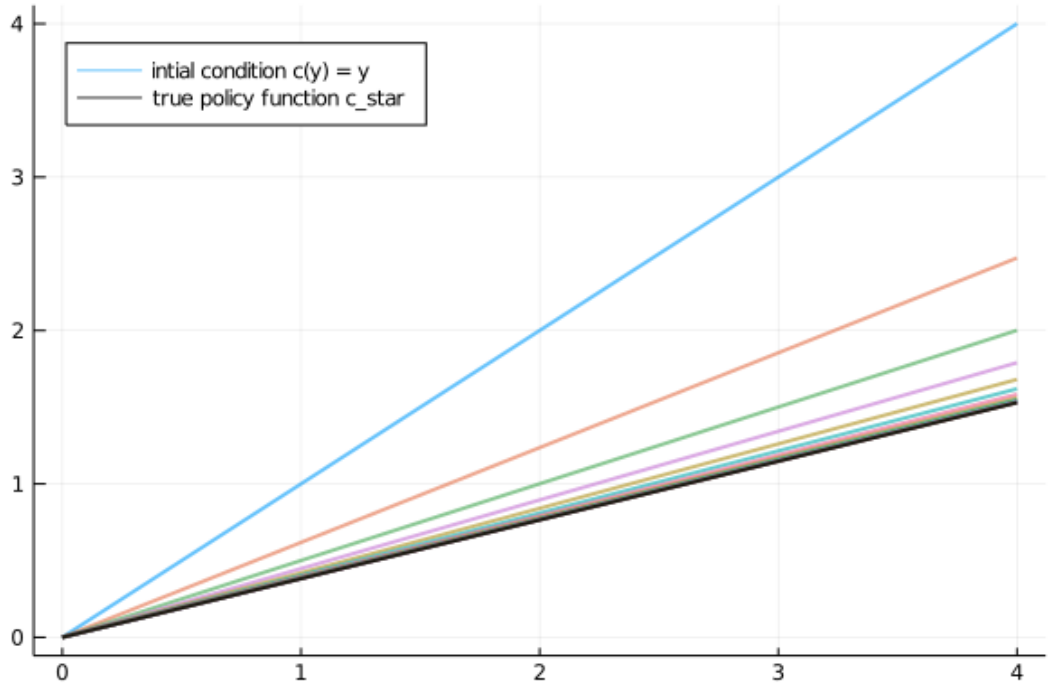
The initial condition we'll use is the one that eats the whole pie: $c(y) = y$

In [11]:
```
function check_convergence(m, shocks, c_star, g_init; n_iter = 15)
    @unpack grid, β, ∂u∂c, f, f' = m
    g = g_init;
    plot(m.grid, g, lw = 2, alpha = 0.6, label = "intial condition c(y) =
↪y")
    for i in 1:n_iter
        new_g = K(g, grid, β, ∂u∂c, f, f', shocks)
        g = new_g
        plot!(grid, g, lw = 2, alpha = 0.6, label = "")
    end
    plot!(grid, c_star, color = :black, lw = 2, alpha = 0.8,
          label = "true policy function c_star")
    plot!(legend = :topleft)
end
```

Out[11]:
```
check_convergence (generic function with 1 method)
```

In [12]:
```
check_convergence(m, shocks, c_star, m.grid, n_iter = 15)
```

Out[12]:



We see that the policy has converged nicely, in only a few steps.

Now let's compare the accuracy of iteration using the Coleman and Bellman operators.

We'll generate

1. $K^n c$ where $c(y) = y$
2. $(M \circ T^n \circ M^{-1})c$ where $c(y) = y$

In each case we'll compare the resulting policy to c^*.

The theory on equivalent dynamics says we will get the same policy function and hence the same errors.

But in fact we expect the first method to be more accurate for reasons discussed above

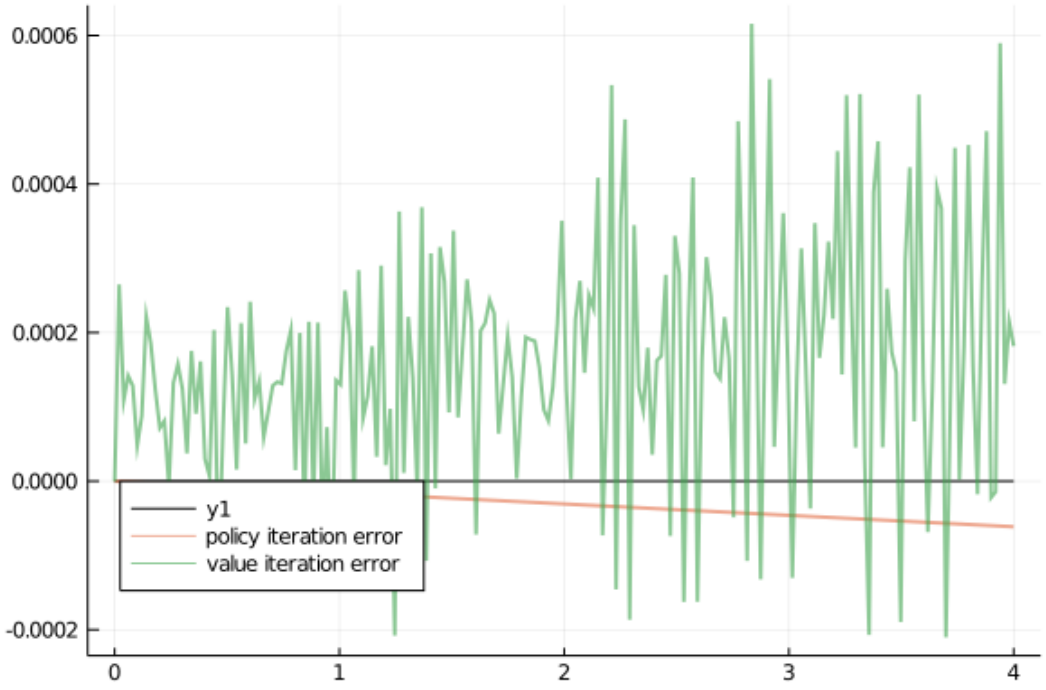
```
In [13]: function iterate_updating(func, arg_init; sim_length = 20)
             arg = arg_init;
             for i in 1:sim_length
                 new_arg = func(arg)
                 arg = new_arg
             end
             return arg
         end

         function compare_error(m, shocks, g_init, w_init; sim_length = 20)
             @unpack grid, β, u, ∂u∂c, f, f' = m
             g, w = g_init, w_init

             # two functions for simplification
             bellman_single_arg(w) = T(w, grid, β, u, f, shocks)
             coleman_single_arg(g) = K(g, grid, β, ∂u∂c, f, f', shocks)
```

```
        g = iterate_updating(coleman_single_arg, grid, sim_length = 20)
        w = iterate_updating(bellman_single_arg, u.(grid), sim_length = 20)
        new_w, vf_g = T(w, grid, β, u, f, shocks, compute_policy = true)

        pf_error = c_star - g
        vf_error = c_star - vf_g

        plot(grid, zero(grid), color = :black, lw = 1)
        plot!(grid, pf_error, lw = 2, alpha = 0.6, label = "policy iteration
↪error")
        plot!(grid, vf_error, lw = 2, alpha = 0.6, label = "value iteration
↪error")
        plot!(legend = :bottomleft)
    end
```

```
Out[13]: compare_error (generic function with 1 method)
```

```
In [14]: compare_error(m, shocks, m.grid, m.u.(m.grid), sim_length=20)
```

```
Out[14]:
```



As you can see, time iteration is much more accurate for a given number of iterations.

32.6 Exercises

32.6.1 Exercise 1

Show that (9) is valid. In particular,

- Let v be strictly concave and continuously differentiable on $(0, \infty)$
- Fix $y \in (0, \infty)$ and show that $MTv(y) = KMv(y)$

32.6.2 Exercise 2

Show that M is a bijection from $\mathcal{V}$ to $\mathcal{P}$.

32.6.3 Exercise 3

Consider the same model as above but with the CRRA utility function

$$u(c) = \frac{c^{1-\gamma} - 1}{1 - \gamma}$$

Iterate 20 times with Bellman iteration and Euler equation time iteration

- start time iteration from $c(y) = y$
- start value function iteration from $v(y) = u(y)$
- set $\gamma = 1.5$

Compare the resulting policies and check that they are close.

32.6.4 Exercise 4

Do the same exercise, but now, rather than plotting results, benchmark both approaches with 20 iterations.

32.7 Solutions

32.7.1 Solution to Exercise 1

Let T, K, M, v and y be as stated in the exercise.

Using the envelope theorem, one can show that $(Tv)'(y) = u'(c(y))$ where $c(y)$ solves

$$u'(c(y)) = \beta \int v'(f(y - c(y))z) f'(y - c(y)) z \phi(dz) \tag{10}$$

Hence $MTv(y) = (u')^{-1}(u'(c(y))) = c(y)$.

On the other hand, $KMv(y)$ is the $c(y)$ that solves

$$\begin{aligned} u'(c(y)) &= \beta \int (u' \circ (Mv))(f(y - c(y))z) f'(y - c(y)) z \phi(dz) \\ &= \beta \int (u' \circ ((u')^{-1} \circ v'))(f(y - c(y))z) f'(y - c(y)) z \phi(dz) \\ &= \beta \int v'(f(y - c(y))z) f'(y - c(y)) z \phi(dz) \end{aligned}$$

We see that $c(y)$ is the same in each case.

32.7.2 Solution to Exercise 2

We need to show that M is a bijection from $\mathcal{V}$ to $\mathcal{P}$.

To see this, first observe that, in view of our assumptions above, u' is a strictly decreasing continuous bijection from $(0, \infty)$ to itself.

It follows that h has the same properties.

Moreover, for fixed $v \in \mathcal{V}$, the derivative v' is a continuous, strictly decreasing function.

Hence, for fixed $v \in \mathcal{V}$, the map $Mv = h \circ v'$ is strictly increasing and continuous, taking values in $(0, \infty)$.

Moreover, interiority holds because v' strictly dominates u', implying that

$$(Mv)(y) = h(v'(y)) < h(u'(y)) = y$$

In particular, $\sigma(y) := (Mv)(y)$ is an element of $\mathcal{P}$.

To see that each $\sigma \in \mathcal{P}$ has a preimage $v \in \mathcal{V}$ with $Mv = \sigma$, fix any $\sigma \in \mathcal{P}$.

Let $v(y) := \int_0^y u'(\sigma(x))dx$ with $v(0) = 0$.

With a small amount of effort you will be able to show that $v \in \mathcal{V}$ and $Mv = \sigma$.

It's also true that M is one-to-one on $\mathcal{V}$.

To see this, suppose that v and w are elements of $\mathcal{V}$ satisfying $Mv = Mw$.

Then $v(0) = w(0) = 0$ and $v' = w'$ on $(0, \infty)$.

The fundamental theorem of calculus then implies that $v = w$ on $\mathbb{R}_+$.

32.7.3 Solution to Exercise 3

Here's the code, which will execute if you've run all the code above

In [15]:
```
# Model instance with risk aversion = 1.5
# others are the same as the previous instance
m_ex = Model(γ = 1.5);
```

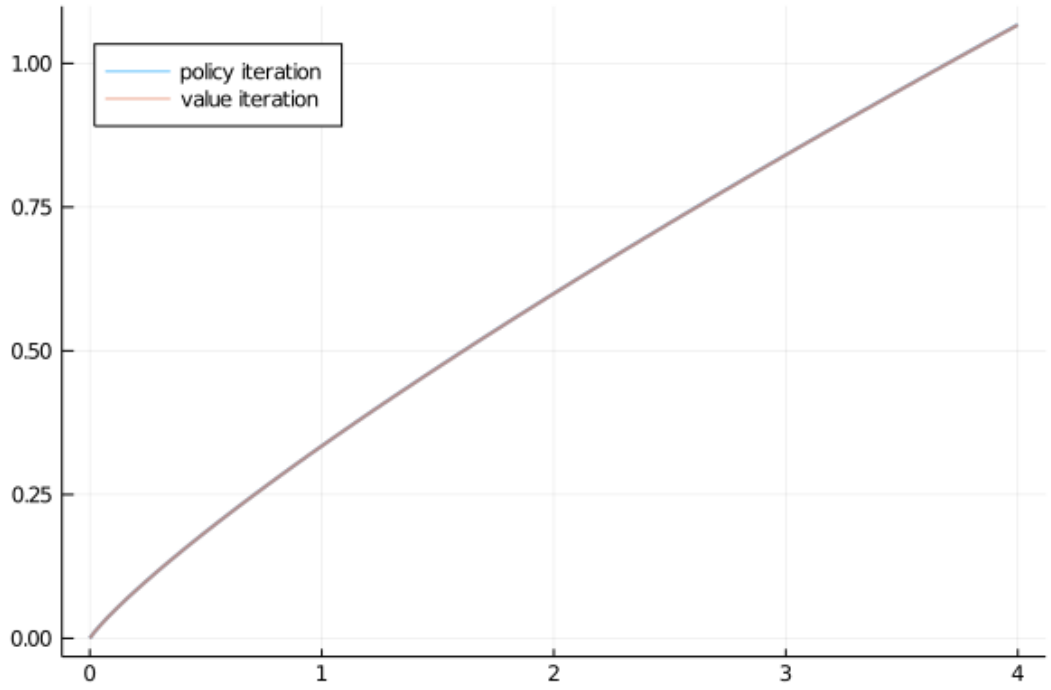
In [16]:
```
function exercise2(m, shocks, g_init = m.grid, w_init = m.u.(m.grid);
↪sim_length = 20)

    @unpack grid, β, u, ∂u∂c, f, f' = m
    # initial policy and value
    g, w = g_init, w_init
    # iteration
    bellman_single_arg(w) = T(w, grid, β, u, f, shocks)
    coleman_single_arg(g) = K(g, grid, β, ∂u∂c, f, f', shocks)

    g = iterate_updating(coleman_single_arg, grid, sim_length = 20)
    w = iterate_updating(bellman_single_arg, u.(m.grid), sim_length = 20)
    new_w, vf_g = T(w, grid, β, u, f, shocks, compute_policy = true)

    plot(grid, g, lw = 2, alpha = 0.6, label = "policy iteration")
    plot!(grid, vf_g, lw = 2, alpha = 0.6, label = "value iteration")
```

```
        return plot!(legend = :topleft)
    end
```

```
Out[16]: exercise2 (generic function with 3 methods)
```

```
In [17]: exercise2(m_ex, shocks, m.grid, m.u.(m.grid), sim_length=20)
```

```
Out[17]:
```



The policies are indeed close.

32.7.4 Solution to Exercise 4

Here's the code.

It assumes that you've just run the code from the previous exercise

```
In [18]: function bellman(m, shocks)
             @unpack grid, β, u, ∂u∂c, f, f' = m
             bellman_single_arg(w) = T(w, grid, β, u, f, shocks)
             iterate_updating(bellman_single_arg, u.(grid), sim_length = 20)
         end
         function coleman(m, shocks)
             @unpack grid, β, ∂u∂c, f, f' = m
             coleman_single_arg(g) = K(g, grid, β, ∂u∂c, f, f', shocks)
             iterate_updating(coleman_single_arg, grid, sim_length = 20)
         end
```

```
Out[18]: coleman (generic function with 1 method)
```

```
In [19]: @benchmark bellman(m_ex, shocks)
```

```
Out[19]: BenchmarkTools.Trial:
           memory estimate:  155.94 MiB
           allocs estimate:  90741
           --------------
           minimum time:     393.432 ms (4.12% GC)
           median time:      396.649 ms (4.15% GC)
           mean time:        396.624 ms (4.45% GC)
           maximum time:     399.935 ms (5.50% GC)
           --------------
           samples:          13
           evals/sample:     1
```

```
In [20]: @benchmark bellman(m_ex, shocks)
```

```
Out[20]: BenchmarkTools.Trial:
           memory estimate:  155.94 MiB
           allocs estimate:  90741
           --------------
           minimum time:     390.393 ms (4.21% GC)
           median time:      394.890 ms (4.16% GC)
           mean time:        394.367 ms (4.49% GC)
           maximum time:     402.473 ms (5.44% GC)
           --------------
           samples:          13
           evals/sample:     1
```

Chapter 33

Optimal Growth III: The Endogenous Grid Method

33.1 Contents

33.2 Overview

We solved the stochastic optimal growth model using

1. value function iteration
2. Euler equation based time iteration

We found time iteration to be significantly more accurate at each step.

In this lecture we'll look at an ingenious twist on the time iteration technique called the **endogenous grid method** (EGM).

EGM is a numerical method for implementing policy iteration invented by Chris Carroll.

It is a good example of how a clever algorithm can save a massive amount of computer time.

(Massive when we multiply saved CPU cycles on each implementation times the number of implementations worldwide)

The original reference is [16].

33.3 Key Idea

Let's start by reminding ourselves of the theory and then see how the numerics fit in.

33.3.1 Theory

Take the model set out in the time iteration lecture, following the same terminology and notation.

The Euler equation is

$$(u' \circ c^*)(y) = \beta \int (u' \circ c^*)(f(y - c^*(y))z) f'(y - c^*(y)) z \phi(dz) \tag{1}$$

As we saw, the Coleman operator is a nonlinear operator K engineered so that c^* is a fixed point of K.

It takes as its argument a continuous strictly increasing consumption policy $g \in \Sigma$.

It returns a new function Kg, where $(Kg)(y)$ is the $c \in (0, \infty)$ that solves

$$u'(c) = \beta \int (u' \circ g)(f(y - c)z) f'(y - c) z \phi(dz) \tag{2}$$

33.3.2 Exogenous Grid

As discussed in the lecture on time iteration, to implement the method on a computer we need numerical approximation.

In particular, we represent a policy function by a set of values on a finite grid.

The function itself is reconstructed from this representation when necessary, using interpolation or some other method.

Previously, to obtain a finite representation of an updated consumption policy we

- fixed a grid of income points $\{y_i\}$
- calculated the consumption value c_i corresponding to each y_i using (2) and a root finding routine

Each c_i is then interpreted as the value of the function Kg at y_i.

Thus, with the points $\{y_i, c_i\}$ in hand, we can reconstruct Kg via approximation.

Iteration then continues…

33.3.3 Endogenous Grid

The method discussed above requires a root finding routine to find the c_i corresponding to a given income value y_i.

Root finding is costly because it typically involves a significant number of function evaluations.

As pointed out by Carroll [16], we can avoid this if y_i is chosen endogenously.

The only assumption required is that u' is invertible on $(0, \infty)$.

The idea is this:

First we fix an *exogenous* grid $\{k_i\}$ for capital ($k = y - c$).

Then we obtain c_i via

$$c_i = (u')^{-1} \left\{ \beta \int (u' \circ g)(f(k_i)z) \, f'(k_i) \, z \, \phi(dz) \right\} \tag{3}$$

where $(u')^{-1}$ is the inverse function of u'.

Finally, for each c_i we set $y_i = c_i + k_i$.

It is clear that each (y_i, c_i) pair constructed in this manner satisfies (2).

With the points $\{y_i, c_i\}$ in hand, we can reconstruct Kg via approximation as before.

The name EGM comes from the fact that the grid $\{y_i\}$ is determined **endogenously**.

33.4 Implementation

Let's implement this version of the Coleman operator and see how it performs.

33.4.1 The Operator

Here's an implementation of K using EGM as described above.

33.4.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using BenchmarkTools, Interpolations, Parameters, Plots, QuantEcon,
        Random, Roots
        gr(fmt = :png);
```

```
In [3]: function coleman_egm(g, k_grid, β, u', u'_inv, f, f', shocks)

            # Allocate memory for value of consumption on endogenous grid points
            c = similar(k_grid)

            # Solve for updated consumption value
            for (i, k) in enumerate(k_grid)
                vals = u'.(g.(f(k) * shocks)) .* f'(k) .* shocks
                c[i] = u'_inv(β * mean(vals))
            end

            # Determine endogenous grid
            y = k_grid + c  # y_i = k_i + c_i

            # Update policy function and return
            Kg = LinearInterpolation(y,c, extrapolation_bc=Line())
            Kg_f(x) = Kg(x)
            return Kg_f
        end
```

```
Out[3]: coleman_egm (generic function with 1 method)
```

Note the lack of any root finding algorithm.

We'll also run our original implementation, which uses an exogenous grid and requires root finding, so we can perform some comparisons

```
In [4]: function K!(Kg, g, grid, β, u', f, f', shocks)

            # This function requires the container of the output value as argument Kg

            # Construct linear interpolation object #
            g_func = LinearInterpolation(grid, g, extrapolation_bc = Line())

            # solve for updated consumption value #
            for (i, y) in enumerate(grid)
                function h(c)
                    vals = u'.(g_func.(f(y - c) * shocks)) .* f'(y - c) .* shocks
                    return u'(c) - β * mean(vals)
                end
                Kg[i] = find_zero(h, (1e-10, y - 1e-10))
            end
            return Kg
        end

        # The following function does NOT require the container of the output
        ↪value as argument
        K(g, grid, β, u', f, f', shocks) =
            K!(similar(g), g, grid, β, u', f, f', shocks)
```

```
Out[4]: K (generic function with 1 method)
```

Let's test out the code above on some example parameterizations, after the following imports.

33.4.3 Testing on the Log / Cobb–Douglas case

As we did for value function iteration and time iteration, let's start by testing our method with the log-linear benchmark.

The first step is to bring in the model that we used in the Coleman policy function iteration

```
In [5]: # model

        Model = @with_kw (α = 0.65, # productivity parameter
                          β = 0.95, # discount factor
                          γ = 1.0,  # risk aversion
                          μ = 0.0,  # lognorm(μ, σ)
                          s = 0.1,  # lognorm(μ, σ)
                          grid_min = 1e-6, # smallest grid point
                          grid_max = 4.0,  # largest grid point
                          grid_size = 200, # grid size
                         u = γ == 1 ? log : c->(c^(1-γ)-1)/(1-γ), # utility function
                          u' = c-> c^(-γ), # u'
                          f = k-> k^α, # production function
                          f' = k -> α*k^(α-1), # f'
                        grid = range(grid_min, grid_max, length = grid_size)) # grid
```

```
Out[5]: ##NamedTuple_kw#253 (generic function with 2 methods)
```

Next we generate an instance

```
In [6]: mlog = Model(); # Log Linear model
```

We also need some shock draws for Monte Carlo integration

```
In [7]: Random.seed!(42); # For reproducible behavior.

        shock_size = 250     # Number of shock draws in Monte Carlo integral
        shocks = exp.(mlog.μ .+ mlog.s * randn(shock_size));
```

As a preliminary test, let's see if $Kc^* = c^*$, as implied by the theory

```
In [8]: c_star(y) = (1 - mlog.α * mlog.β) * y

        # some useful constants
        ab = mlog.α * mlog.β
        c1 = log(1 - ab) / (1 - mlog.β)
        c2 = (mlog.μ + mlog.α * log(ab)) / (1 - mlog.α)
        c3 = 1 / (1 - mlog.β)
        c4 = 1 / (1 - ab)

        v_star(y) = c1 + c2 * (c3 - c4) + c4 * log(y)
```

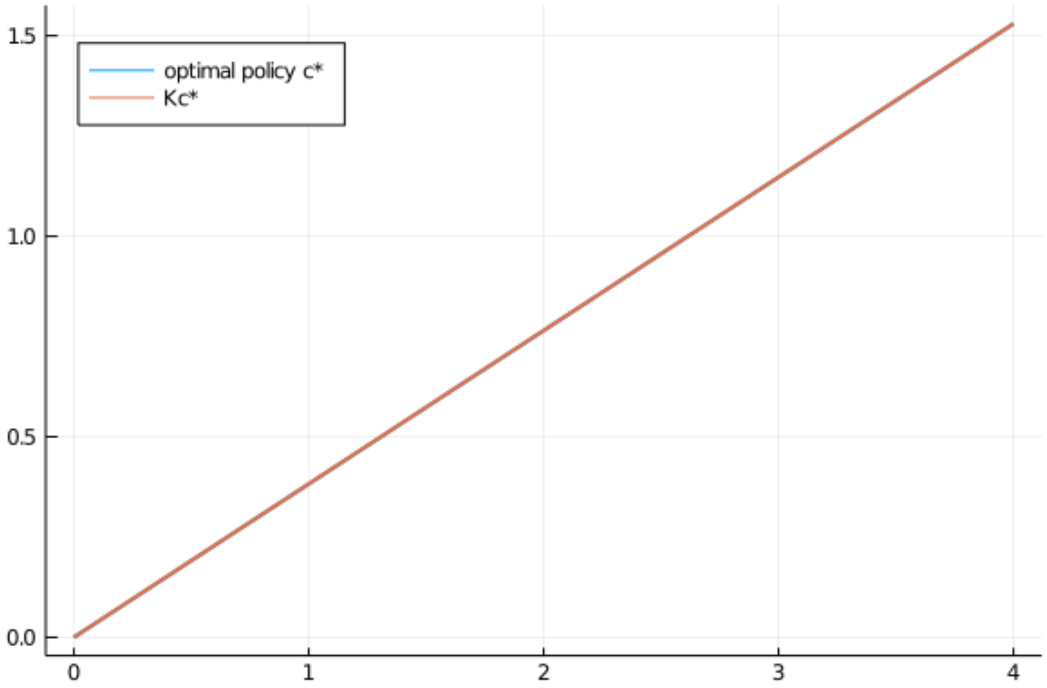
```
Out[8]: v_star (generic function with 1 method)
```

```
In [9]: function verify_true_policy(m, shocks, c_star)
            k_grid = m.grid
            c_star_new = coleman_egm(c_star, k_grid, m.β, m.u', m.u', m.f, m.f',
 ↪shocks)

            plt = plot()
           plot!(plt, k_grid, c_star.(k_grid), lw = 2, label = "optimal policy c*")
            plot!(plt, k_grid, c_star_new.(k_grid), lw = 2, label = "Kc*")
            plot!(plt, legend = :topleft)
        end
```

```
Out[9]: verify_true_policy (generic function with 1 method)
```

```
In [10]: verify_true_policy(mlog, shocks, c_star)
```

```
Out[10]:
```



Notice that we're passing u to coleman_egm twice.

The reason is that, in the case of log utility, $u'(c) = (u')^{-1}(c) = 1/c$.

Hence u and u _inv are the same.

We can't really distinguish the two plots.

In fact it's easy to see that the difference is essentially zero:

```
In [11]: c_star_new = coleman_egm(c_star, mlog.grid, mlog.β, mlog.u',
                                  mlog.u', mlog.f, mlog.f', shocks)
         maximum(abs(c_star_new(g) - c_star(g)) for g in mlog.grid)
```

```
Out[11]: 1.3322676295501878e-15
```

Next let's try iterating from an arbitrary initial condition and see if we converge towards c^*.

Let's start from the consumption policy that eats the whole pie: $c(y) = y$

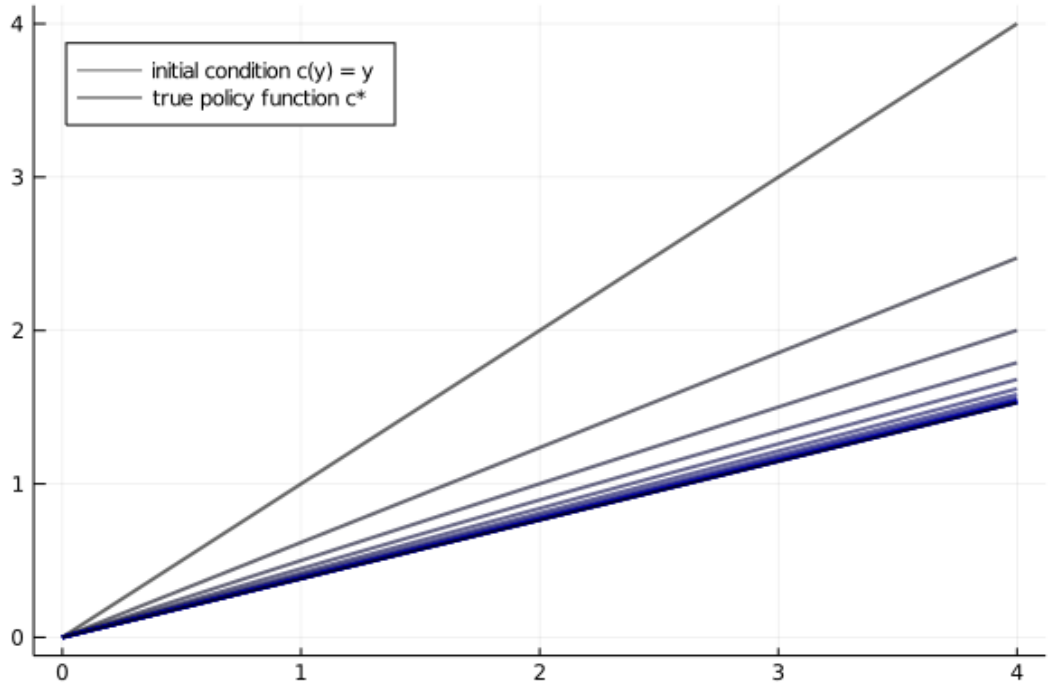
```
In [12]: n = 15
         function check_convergence(m, shocks, c_star, g_init, n_iter)
             k_grid = m.grid
             g = g_init
             plt = plot()
             plot!(plt, m.grid, g.(m.grid),
                   color = RGBA(0,0,0,1), lw = 2, alpha = 0.6, label = "initial
 ↪condition c(y) =
         y")
             for i in 1:n_iter
                 new_g = coleman_egm(g, k_grid, m.β, m.u', m.u', m.f, m.f', shocks)
                 g = new_g
                 plot!(plt, k_grid, new_g.(k_grid), alpha = 0.6, color =
 ↪RGBA(0,0,(i / n_iter),
```

```
        1),
                    lw = 2, label = "")
        end

        plot!(plt, k_grid, c_star.(k_grid),
              color = :black, lw = 2, alpha = 0.8, label = "true policy
↪function c*")
        plot!(plt, legend = :topleft)
    end
```

```
Out[12]: check_convergence (generic function with 1 method)
```

```
In [13]: check_convergence(mlog, shocks, c_star, identity, n)
```

```
Out[13]:
```



We see that the policy has converged nicely, in only a few steps.

33.5 Speed

Now let's compare the clock times per iteration for the standard Coleman operator (with exogenous grid) and the EGM version.

We'll do so using the CRRA model adopted in the exercises of the Euler equation time iteration lecture.

Here's the model and some convenient functions

```
In [14]: mcrra = Model(α = 0.65, β = 0.95, γ = 1.5)
         u'_inv(c) = c^(-1 / mcrra.γ)
```

```
Out[14]: u'_inv (generic function with 1 method)
```

Here's the result

```
In [15]: crra_coleman(g, m, shocks) = K(g, m.grid, m.β, m.u', m.f, m.f', shocks)
         crra_coleman_egm(g, m, shocks) = coleman_egm(g, m.grid, m.β, m.u',
                                                      u'_inv, m.f, m.f', shocks)
         function coleman(m = m, shocks = shocks; sim_length = 20)
             g = m.grid
             for i in 1:sim_length
                 g = crra_coleman(g, m, shocks)
             end
             return g
         end
         function egm(m, g = identity, shocks = shocks; sim_length = 20)
             for i in 1:sim_length
                 g = crra_coleman_egm(g, m, shocks)
             end
             return g.(m.grid)
         end
```

```
Out[15]: egm (generic function with 3 methods)
```

```
In [16]: @benchmark coleman($mcrra)
```

```
Out[16]: BenchmarkTools.Trial:
           memory estimate:  1.03 GiB
           allocs estimate:  615012
           --------------
           minimum time:     8.433 s (1.38% GC)
           median time:      8.433 s (1.38% GC)
           mean time:        8.433 s (1.38% GC)
           maximum time:     8.433 s (1.38% GC)
           --------------
           samples:          1
           evals/sample:     1
```

```
In [17]: @benchmark egm($mcrra)
```

```
Out[17]: BenchmarkTools.Trial:
           memory estimate:  18.50 MiB
           allocs estimate:  76226
           --------------
           minimum time:     180.788 ms (0.00% GC)
           median time:      183.655 ms (0.00% GC)
           mean time:        184.908 ms (1.14% GC)
           maximum time:     190.417 ms (3.11% GC)
           --------------
           samples:          28
           evals/sample:     1
```

We see that the EGM version is about 30 times faster.

At the same time, the absence of numerical root finding means that it is typically more accurate at each step as well.

Chapter 34

LQ Dynamic Programming Problems

34.1 Contents

34.2 Overview

Linear quadratic (LQ) control refers to a class of dynamic optimization problems that have found applications in almost every scientific field.

This lecture provides an introduction to LQ control and its economic applications.

As we will see, LQ systems have a simple structure that makes them an excellent workhorse for a wide variety of economic problems.

Moreover, while the linear-quadratic structure is restrictive, it is in fact far more flexible than it may appear initially.

These themes appear repeatedly below.

Mathematically, LQ control problems are closely related to the Kalman filter.

- Recursive formulations of linear-quadratic control problems and Kalman filtering problems both involve matrix **Riccati equations**.
- Classical formulations of linear control and linear filtering problems make use of similar matrix decompositions (see for example this lecture and this lecture).

In reading what follows, it will be useful to have some familiarity with

- matrix manipulations
- vectors of random variables

- dynamic programming and the Bellman equation (see for example this lecture and this lecture)

For additional reading on LQ control, see, for example,

- [68], chapter 5
- [39], chapter 4
- [53], section 3.5

In order to focus on computation, we leave longer proofs to these sources (while trying to provide as much intuition as possible).

34.3 Introduction

The "linear" part of LQ is a linear law of motion for the state, while the "quadratic" part refers to preferences.

Let's begin with the former, move on to the latter, and then put them together into an optimization problem.

34.3.1 The Law of Motion

Let x_t be a vector describing the state of some economic system.

Suppose that x_t follows a linear law of motion given by

$$x_{t+1} = Ax_t + Bu_t + Cw_{t+1}, \qquad t = 0, 1, 2, ... \tag{1}$$

Here

- u_t is a "control" vector, incorporating choices available to a decision maker confronting the current state x_t.
- $\{w_t\}$ is an uncorrelated zero mean shock process satisfying $\mathbb{E}w_t w_t' = I$, where the right-hand side is the identity matrix.

Regarding the dimensions

- x_t is $n \times 1$, A is $n \times n$
- u_t is $k \times 1$, B is $n \times k$
- w_t is $j \times 1$, C is $n \times j$

Example 1

Consider a household budget constraint given by

$$a_{t+1} + c_t = (1 + r)a_t + y_t$$

Here a_t is assets, r is a fixed interest rate, c_t is current consumption, and y_t is current non-financial income.

If we suppose that $\{y_t\}$ is serially uncorrelated and $N(0, \sigma^2)$, then, taking $\{w_t\}$ to be standard normal, we can write the system as

$$a_{t+1} = (1+r)a_t - c_t + \sigma w_{t+1}$$

This is clearly a special case of (1), with assets being the state and consumption being the control.

Example 2

One unrealistic feature of the previous model is that non-financial income has a zero mean and is often negative.

This can easily be overcome by adding a sufficiently large mean.

Hence in this example we take $y_t = \sigma w_{t+1} + \mu$ for some positive real number μ.

Another alteration that's useful to introduce (we'll see why soon) is to change the control variable from consumption to the deviation of consumption from some "ideal" quantity $\bar{c}$.

(Most parameterizations will be such that $\bar{c}$ is large relative to the amount of consumption that is attainable in each period, and hence the household wants to increase consumption)

For this reason, we now take our control to be $u_t := c_t - \bar{c}$.

In terms of these variables, the budget constraint $a_{t+1} = (1+r)a_t - c_t + y_t$ becomes

$$a_{t+1} = (1+r)a_t - u_t - \bar{c} + \sigma w_{t+1} + \mu \tag{2}$$

How can we write this new system in the form of equation (1)?

If, as in the previous example, we take a_t as the state, then we run into a problem: the law of motion contains some constant terms on the right-hand side.

This means that we are dealing with an *affine* function, not a linear one (recall this discussion).

Fortunately, we can easily circumvent this problem by adding an extra state variable.

In particular, if we write

$$\begin{pmatrix} a_{t+1} \\ 1 \end{pmatrix} = \begin{pmatrix} 1+r & -\bar{c}+\mu \\ 0 & 1 \end{pmatrix} \begin{pmatrix} a_t \\ 1 \end{pmatrix} + \begin{pmatrix} -1 \\ 0 \end{pmatrix} u_t + \begin{pmatrix} \sigma \\ 0 \end{pmatrix} w_{t+1} \tag{3}$$

then the first row is equivalent to (2).

Moreover, the model is now linear, and can be written in the form of (1) by setting

$$x_t := \begin{pmatrix} a_t \\ 1 \end{pmatrix}, \quad A := \begin{pmatrix} 1+r & -\bar{c}+\mu \\ 0 & 1 \end{pmatrix}, \quad B := \begin{pmatrix} -1 \\ 0 \end{pmatrix}, \quad C := \begin{pmatrix} \sigma \\ 0 \end{pmatrix} \tag{4}$$

In effect, we've bought ourselves linearity by adding another state.

34.3.2 Preferences

In the LQ model, the aim is to minimize a flow of losses, where time-t loss is given by the quadratic expression

$$x_t' R x_t + u_t' Q u_t \tag{5}$$

Here

- R is assumed to be $n \times n$, symmetric and nonnegative definite
- Q is assumed to be $k \times k$, symmetric and positive definite

Note

In fact, for many economic problems, the definiteness conditions on R and Q can be relaxed. It is sufficient that certain submatrices of R and Q be nonnegative definite. See [39] for details

Example 1

A very simple example that satisfies these assumptions is to take R and Q to be identity matrices, so that current loss is

$$x_t' I x_t + u_t' I u_t = \|x_t\|^2 + \|u_t\|^2$$

Thus, for both the state and the control, loss is measured as squared distance from the origin.

(In fact the general case (5) can also be understood in this way, but with R and Q identifying other – non-Euclidean – notions of "distance" from the zero vector).

Intuitively, we can often think of the state x_t as representing deviation from a target, such as

- deviation of inflation from some target level
- deviation of a firm's capital stock from some desired quantity

The aim is to put the state close to the target, while using controls parsimoniously.

Example 2

In the household problem studied above, setting $R = 0$ and $Q = 1$ yields preferences

$$x_t' R x_t + u_t' Q u_t = u_t^2 = (c_t - \bar{c})^2$$

Under this specification, the household's current loss is the squared deviation of consumption from the ideal level $\bar{c}$.

34.4 Optimality – Finite Horizon

Let's now be precise about the optimization problem we wish to consider, and look at how to solve it.

34.4.1 The Objective

We will begin with the finite horizon case, with terminal time $T \in \mathbb{N}$.

In this case, the aim is to choose a sequence of controls $\{u_0, \dots, u_{T-1}\}$ to minimize the objective

$$\mathbb{E}\left\{\sum_{t=0}^{T-1} \beta^t (x_t' R x_t + u_t' Q u_t) + \beta^T x_T' R_f x_T\right\} \tag{6}$$

subject to the law of motion (1) and initial state x_0.

The new objects introduced here are β and the matrix R_f.

The scalar β is the discount factor, while $x' R_f x$ gives terminal loss associated with state x.

Comments:

- We assume R_f to be $n \times n$, symmetric and nonnegative definite
- We allow $\beta = 1$, and hence include the undiscounted case
- x_0 may itself be random, in which case we require it to be independent of the shock sequence $w_1, \dots, w_T$

34.4.2 Information

There's one constraint we've neglected to mention so far, which is that the decision maker who solves this LQ problem knows only the present and the past, not the future.

To clarify this point, consider the sequence of controls $\{u_0, \dots, u_{T-1}\}$.

When choosing these controls, the decision maker is permitted to take into account the effects of the shocks $\{w_1, \dots, w_T\}$ on the system.

However, it is typically assumed — and will be assumed here — that the time-t control u_t can be made with knowledge of past and present shocks only.

The fancy measure-theoretic way of saying this is that u_t must be measurable with respect to the σ-algebra generated by $x_0, w_1, w_2, \dots, w_t$.

This is in fact equivalent to stating that u_t can be written in the form $u_t = g_t(x_0, w_1, w_2, \dots, w_t)$ for some Borel measurable function g_t.

(Just about every function that's useful for applications is Borel measurable, so, for the purposes of intuition, you can read that last phrase as "for some function g_t").

Now note that x_t will ultimately depend on the realizations of $x_0, w_1, w_2, \dots, w_t$.

In fact it turns out that x_t summarizes all the information about these historical shocks that the decision maker needs to set controls optimally.

More precisely, it can be shown that any optimal control u_t can always be written as a function of the current state alone.

Hence in what follows we restrict attention to control policies (i.e., functions) of the form $u_t = g_t(x_t)$.

Actually, the preceding discussion applies to all standard dynamic programming problems.

What's special about the LQ case is that – as we shall soon see — the optimal u_t turns out to be a linear function of x_t.

34.4.3 Solution

To solve the finite horizon LQ problem we can use a dynamic programming strategy based on backwards induction that is conceptually similar to the approach adopted in this lecture.

For reasons that will soon become clear, we first introduce the notation $J_T(x) = x' R_f x$.

Now consider the problem of the decision maker in the second to last period.

In particular, let the time be $T-1$, and suppose that the state is x_{T-1}.

The decision maker must trade off current and (discounted) final losses, and hence solves

$$\min_u \{x'_{T-1} R x_{T-1} + u' Q u + \beta \, \mathbb{E} J_T(A x_{T-1} + B u + C w_T)\}$$

At this stage, it is convenient to define the function

$$J_{T-1}(x) = \min_u \{x' R x + u' Q u + \beta \, \mathbb{E} J_T(A x + B u + C w_T)\} \tag{7}$$

The function J_{T-1} will be called the $T-1$ value function, and $J_{T-1}(x)$ can be thought of as representing total "loss-to-go" from state x at time $T-1$ when the decision maker behaves optimally.

Now let's step back to $T-2$.

For a decision maker at $T-2$, the value $J_{T-1}(x)$ plays a role analogous to that played by the terminal loss $J_T(x) = x' R_f x$ for the decision maker at $T-1$.

That is, $J_{T-1}(x)$ summarizes the future loss associated with moving to state x.

The decision maker chooses her control u to trade off current loss against future loss, where

- the next period state is $x_{T-1} = A x_{T-2} + B u + C w_{T-1}$, and hence depends on the choice of current control
- the "cost" of landing in state x_{T-1} is $J_{T-1}(x_{T-1})$

Her problem is therefore

$$\min_u \{x'_{T-2} R x_{T-2} + u' Q u + \beta \, \mathbb{E} J_{T-1}(A x_{T-2} + B u + C w_{T-1})\}$$

Letting

$$J_{T-2}(x) = \min_u \{x' R x + u' Q u + \beta \, \mathbb{E} J_{T-1}(A x + B u + C w_{T-1})\}$$

the pattern for backwards induction is now clear.

In particular, we define a sequence of value functions $\{J_0, \ldots, J_T\}$ via

$$J_{t-1}(x) = \min_u \{x' R x + u' Q u + \beta \, \mathbb{E} J_t(A x + B u + C w_t)\} \quad \text{and} \quad J_T(x) = x' R_f x$$

The first equality is the Bellman equation from dynamic programming theory specialized to the finite horizon LQ problem.

Now that we have $\{J_0, \ldots, J_T\}$, we can obtain the optimal controls.

As a first step, let's find out what the value functions look like.

It turns out that every J_t has the form $J_t(x) = x' P_t x + d_t$ where P_t is a $n \times n$ matrix and d_t is a constant.

We can show this by induction, starting from $P_T := R_f$ and $d_T = 0$.

Using this notation, (7) becomes

$$J_{T-1}(x) = \min_u \{x' R x + u' Q u + \beta \, \mathbb{E}(Ax + Bu + Cw_T)' P_T (Ax + Bu + Cw_T)\} \tag{8}$$

To obtain the minimizer, we can take the derivative of the r.h.s. with respect to u and set it equal to zero.

Applying the relevant rules of matrix calculus, this gives

$$u = -(Q + \beta B' P_T B)^{-1} \beta B' P_T A x \tag{9}$$

Plugging this back into (8) and rearranging yields

$$J_{T-1}(x) = x' P_{T-1} x + d_{T-1}$$

where

$$P_{T-1} = R - \beta^2 A' P_T B (Q + \beta B' P_T B)^{-1} B' P_T A + \beta A' P_T A \tag{10}$$

and

$$d_{T-1} := \beta \, \text{trace}(C' P_T C) \tag{11}$$

(The algebra is a good exercise — we'll leave it up to you).

If we continue working backwards in this manner, it soon becomes clear that $J_t(x) = x' P_t x + d_t$ as claimed, where $\{P_t\}$ and $\{d_t\}$ satisfy the recursions

$$P_{t-1} = R - \beta^2 A' P_t B (Q + \beta B' P_t B)^{-1} B' P_t A + \beta A' P_t A \quad \text{with} \quad P_T = R_f \tag{12}$$

and

$$d_{t-1} = \beta (d_t + \text{trace}(C' P_t C)) \quad \text{with} \quad d_T = 0 \tag{13}$$

Recalling (9), the minimizers from these backward steps are

$$u_t = -F_t x_t \quad \text{where} \quad F_t := (Q + \beta B' P_{t+1} B)^{-1} \beta B' P_{t+1} A \tag{14}$$

These are the linear optimal control policies we discussed above.

In particular, the sequence of controls given by (14) and (1) solves our finite horizon LQ problem.

Rephrasing this more precisely, the sequence $u_0, \ldots, u_{T-1}$ given by

$$u_t = -F_t x_t \quad \text{with} \quad x_{t+1} = (A - BF_t)x_t + Cw_{t+1} \tag{15}$$

for $t = 0, \ldots, T-1$ attains the minimum of (6) subject to our constraints.

34.5 Implementation

We will use code from lqcontrol.jl in QuantEcon.jl to solve finite and infinite horizon linear quadratic control problems.

In the module, the various updating, simulation and fixed point methods act on a type called `LQ`, which includes

- Instance data:
  - The required parameters Q, R, A, B and optional parameters C, β, T, R_f, N specifying a given LQ model
    - set T and R_f to `None` in the infinite horizon case
    - set `C = None` (or zero) in the deterministic case
  - the value function and policy data
    - d_t, P_t, F_t in the finite horizon case
    - d, P, F in the infinite horizon case
- Methods:
  - `update_values` — shifts d_t, P_t, F_t to their $t-1$ values via (12), (13) and (14)
  - `stationary_values` — computes P, d, F in the infinite horizon case
  - `compute_sequence` —- simulates the dynamics of x_t, u_t, w_t given x_0 and assuming standard normal shocks

34.5.1 An Application

Early Keynesian models assumed that households have a constant marginal propensity to consume from current income.

Data contradicted the constancy of the marginal propensity to consume.

In response, Milton Friedman, Franco Modigliani and others built models based on a consumer's preference for an intertemporally smooth consumption stream.

(See, for example, [32] or [79]).

One property of those models is that households purchase and sell financial assets to make consumption streams smoother than income streams.

The household savings problem outlined above captures these ideas.

The optimization problem for the household is to choose a consumption sequence in order to minimize

$$\mathbb{E}\left\{\sum_{t=0}^{T-1} \beta^t (c_t - \bar{c})^2 + \beta^T q a_T^2\right\} \tag{16}$$

subject to the sequence of budget constraints $a_{t+1} = (1+r)a_t - c_t + y_t, \ t \geq 0$.

Here q is a large positive constant, the role of which is to induce the consumer to target zero debt at the end of her life.

(Without such a constraint, the optimal choice is to choose $c_t = \bar{c}$ in each period, letting assets adjust accordingly).

As before we set $y_t = \sigma w_{t+1} + \mu$ and $u_t := c_t - \bar{c}$, after which the constraint can be written as in (2).

We saw how this constraint could be manipulated into the LQ formulation $x_{t+1} = Ax_t + Bu_t + Cw_{t+1}$ by setting $x_t = (a_t \ 1)'$ and using the definitions in (4).

To match with this state and control, the objective function (16) can be written in the form of (6) by choosing

$$Q := 1, \quad R := \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}, \quad \text{and} \quad R_f := \begin{pmatrix} q & 0 \\ 0 & 0 \end{pmatrix}$$

Now that the problem is expressed in LQ form, we can proceed to the solution by applying (12) and (14).

After generating shocks $w_1, \ldots, w_T$, the dynamics for assets and consumption can be simulated via (15).

The following figure was computed using $r = 0.05, \beta = 1/(1+r), \bar{c} = 2, \mu = 1, \sigma = 0.25, T = 45$ and $q = 10^6$.

The shocks $\{w_t\}$ were taken to be iid and standard normal.

34.5.2 Setup

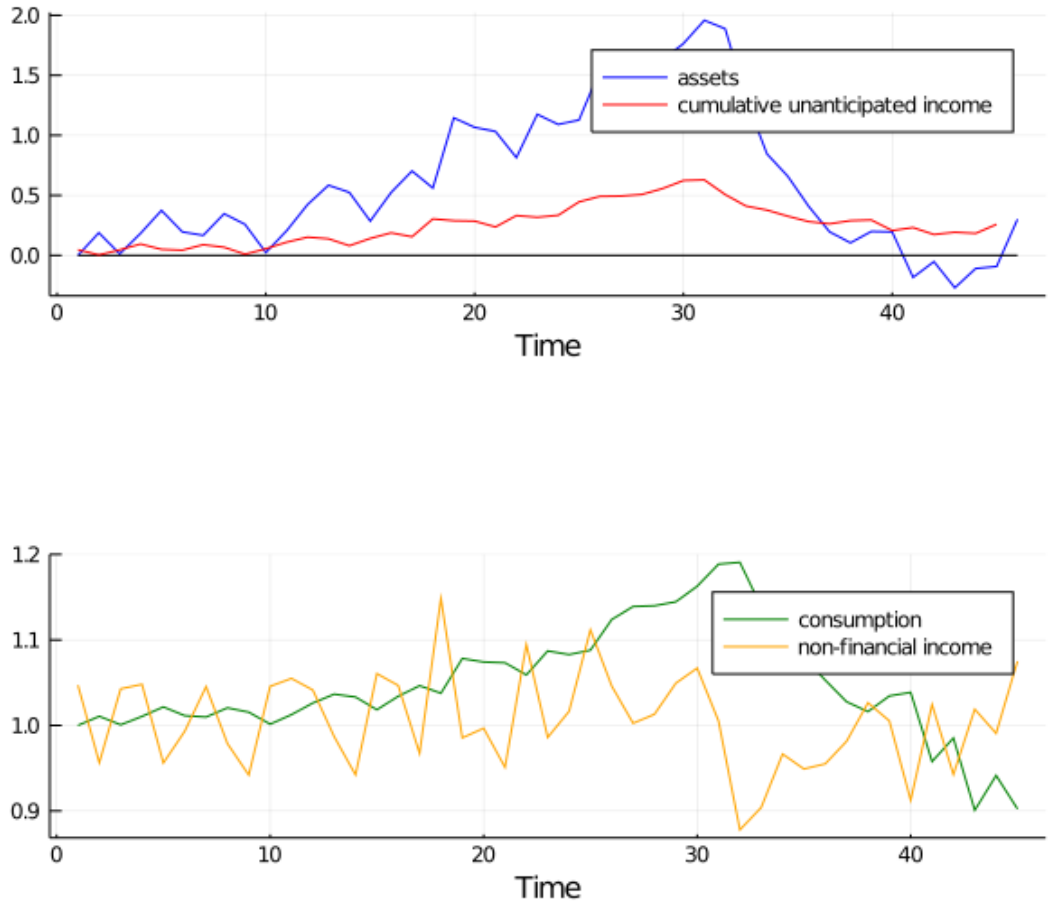
```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Plots, Plots.PlotMeasures, QuantEcon
        gr(fmt = :png);
```

```
In [3]: # model parameters
        r = 0.05
        β = 1 / (1 + r)
        T = 45

        c̄ = 2.0
        σ = 0.25
        μ = 1.0
        q = 1e6

        # formulate as an LQ problem
        Q = 1.0
        R = zeros(2, 2)
        Rf = zeros(2, 2); Rf[1, 1] = q

        A = [1 + r -c̄ + μ; 0  1]
        B = [-1.0, 0]
        C = [σ, 0]

        # compute solutions and simulate
```

```
lq = QuantEcon.LQ(Q, R, A, B, C; bet = β, capT = T, rf = Rf)
x0 = [0.0, 1]
xp, up, wp = compute_sequence(lq, x0)

# convert back to assets, consumption and income
assets = vec(xp[1, :]) # a_t
c = vec(up .+ c̄) # c_t
income = vec(σ * wp[1, 2:end] .+ μ) # y_t

# plot results
p = plot([assets, c, zeros(T + 1), income, cumsum(income .- μ)],
        lab = ["assets" "consumption" "" "non-financial income" "cumulative
unanticipated income"],
         color = [:blue :green :black :orange :red],
         xaxis = "Time", layout = (2, 1),
         bottom_margin = 20mm, size = (600, 600))
```

Out[3]:



The top panel shows the time path of consumption c_t and income y_t in the simulation.

As anticipated by the discussion on consumption smoothing, the time path of consumption is much smoother than that for income.

(But note that consumption becomes more irregular towards the end of life, when the zero final asset requirement impinges more on consumption choices).

The second panel in the figure shows that the time path of assets a_t is closely correlated with cumulative unanticipated income, where the latter is defined as

$$z_t := \sum_{j=0}^{t} \sigma w_t$$

A key message is that unanticipated windfall gains are saved rather than consumed, while unanticipated negative shocks are met by reducing assets.

(Again, this relationship breaks down towards the end of life due to the zero final asset requirement).

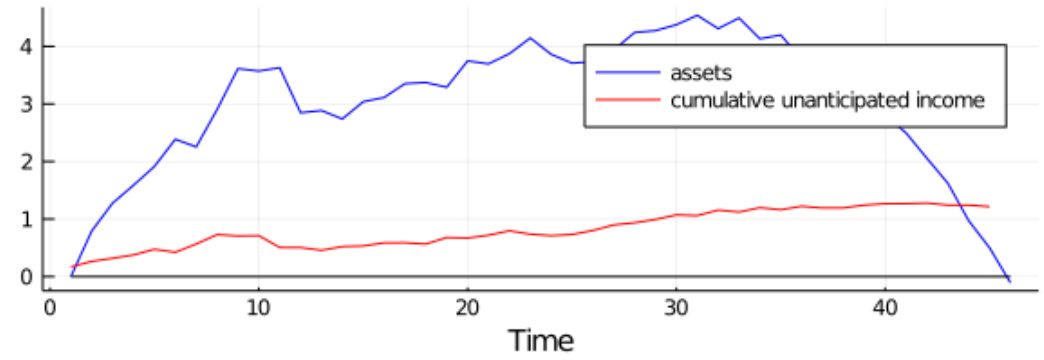
These results are relatively robust to changes in parameters.

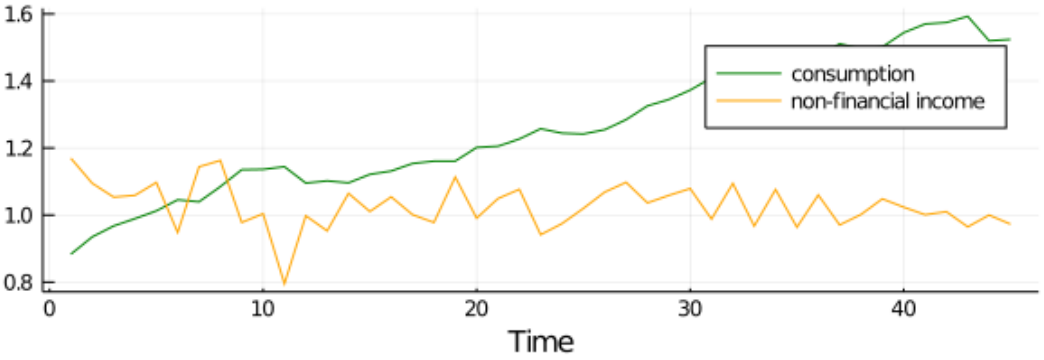
For example, let's increase β from $1/(1+r) \approx 0.952$ to 0.96 while keeping other parameters fixed.

This consumer is slightly more patient than the last one, and hence puts relatively more weight on later consumption values

In [4]:
```
# compute solutions and simulate
lq = QuantEcon.LQ(Q, R, A, B, C; bet = 0.96, capT = T, rf = Rf)
x0 = [0.0, 1]
xp, up, wp = compute_sequence(lq, x0)

# convert back to assets, consumption and income
assets = vec(xp[1, :]) # a_t
c = vec(up .+ c̄) # c_t
income = vec(σ * wp[1, 2:end] .+ μ) # y_t

# plot results
p = plot([assets, c, zeros(T + 1), income, cumsum(income .- μ)],
        lab = ["assets" "consumption" "" "non-financial income" "cumulative
unanticipated income"],
         color = [:blue :green :black :orange :red],
         xaxis = "Time", layout = (2, 1),
         bottom_margin = 20mm, size = (600, 600))
```

Out[4]:





We now have a slowly rising consumption stream and a hump-shaped build up of assets in the middle periods to fund rising consumption.

However, the essential features are the same: consumption is smooth relative to income, and assets are strongly positively correlated with cumulative unanticipated income.

34.6 Extensions and Comments

Let's now consider a number of standard extensions to the LQ problem treated above.

34.6.1 Time-Varying Parameters

In some settings it can be desirable to allow A, B, C, R and Q to depend on t.

For the sake of simplicity, we've chosen not to treat this extension in our implementation given below.

However, the loss of generality is not as large as you might first imagine.

In fact, we can tackle many models with time-varying parameters by suitable choice of state

variables.

One illustration is given below.

For further examples and a more systematic treatment, see [40], section 2.4.

34.6.2 Adding a Cross-Product Term

In some LQ problems, preferences include a cross-product term $u_t' N x_t$, so that the objective function becomes

$$\mathbb{E}\left\{\sum_{t=0}^{T-1} \beta^t (x_t' R x_t + u_t' Q u_t + 2 u_t' N x_t) + \beta^T x_T' R_f x_T\right\} \tag{17}$$

Our results extend to this case in a straightforward way.

The sequence $\{P_t\}$ from (12) becomes

$$P_{t-1} = R - (\beta B' P_t A + N)'(Q + \beta B' P_t B)^{-1}(\beta B' P_t A + N) + \beta A' P_t A \quad \text{with} \quad P_T = R_f \tag{18}$$

The policies in (14) are modified to

$$u_t = -F_t x_t \quad \text{where} \quad F_t := (Q + \beta B' P_{t+1} B)^{-1}(\beta B' P_{t+1} A + N) \tag{19}$$

The sequence $\{d_t\}$ is unchanged from (13).

We leave interested readers to confirm these results (the calculations are long but not overly difficult).

34.6.3 Infinite Horizon

Finally, we consider the infinite horizon case, with cross-product term, unchanged dynamics and objective function given by

$$\mathbb{E}\left\{\sum_{t=0}^{\infty} \beta^t (x_t' R x_t + u_t' Q u_t + 2 u_t' N x_t)\right\} \tag{20}$$

In the infinite horizon case, optimal policies can depend on time only if time itself is a component of the state vector x_t.

In other words, there exists a fixed matrix F such that $u_t = -F x_t$ for all t.

That decision rules are constant over time is intuitive — after all, the decision maker faces the same infinite horizon at every stage, with only the current state changing.

Not surprisingly, P and d are also constant.

The stationary matrix P is the solution to the discrete time algebraic Riccati equation.

$$P = R - (\beta B' P A + N)'(Q + \beta B' P B)^{-1}(\beta B' P A + N) + \beta A' P A \tag{21}$$

Equation (21) is also called the *LQ Bellman equation*, and the map that sends a given P into the right-hand side of (21) is called the *LQ Bellman operator*.

The stationary optimal policy for this model is

$$u = -Fx \quad \text{where} \quad F = (Q + \beta B'PB)^{-1}(\beta B'PA + N) \tag{22}$$

The sequence $\{d_t\}$ from (13) is replaced by the constant value

$$d := \text{trace}(C'PC)\frac{\beta}{1-\beta} \tag{23}$$

The state evolves according to the time-homogeneous process $x_{t+1} = (A - BF)x_t + Cw_{t+1}$.

An example infinite horizon problem is treated below.

34.6.4 Certainty Equivalence

Linear quadratic control problems of the class discussed above have the property of *certainty equivalence*.

By this we mean that the optimal policy F is not affected by the parameters in C, which specify the shock process.

This can be confirmed by inspecting (22) or (19).

It follows that we can ignore uncertainty when solving for optimal behavior, and plug it back in when examining optimal state dynamics.

34.7 Further Applications

34.7.1 Application 1: Age-Dependent Income Process

Previously we studied a permanent income model that generated consumption smoothing.

One unrealistic feature of that model is the assumption that the mean of the random income process does not depend on the consumer's age.

A more realistic income profile is one that rises in early working life, peaks towards the middle and maybe declines toward end of working life, and falls more during retirement.

In this section, we will model this rise and fall as a symmetric inverted "U" using a polynomial in age.

As before, the consumer seeks to minimize

$$\mathbb{E}\left\{\sum_{t=0}^{T-1} \beta^t (c_t - \bar{c})^2 + \beta^T q a_T^2\right\} \tag{24}$$

subject to $a_{t+1} = (1+r)a_t - c_t + y_t,\ t \geq 0$.

For income we now take $y_t = p(t) + \sigma w_{t+1}$ where $p(t) := m_0 + m_1 t + m_2 t^2$.

(In the next section we employ some tricks to implement a more sophisticated model).

The coefficients m_0, m_1, m_2 are chosen such that $p(0) = 0, p(T/2) = \mu$, and $p(T) = 0$.

You can confirm that the specification $m_0 = 0, m_1 = T\mu/(T/2)^2, m_2 = -\mu/(T/2)^2$ satisfies these constraints.

To put this into an LQ setting, consider the budget constraint, which becomes

$$a_{t+1} = (1+r)a_t - u_t - \bar{c} + m_1 t + m_2 t^2 + \sigma w_{t+1} \tag{25}$$

The fact that a_{t+1} is a linear function of $(a_t, 1, t, t^2)$ suggests taking these four variables as the state vector x_t.

Once a good choice of state and control (recall $u_t = c_t - \bar{c}$) has been made, the remaining specifications fall into place relatively easily.

Thus, for the dynamics we set

$$x_t := \begin{pmatrix} a_t \\ 1 \\ t \\ t^2 \end{pmatrix}, \quad A := \begin{pmatrix} 1+r & -\bar{c} & m_1 & m_2 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 2 & 1 \end{pmatrix}, \quad B := \begin{pmatrix} -1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad C := \begin{pmatrix} \sigma \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{26}$$

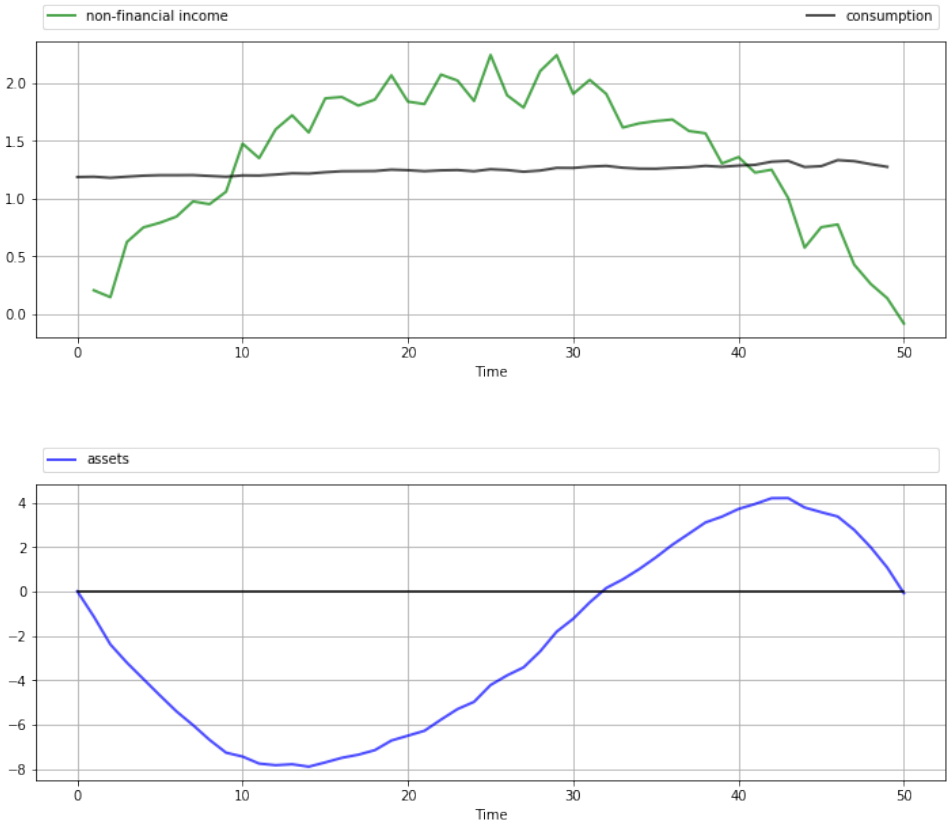
If you expand the expression $x_{t+1} = Ax_t + Bu_t + Cw_{t+1}$ using this specification, you will find that assets follow (25) as desired, and that the other state variables also update appropriately.

To implement preference specification (24) we take

$$Q := 1, \quad R := \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad R_f := \begin{pmatrix} q & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{27}$$

The next figure shows a simulation of consumption and assets computed using the

`compute_sequence` method of `lqcontrol.jl` with initial assets set to zero.



Once again, smooth consumption is a dominant feature of the sample paths.

The asset path exhibits dynamics consistent with standard life cycle theory.

Exercise 1 gives the full set of parameters used here and asks you to replicate the figure.

34.7.2 Application 2: A Permanent Income Model with Retirement

In the previous application, we generated income dynamics with an inverted U shape using polynomials, and placed them in an LQ framework.

It is arguably the case that this income process still contains unrealistic features.

A more common earning profile is where

1. income grows over working life, fluctuating around an increasing trend, with growth flattening off in later years
2. retirement follows, with lower but relatively stable (non-financial) income

Letting K be the retirement date, we can express these income dynamics by

$$y_t = \begin{cases} p(t) + \sigma w_{t+1} & \text{if } t \leq K \\ s & \text{otherwise} \end{cases} \tag{28}$$

Here

- $p(t) := m_1 t + m_2 t^2$ with the coefficients m_1, m_2 chosen such that $p(K) = \mu$ and $p(0) = p(2K) = 0$
- s is retirement income

We suppose that preferences are unchanged and given by (16).

The budget constraint is also unchanged and given by $a_{t+1} = (1 + r)a_t - c_t + y_t$.

Our aim is to solve this problem and simulate paths using the LQ techniques described in this lecture.

In fact this is a nontrivial problem, as the kink in the dynamics (28) at K makes it very difficult to express the law of motion as a fixed-coefficient linear system.

However, we can still use our LQ methods here by suitably linking two component LQ problems.

These two LQ problems describe the consumer's behavior during her working life (`lq_working`) and retirement (`lq_retired`).

(This is possible because in the two separate periods of life, the respective income processes [polynomial trend and constant] each fit the LQ framework)

The basic idea is that although the whole problem is not a single time-invariant LQ problem, it is still a dynamic programming problem, and hence we can use appropriate Bellman equations at every stage.

Based on this logic, we can

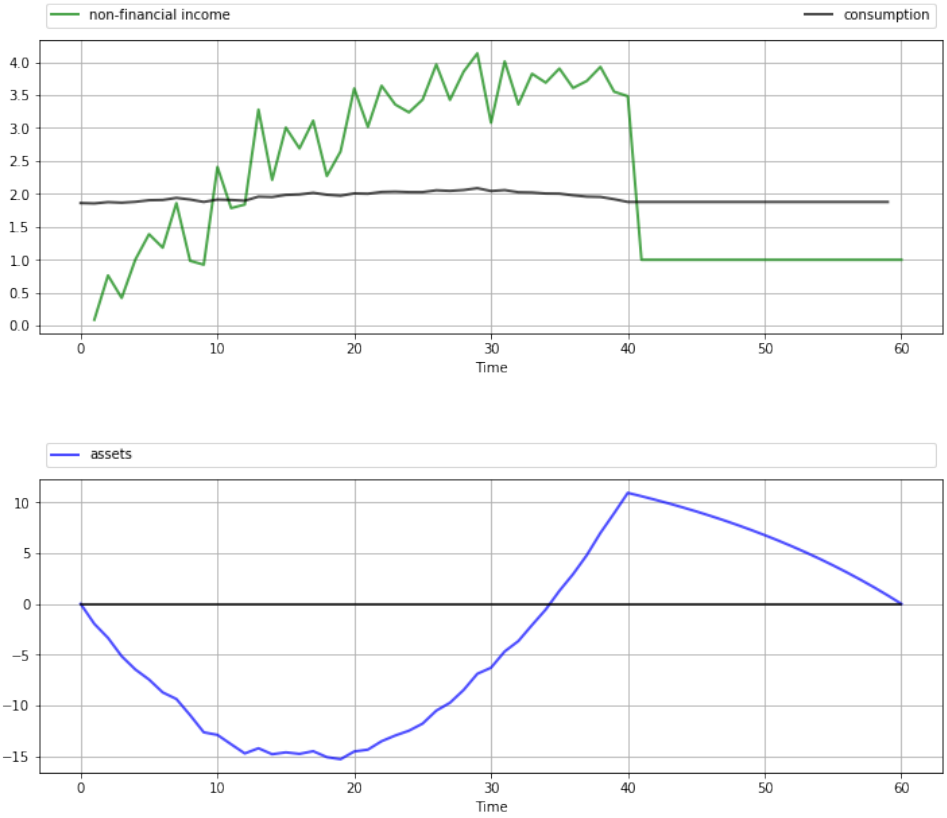
1. solve `lq_retired` by the usual backwards induction procedure, iterating back to the start of retirement

2. take the start-of-retirement value function generated by this process, and use it as the terminal condition R_f to feed into the `lq_working` specification

3. solve `lq_working` by backwards induction from this choice of R_f, iterating back to the start of working life

This process gives the entire life-time sequence of value functions and optimal policies.

The next figure shows one simulation based on this procedure.



The full set of parameters used in the simulation is discussed in Exercise 2, where you are asked to replicate the figure.

Once again, the dominant feature observable in the simulation is consumption smoothing.

The asset path fits well with standard life cycle theory, with dissaving early in life followed by later saving.

Assets peak at retirement and subsequently decline.

34.7.3 Application 3: Monopoly with Adjustment Costs

Consider a monopolist facing stochastic inverse demand function

$$p_t = a_0 - a_1 q_t + d_t$$

Here q_t is output, and the demand shock d_t follows

$$d_{t+1} = \rho d_t + \sigma w_{t+1}$$

where $\{w_t\}$ is iid and standard normal.

The monopolist maximizes the expected discounted sum of present and future profits

$$\mathbb{E}\left\{\sum_{t=0}^{\infty}\beta^t\pi_t\right\} \quad \text{where} \quad \pi_t := p_t q_t - cq_t - \gamma(q_{t+1}-q_t)^2 \tag{29}$$

Here

- $\gamma(q_{t+1}-q_t)^2$ represents adjustment costs
- c is average cost of production

This can be formulated as an LQ problem and then solved and simulated, but first let's study the problem and try to get some intuition.

One way to start thinking about the problem is to consider what would happen if $\gamma = 0$.

Without adjustment costs there is no intertemporal trade-off, so the monopolist will choose output to maximize current profit in each period.

It's not difficult to show that profit-maximizing output is

$$\bar{q}_t := \frac{a_0 - c + d_t}{2a_1}$$

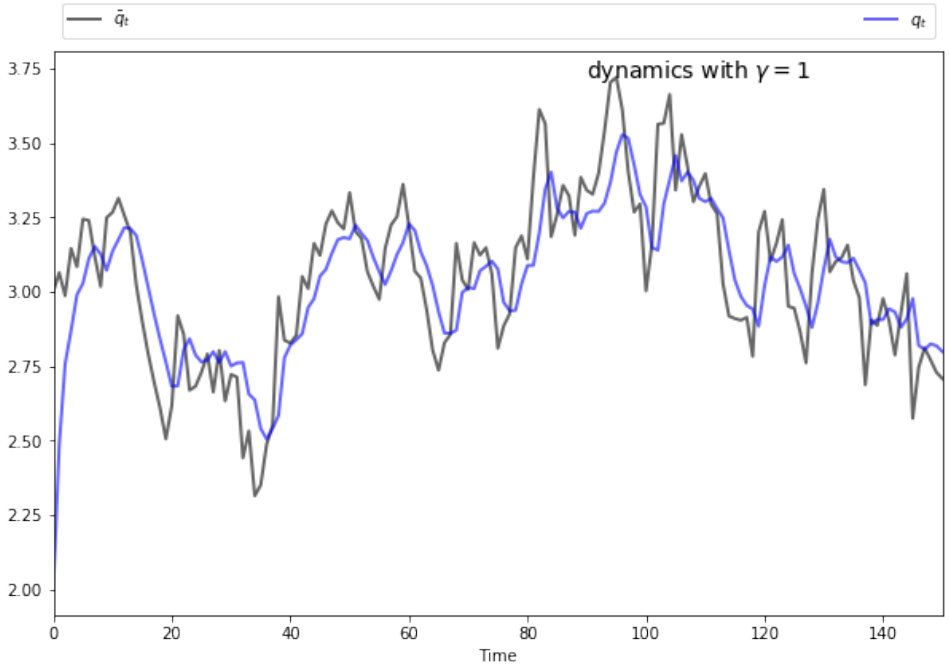
In light of this discussion, what we might expect for general γ is that

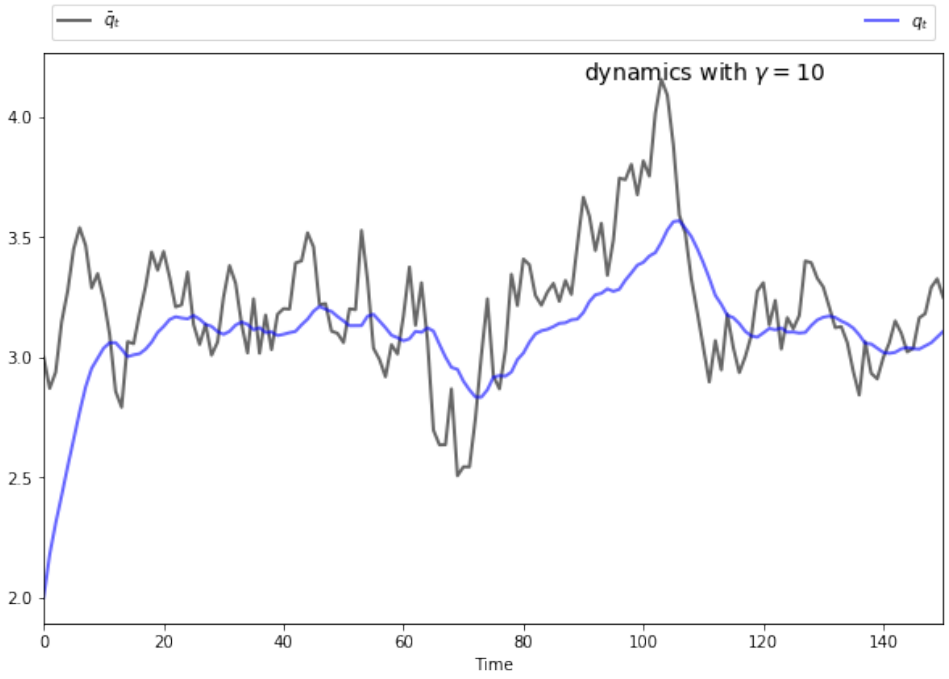
- if γ is close to zero, then q_t will track the time path of $\bar{q}_t$ relatively closely
- if γ is larger, then q_t will be smoother than $\bar{q}_t$, as the monopolist seeks to avoid adjustment costs

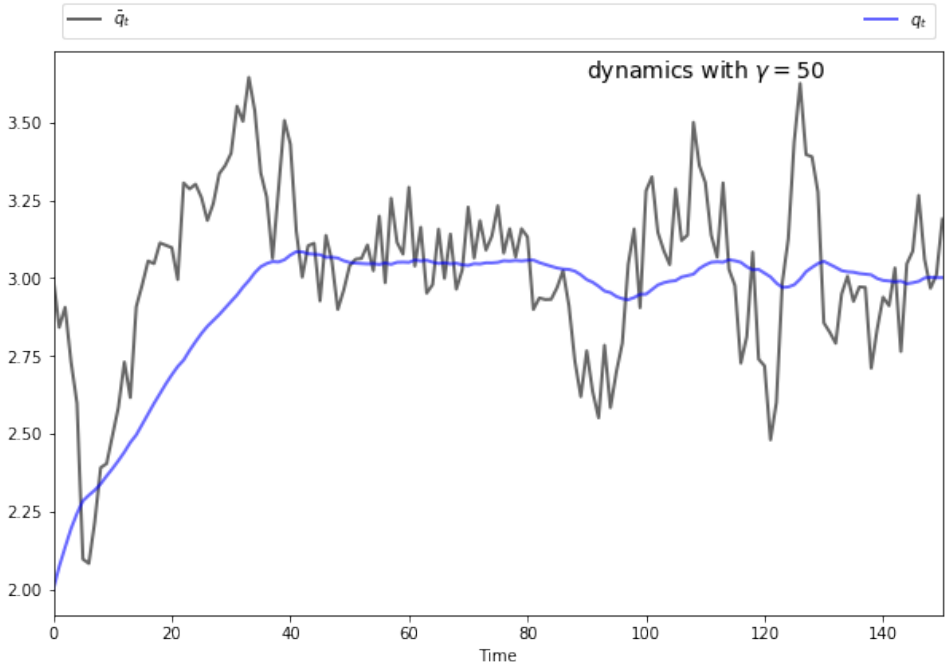
This intuition turns out to be correct.

The following figures show simulations produced by solving the corresponding LQ problem.

The only difference in parameters across the figures is the size of γ.







To produce these figures we converted the monopolist problem into an LQ problem.

The key to this conversion is to choose the right state — which can be a bit of an art.

Here we take $x_t = (\bar{q}_t \;\; q_t \;\; 1)'$, while the control is chosen as $u_t = q_{t+1} - q_t$.

We also manipulated the profit function slightly.

In (29), current profits are $\pi_t := p_t q_t - c q_t - \gamma(q_{t+1} - q_t)^2$.

Let's now replace π_t in (29) with $\hat{\pi}_t := \pi_t - a_1 \bar{q}_t^2$.

This makes no difference to the solution, since $a_1 \bar{q}_t^2$ does not depend on the controls.

(In fact we are just adding a constant term to (29), and optimizers are not affected by constant terms)

The reason for making this substitution is that, as you will be able to verify, $\hat{\pi}_t$ reduces to the simple quadratic

$$\hat{\pi}_t = -a_1 (q_t - \bar{q}_t)^2 - \gamma u_t^2$$

After negation to convert to a minimization problem, the objective becomes

$$\min \mathbb{E} \sum_{t=0}^{\infty} \beta^t \left\{ a_1 (q_t - \bar{q}_t)^2 + \gamma u_t^2 \right\} \tag{30}$$

It's now relatively straightforward to find R and Q such that (30) can be written as (20).

Furthermore, the matrices A, B and C from (1) can be found by writing down the dynamics of each element of the state.

Exercise 3 asks you to complete this process, and reproduce the preceding figures.

34.8 Exercises

34.8.1 Exercise 1

Replicate the figure with polynomial income shown above.

The parameters are $r = 0.05, \beta = 1/(1+r), \bar{c} = 1.5, \mu = 2, \sigma = 0.15, T = 50$ and $q = 10^4$.

34.8.2 Exercise 2

Replicate the figure on work and retirement shown above.

The parameters are $r = 0.05, \beta = 1/(1+r), \bar{c} = 4, \mu = 4, \sigma = 0.35, K = 40, T = 60, s = 1$ and $q = 10^4$.

To understand the overall procedure, carefully read the section containing that figure.

Some hints are as follows:

First, in order to make our approach work, we must ensure that both LQ problems have the same state variables and control.

As with previous applications, the control can be set to $u_t = c_t - \bar{c}$.

For `lq_working`, x_t, A, B, C can be chosen as in (26).

- Recall that m_1, m_2 are chosen so that $p(K) = \mu$ and $p(2K) = 0$.

For `lq_retired`, use the same definition of x_t and u_t, but modify A, B, C to correspond to constant income $y_t = s$.

For `lq_retired`, set preferences as in (27).

For `lq_working`, preferences are the same, except that R_f should be replaced by the final value function that emerges from iterating `lq_retired` back to the start of retirement.

With some careful footwork, the simulation can be generated by patching together the simulations from these two separate models.

34.8.3 Exercise 3

Reproduce the figures from the monopolist application given above.

For parameters, use $a_0 = 5, a_1 = 0.5, \sigma = 0.15, \rho = 0.9, \beta = 0.95$ and $c = 2$, while γ varies between 1 and 50 (see figures).

34.9 Solutions

34.9.1 Exercise 1

Here's one solution.

We use some fancy plot commands to get a certain style — feel free to use simpler ones.

The model is an LQ permanent income / life-cycle model with hump-shaped income.

$$y_t = m_1 t + m_2 t^2 + \sigma w_{t+1}$$

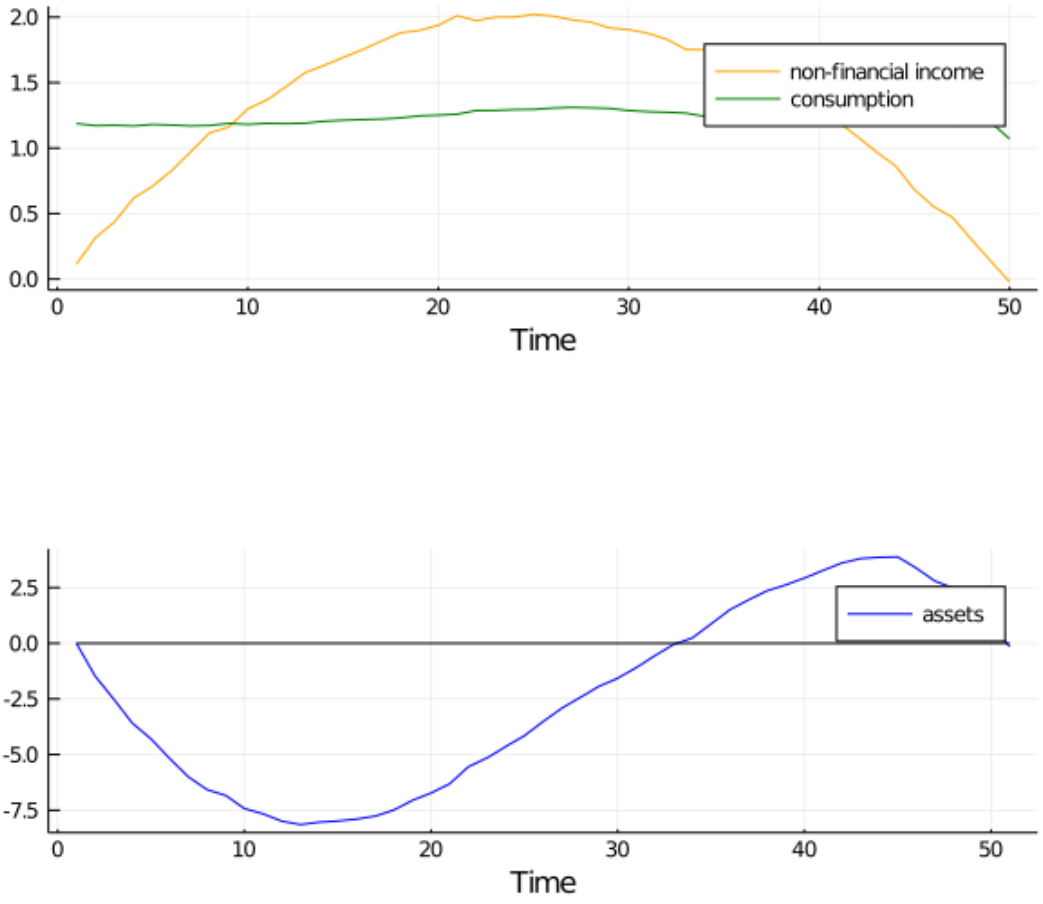
where $\{w_t\}$ is iid $N(0, 1)$ and the coefficients m_1 and m_2 are chosen so that $p(t) = m_1 t + m_2 t^2$ has an inverted U shape with

- $p(0) = 0, p(T/2) = \mu$, and
- $p(T) = 0$.

```
In [5]: # model parameters
        r = 0.05
        β = 1 / (1 + r)
        T = 50
        c = 1.5
        σ = 0.15
        μ = 2
        q = 1e4
        m1 = T * (μ / (T / 2)^2)
        m2 = -(μ / (T / 2)^2)

        # formulate as an LQ problem
        Q = 1.0
        R = zeros(4, 4)
        Rf = zeros(4, 4); Rf[1, 1] = q
        A = [1 + r -c m1 m2;
             0     1      0  0;
             0     1      1  0;
             0     1      2  1]
        B = [-1.0, 0.0, 0.0, 0.0]
        C = [σ, 0.0, 0.0, 0.0]

        # compute solutions and simulate
        lq = QuantEcon.LQ(Q, R, A, B, C; bet = β, capT = T, rf = Rf)
        x0 = [0.0, 1, 0, 0]
```

```
xp, up, wp = compute_sequence(lq, x0)

# convert results back to assets, consumption and income
ap = vec(xp[1, 1:end]) # assets
c = vec(up .+ c̄) # consumption
time = 1:T
income = σ * vec(wp[1, 2:end]) + m1 * time + m2 * time.^2 # income

# plot results
p1 = plot(Vector[income, ap, c, zeros(T + 1)],
          lab = ["non-financial income" "assets" "consumption" ""],
          color = [:orange :blue :green :black],
          xaxis = "Time", layout = (2,1),
          bottom_margin = 20mm, size = (600, 600))
```

Out[5]:



34.9.2 Exercise 2

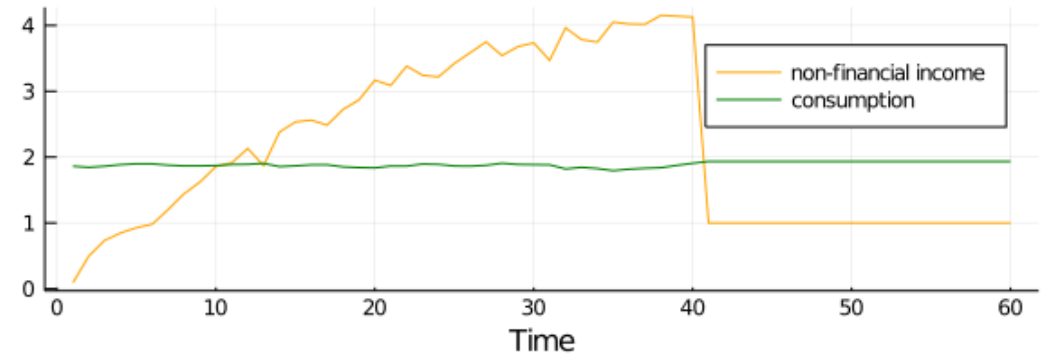
This is a permanent income / life-cycle model with polynomial growth in income over working life followed by a fixed retirement income. The model is solved by combining two LQ pro-

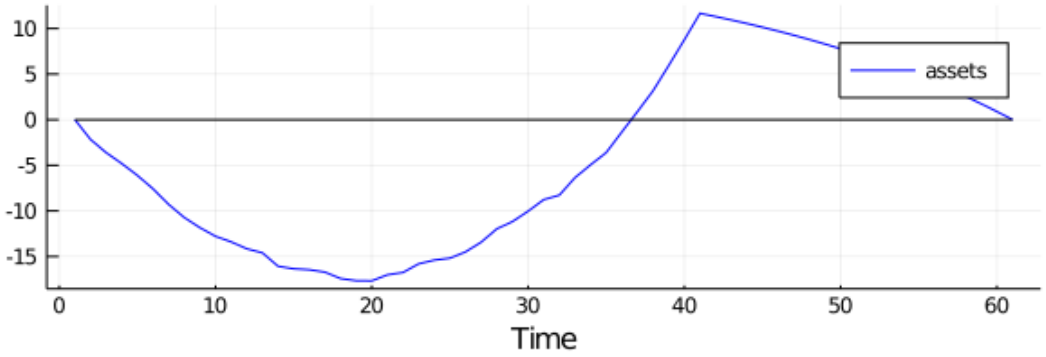
gramming problems as described in the lecture.

In [6]:
```
# model parameters
r = 0.05
β = 1/(1 + r)
T = 60
K = 40
c = 4
σ = 0.35
μ = 4
q = 1e4
s = 1
m1 = 2 * μ / K
m2 = - μ / K^2

# formulate LQ problem 1 (retirement)
Q = 1.0
R = zeros(4, 4)
Rf = zeros(4, 4); Rf[1, 1] = q
A = [1+r  s-c 0 0;
     0     1      0 0;
     0     1      1 0;
     0     1      2 1]
B = [-1.0, 0, 0, 0]
C = zeros(4)

# initialize LQ instance for retired agent
lq_retired = QuantEcon.LQ(Q, R, A, B, C; bet = β, capT = T - K, rf = Rf)

# since update_values!() changes its argument in place, we need another
↪identical
instance
# just to get the correct value function
lq_retired_proxy = QuantEcon.LQ(Q, R, A, B, C; bet = β, capT = T - K, rf =
↪Rf)

# iterate back to start of retirement, record final value function
for i in 1:(T - K)
    update_values!(lq_retired_proxy)
end
Rf2 = lq_retired_proxy.P

# formulate LQ problem 2 (working life)
Q = 1.0
R = zeros(4, 4)
A = [1 + r -c m1 m2;
     0     1      0  0;
     0     1      1  0;
     0     1      2  1]
B = [-1.0, 0, 0, 0]
C = [σ, 0, 0, 0]

# set up working life LQ instance with terminal Rf from lq_retired
lq_working = QuantEcon.LQ(Q, R, A, B, C; bet = β, capT = K, rf = Rf2)

# simulate working state / control paths
```

```
x0 = [0.0, 1, 0, 0]
xp_w, up_w, wp_w = compute_sequence(lq_working, x0)

# simulate retirement paths (note the initial condition)
xp_r, up_r, wp_r = compute_sequence(lq_retired, xp_w[:, end])

# convert results back to assets, consumption and income
xp = [xp_w xp_r[:, 2:end]]
assets = vec(xp[1, :]) # assets

up = [up_w up_r]
c = vec(up .+ c) # consumption

time = 1:K
income_w = σ * vec(wp_w[1, 2:K+1]) + m1 .* time + m2 .* time.^2 # income
income_r = ones(T - K) * s
income = [income_w; income_r]

# plot results
p2 = plot([income, assets, c, zeros(T + 1)],
          lab = ["non-financial income" "assets" "consumption" ""],
          color = [:orange :blue :green :black],
          xaxis = "Time", layout = (2, 1),
          bottom_margin = 20mm, size = (600, 600))
```

Out[6]:





34.9.3 Exercise 3

The first task is to find the matrices A, B, C, Q, R that define the LQ problem.

Recall that $x_t = (\bar{q}_t \;\; q_t \;\; 1)'$, while $u_t = q_{t+1} - q_t$.

Letting $m_0 := (a_0 - c)/2a_1$ and $m_1 := 1/2a_1$, we can write $\bar{q}_t = m_0 + m_1 d_t$, and then, with some manipulation

$$\bar{q}_{t+1} = m_0(1-\rho) + \rho\bar{q}_t + m_1\sigma w_{t+1}$$

By our definition of u_t, the dynamics of q_t are $q_{t+1} = q_t + u_t$.

Using these facts you should be able to build the correct A, B, C matrices (and then check them against those found in the solution code below).

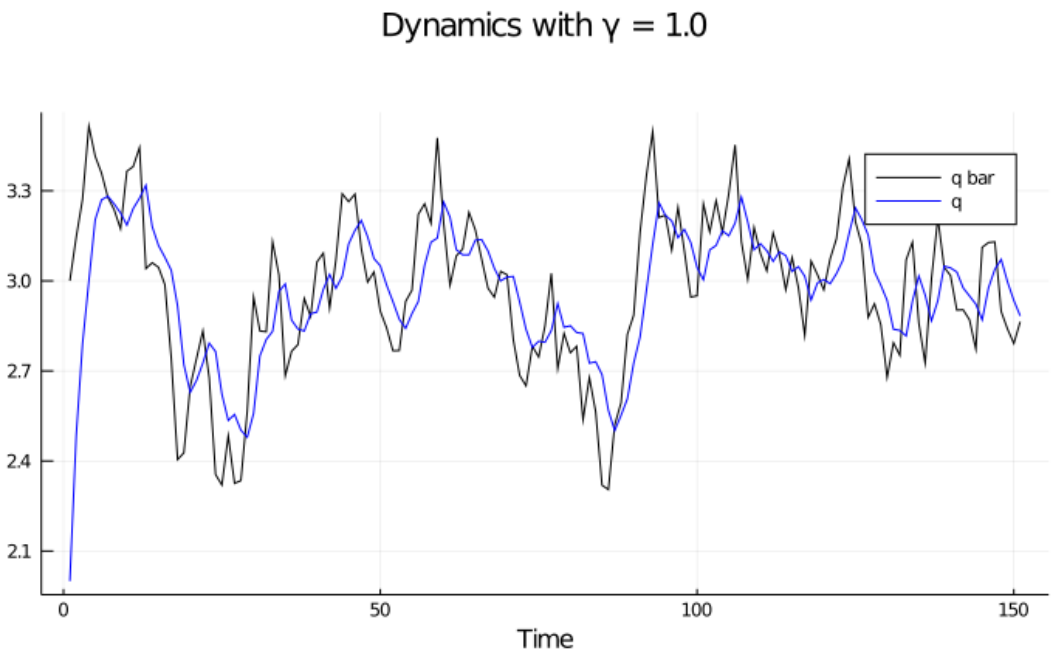
Suitable R, Q matrices can be found by inspecting the objective function, which we repeat here for convenience:

$$\min \mathbb{E}\left\{\sum_{t=0}^{\infty} \beta^t a_1(q_t - \bar{q}_t)^2 + \gamma u_t^2\right\}$$

Our solution code is

In [7]:
```
# model parameters
a0 = 5.0
a1 = 0.5
σ = 0.15
ρ = 0.9
γ = 1.0
β = 0.95
c = 2.0
T = 120

# useful constants
m0 = (a0 - c) / (2 * a1)
m1 = 1 / (2 * a1)

# formulate LQ problem
Q = γ
R = [a1 -a1 0; -a1 a1 0; 0 0 0]
A = [ρ 0 m0 * (1 - ρ); 0 1 0; 0 0 1]

B = [0.0, 1, 0]
C = [m1 * σ, 0, 0]

lq = QuantEcon.LQ(Q, R, A, B, C; bet = β)

# simulate state / control paths
x0 = [m0, 2, 1]
xp, up, wp = compute_sequence(lq, x0, 150)
q̄ = vec(xp[1, :])
q = vec(xp[2, :])

# plot simulation results
p3 = plot(eachindex(q), [q̄ q],
          lab = ["q bar" "q"],
          color = [:black :blue],
          xaxis = "Time", title = "Dynamics with γ = $γ",
          bottom_margin = 20mm, top_margin = 10mm,
          size = (700, 500))
```

Out[7]:


Dynamics with γ = 1.0
q bar
q
3.3
3.0
2.7
2.4
2.1
0
50
100
150
Time

Chapter 35

Optimal Savings I: The Permanent Income Model

35.1 Contents

35.2 Overview

This lecture describes a rational expectations version of the famous permanent income model of Milton Friedman [32].

Robert Hall cast Friedman's model within a linear-quadratic setting [36].

Like Hall, we formulate an infinite-horizon linear-quadratic savings problem.

We use the model as a vehicle for illustrating

- alternative formulations of the *state* of a dynamic system
- the idea of *cointegration*
- impulse response functions
- the idea that changes in consumption are useful as predictors of movements in income

Background readings on the linear-quadratic-Gaussian permanent income model are Hall's [36] and chapter 2 of [68].

35.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

35.3 The Savings Problem

In this section we state and solve the savings and consumption problem faced by the consumer.

35.3.1 Preliminaries

We use a class of stochastic processes called martingales.

A discrete time martingale is a stochastic process (i.e., a sequence of random variables) $\{X_t\}$ with finite mean at each t and satisfying

$$\mathbb{E}_t[X_{t+1}] = X_t, \qquad t = 0, 1, 2, ...$$

Here $\mathbb{E}_t := \mathbb{E}[\cdot \,|\, \mathcal{F}_t]$ is a conditional mathematical expectation conditional on the time t *information set* $\mathcal{F}_t$.

The latter is just a collection of random variables that the modeler declares to be visible at t.

- When not explicitly defined, it is usually understood that $\mathcal{F}_t = \{X_t, X_{t-1}, ..., X_0\}$.

Martingales have the feature that the history of past outcomes provides no predictive power for changes between current and future outcomes.

For example, the current wealth of a gambler engaged in a "fair game" has this property.

One common class of martingales is the family of *random walks*.

A **random walk** is a stochastic process $\{X_t\}$ that satisfies

$$X_{t+1} = X_t + w_{t+1}$$

for some iid zero mean *innovation* sequence $\{w_t\}$.

Evidently X_t can also be expressed as

$$X_t = \sum_{j=1}^{t} w_j + X_0$$

Not every martingale arises as a random walk (see, for example, Wald's martingale).

35.3.2 The Decision Problem

A consumer has preferences over consumption streams that are ordered by the utility functional

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t u(c_t) \right] \tag{1}$$

where

- $\mathbb{E}_t$ is the mathematical expectation conditioned on the consumer's time t information
- c_t is time t consumption
- u is a strictly concave one-period utility function
- $\beta \in (0,1)$ is a discount factor

The consumer maximizes (1) by choosing a consumption, borrowing plan $\{c_t, b_{t+1}\}_{t=0}^{\infty}$ subject to the sequence of budget constraints

$$c_t + b_t = \frac{1}{1+r} b_{t+1} + y_t \quad t \geq 0 \tag{2}$$

Here

- y_t is an exogenous endowment process
- $r > 0$ is a time-invariant risk-free net interest rate
- b_t is one-period risk-free debt maturing at t

The consumer also faces initial conditions b_0 and y_0, which can be fixed or random.

35.3.3 Assumptions

For the remainder of this lecture, we follow Friedman and Hall in assuming that $(1+r)^{-1} = \beta$.

Regarding the endowment process, we assume it has the state-space representation.

$$\begin{aligned} z_{t+1} &= A z_t + C w_{t+1} \\ y_t &= U z_t \end{aligned} \tag{3}$$

where

- $\{w_t\}$ is an iid vector process with $\mathbb{E} w_t = 0$ and $\mathbb{E} w_t w_t' = I$
- the spectral radius of A satisfies $\rho(A) < \sqrt{1/\beta}$
- U is a selection vector that pins down y_t as a particular linear combination of components of z_t.

The restriction on $\rho(A)$ prevents income from growing so fast that discounted geometric sums of some quadratic forms to be described below become infinite.

Regarding preferences, we assume the quadratic utility function

$$u(c_t) = -(c_t - \gamma)^2$$

where γ is a bliss level of consumption

> **Note**
>
> Along with this quadratic utility specification, we allow consumption to be negative. However, by choosing parameters appropriately, we can make the probability that the model generates negative consumption paths over finite time horizons as low as desired.

Finally, we impose the *no Ponzi scheme* condition

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t b_t^2 \right] < \infty \tag{4}$$

This condition rules out an always-borrow scheme that would allow the consumer to enjoy bliss consumption forever.

35.3.4 First-Order Conditions

First-order conditions for maximizing (1) subject to (2) are

$$\mathbb{E}_t[u'(c_{t+1})] = u'(c_t), \qquad t = 0, 1, \ldots \tag{5}$$

These optimality conditions are also known as *Euler equations*.

If you're not sure where they come from, you can find a proof sketch in the appendix.

With our quadratic preference specification, (5) has the striking implication that consumption follows a martingale:

$$\mathbb{E}_t[c_{t+1}] = c_t \tag{6}$$

(In fact quadratic preferences are *necessary* for this conclusion Section **??**)

One way to interpret (6) is that consumption will change only when "new information" about permanent income is revealed.

These ideas will be clarified below.

35.3.5 The Optimal Decision Rule

Now let's deduce the optimal decision rule Section **??**.

> **Note**
>
> One way to solve the consumer's problem is to apply *dynamic programming* as in this lecture. We do this later. But first we use an alternative approach that is revealing and shows the work that dynamic programming does for us behind the scenes.

In doing so, we need to combine

1. the optimality condition (6)
2. the period-by-period budget constraint (2), and
3. the boundary condition (4)

To accomplish this, observe first that (4) implies $\lim_{t \to \infty} \beta^{\frac{t}{2}} b_{t+1} = 0$.

Using this restriction on the debt path and solving (2) forward yields

$$b_t = \sum_{j=0}^{\infty} \beta^j (y_{t+j} - c_{t+j}) \tag{7}$$

Take conditional expectations on both sides of (7) and use the martingale property of consumption and the *law of iterated expectations* to deduce

$$b_t = \sum_{j=0}^{\infty} \beta^j \mathbb{E}_t [y_{t+j}] - \frac{c_t}{1-\beta} \tag{8}$$

Expressed in terms of c_t we get

$$c_t = (1-\beta) \left[\sum_{j=0}^{\infty} \beta^j \mathbb{E}_t [y_{t+j}] - b_t \right] = \frac{r}{1+r} \left[\sum_{j=0}^{\infty} \beta^j \mathbb{E}_t [y_{t+j}] - b_t \right] \tag{9}$$

where the last equality uses $(1+r)\beta = 1$.

These last two equations assert that consumption equals *economic income*

- **financial wealth** equals $-b_t$
- **non-financial wealth** equals $\sum_{j=0}^{\infty} \beta^j \mathbb{E}_t [y_{t+j}]$
- **total wealth** equals the sum of financial and non-financial wealth
- A **marginal propensity to consume out of total wealth** equals the interest factor $\frac{r}{1+r}$
- **economic income** equals
  - a constant marginal propensity to consume times the sum of non-financial wealth and financial wealth
  - the amount the consumer can consume while leaving its wealth intact

Responding to the State

The *state* vector confronting the consumer at t is $\begin{bmatrix} b_t & z_t \end{bmatrix}$.

Here

- z_t is an *exogenous* component, unaffected by consumer behavior
- b_t is an *endogenous* component (since it depends on the decision rule)

Note that z_t contains all variables useful for forecasting the consumer's future endowment.

It is plausible that current decisions c_t and b_{t+1} should be expressible as functions of z_t and b_t.

This is indeed the case.

In fact, from this discussion we see that

$$\sum_{j=0}^{\infty} \beta^j \mathbb{E}_t [y_{t+j}] = \mathbb{E}_t \left[\sum_{j=0}^{\infty} \beta^j y_{t+j} \right] = U(I - \beta A)^{-1} z_t$$

Combining this with (9) gives

$$c_t = \frac{r}{1+r} \left[U(I - \beta A)^{-1} z_t - b_t \right] \tag{10}$$

Using this equality to eliminate c_t in the budget constraint (2) gives

$$\begin{aligned} b_{t+1} &= (1+r)(b_t + c_t - y_t) \\ &= (1+r)b_t + r[U(I-\beta A)^{-1}z_t - b_t] - (1+r)Uz_t \\ &= b_t + U[r(I-\beta A)^{-1} - (1+r)I]z_t \\ &= b_t + U(I-\beta A)^{-1}(A-I)z_t \end{aligned}$$

To get from the second last to the last expression in this chain of equalities is not trivial.

A key is to use the fact that $(1+r)\beta = 1$ and $(I-\beta A)^{-1} = \sum_{j=0}^{\infty}\beta^j A^j$.

We've now successfully written c_t and b_{t+1} as functions of b_t and z_t.

A State-Space Representation

We can summarize our dynamics in the form of a linear state-space system governing consumption, debt and income:

$$\begin{aligned} z_{t+1} &= Az_t + Cw_{t+1} \\ b_{t+1} &= b_t + U[(I-\beta A)^{-1}(A-I)]z_t \\ y_t &= Uz_t \\ c_t &= (1-\beta)[U(I-\beta A)^{-1}z_t - b_t] \end{aligned} \tag{11}$$

To write this more succinctly, let

$$x_t = \begin{bmatrix} z_t \\ b_t \end{bmatrix}, \quad \tilde{A} = \begin{bmatrix} A & 0 \\ U(I-\beta A)^{-1}(A-I) & 1 \end{bmatrix}, \quad \tilde{C} = \begin{bmatrix} C \\ 0 \end{bmatrix}$$

and

$$\tilde{U} = \begin{bmatrix} U & 0 \\ (1-\beta)U(I-\beta A)^{-1} & -(1-\beta) \end{bmatrix}, \quad \tilde{y}_t = \begin{bmatrix} y_t \\ c_t \end{bmatrix}$$

Then we can express equation (11) as

$$\begin{aligned} x_{t+1} &= \tilde{A}x_t + \tilde{C}w_{t+1} \\ \tilde{y}_t &= \tilde{U}x_t \end{aligned} \tag{12}$$

We can use the following formulas from linear state space models to compute population mean $\mu_t = \mathbb{E}x_t$ and covariance $\Sigma_t := \mathbb{E}[(x_t - \mu_t)(x_t - \mu_t)']$

$$\mu_{t+1} = \tilde{A}\mu_t \quad \text{with} \quad \mu_0 \text{ given} \tag{13}$$

$$\Sigma_{t+1} = \tilde{A}\Sigma_t\tilde{A}' + \tilde{C}\tilde{C}' \quad \text{with} \quad \Sigma_0 \text{ given} \tag{14}$$

We can then compute the mean and covariance of $\tilde{y}_t$ from

$$\begin{aligned} \mu_{y,t} &= \tilde{U}\mu_t \\ \Sigma_{y,t} &= \tilde{U}\Sigma_t\tilde{U}' \end{aligned} \tag{15}$$

A Simple Example with iid Income

To gain some preliminary intuition on the implications of (11), let's look at a highly stylized example where income is just iid.

(Later examples will investigate more realistic income streams)

In particular, let $\{w_t\}_{t=1}^{\infty}$ be iid and scalar standard normal, and let

$$z_t = \begin{bmatrix} z_t^1 \\ 1 \end{bmatrix}, \quad A = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, \quad U = \begin{bmatrix} 1 & \mu \end{bmatrix}, \quad C = \begin{bmatrix} \sigma \\ 0 \end{bmatrix}$$

Finally, let $b_0 = z_0^1 = 0$.

Under these assumptions we have $y_t = \mu + \sigma w_t \sim N(\mu, \sigma^2)$.

Further, if you work through the state space representation, you will see that

$$b_t = -\sigma \sum_{j=1}^{t-1} w_j$$

$$c_t = \mu + (1-\beta)\sigma \sum_{j=1}^{t} w_j$$

Thus income is iid and debt and consumption are both Gaussian random walks.

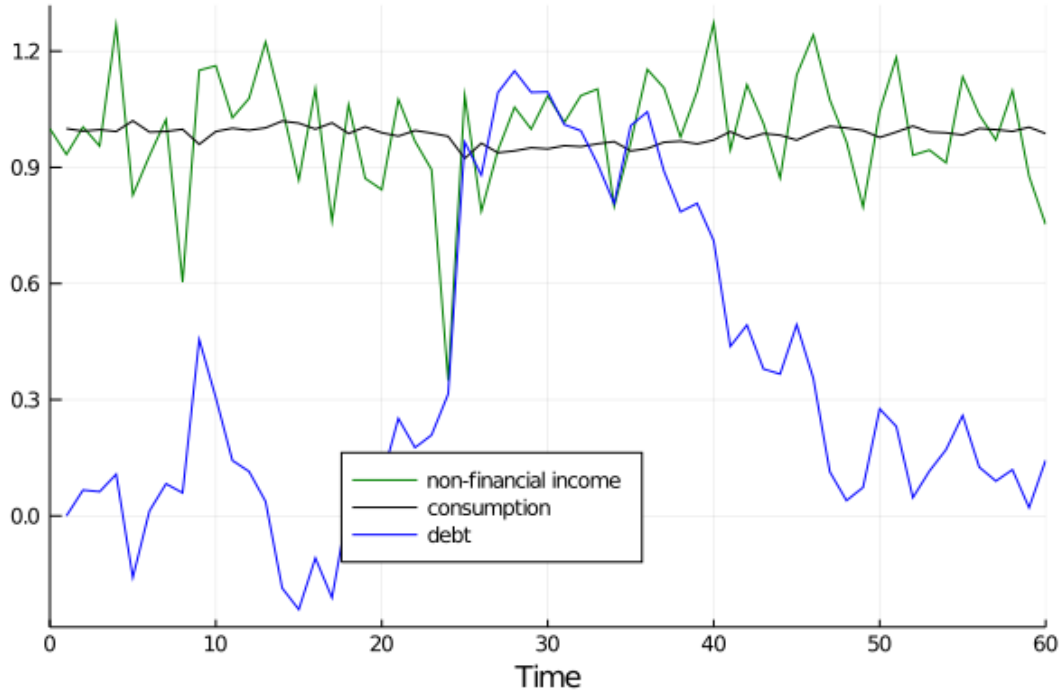
Defining assets as $-b_t$, we see that assets are just the cumulative sum of unanticipated incomes prior to the present date.

The next figure shows a typical realization with $r = 0.05$, $\mu = 1$, and $\sigma = 0.15$

In [3]:
```
using Plots, Random
gr(fmt=:png);

Random.seed!(42)

const r = 0.05
const β = 1.0 / (1.0 + r)
const T = 60
const σ = 0.15
const μ = 1.0

function time_path2()
    w = randn(T+1)
    w[1] =  0.0
    b = zeros(T+1)
    for t=2:T+1
        b[t] = sum(w[1:t])
    end
    b .*= -σ
    c = μ .+ (1.0 - β) .* (σ .* w .- b)
    return w, b, c
end

w, b, c = time_path2()
p = plot(0:T, μ .+ σ .* w, color = :green, label = "non-financial income")
plot!(c, color = :black, label = "consumption")
```

```
plot!(b, color = :blue, label = "debt")
plot!(xlabel = "Time", linewidth = 2, alpha = 0.7,
      xlims = (0, T), legend = :bottom)
```

Out[3]:

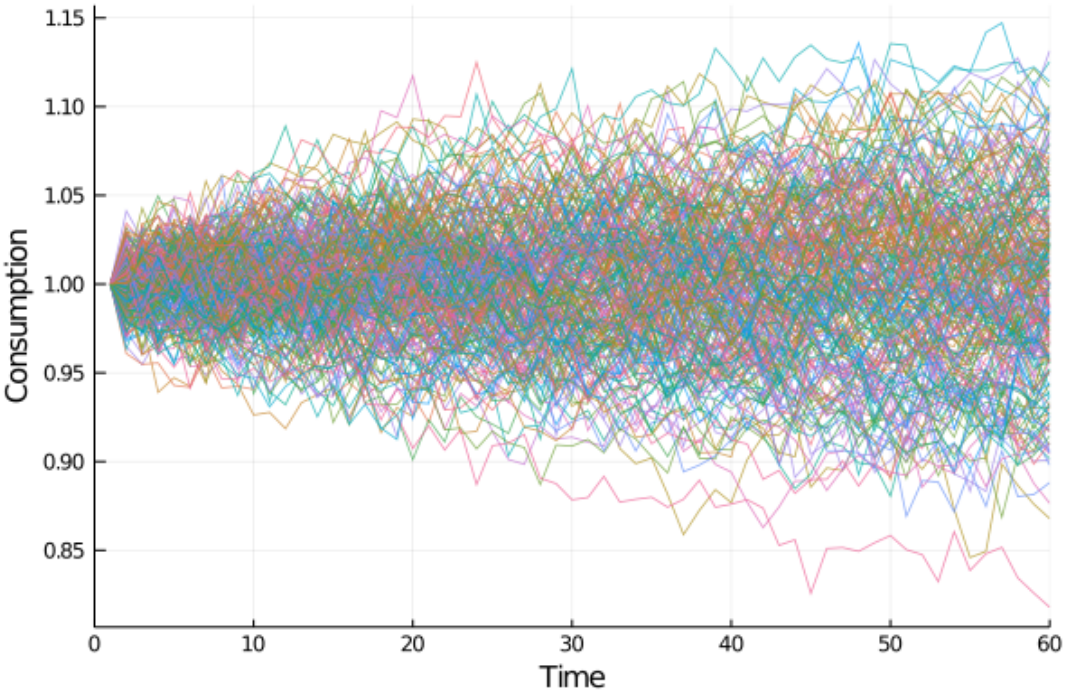


Observe that consumption is considerably smoother than income.

The figure below shows the consumption paths of 250 consumers with independent income streams

In [4]:
```
time_paths = []
n = 250

for i in 1:n
    push!(time_paths, time_path2()[3])
end

p = plot(time_paths, linewidth = 0.8, alpha=0.7, legend = :none)
plot!(xlabel = "Time", ylabel = "Consumption", xlims = (0, T))
```

Out[4]:



35.4 Alternative Representations

In this section we shed more light on the evolution of savings, debt and consumption by representing their dynamics in several different ways.

35.4.1 Hall's Representation

Hall [36] suggested an insightful way to summarize the implications of LQ permanent income theory.

First, to represent the solution for b_t, shift (9) forward one period and eliminate b_{t+1} by using (2) to obtain

$$c_{t+1} = (1-\beta)\sum_{j=0}^{\infty}\beta^j \mathbb{E}_{t+1}[y_{t+j+1}] - (1-\beta)\left[\beta^{-1}(c_t + b_t - y_t)\right]$$

If we add and subtract $\beta^{-1}(1-\beta)\sum_{j=0}^{\infty}\beta^j \mathbb{E}_t y_{t+j}$ from the right side of the preceding equation and rearrange, we obtain

$$c_{t+1} - c_t = (1-\beta)\sum_{j=0}^{\infty}\beta^j\left\{\mathbb{E}_{t+1}[y_{t+j+1}] - \mathbb{E}_t[y_{t+j+1}]\right\} \tag{16}$$

The right side is the time $t+1$ *innovation to the expected present value* of the endowment process $\{y_t\}$.

We can represent the optimal decision rule for (c_t, b_{t+1}) in the form of (16) and (8), which we repeat:

$$b_t = \sum_{j=0}^{\infty} \beta^j \mathbb{E}_t[y_{t+j}] - \frac{1}{1-\beta} c_t \tag{17}$$

Equation (17) asserts that the consumer's debt due at t equals the expected present value of its endowment minus the expected present value of its consumption stream.

A high debt thus indicates a large expected present value of surpluses $y_t - c_t$.

Recalling again our discussion on forecasting geometric sums, we have

$$\begin{aligned}
\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} &= U(I - \beta A)^{-1} z_t \\
\mathbb{E}_{t+1} \sum_{j=0}^{\infty} \beta^j y_{t+j+1} &= U(I - \beta A)^{-1} z_{t+1} \\
\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j+1} &= U(I - \beta A)^{-1} A z_t
\end{aligned}$$

Using these formulas together with (3) and substituting into (16) and (17) gives the following representation for the consumer's optimum decision rule:

$$\begin{aligned}
c_{t+1} &= c_t + (1-\beta) U(I - \beta A)^{-1} C w_{t+1} \\
b_t &= U(I - \beta A)^{-1} z_t - \frac{1}{1-\beta} c_t \\
y_t &= U z_t \\
z_{t+1} &= A z_t + C w_{t+1}
\end{aligned} \tag{18}$$

Representation (18) makes clear that

- The state can be taken as (c_t, z_t).
  - The endogenous part is c_t and the exogenous part is z_t.
  - Debt b_t has disappeared as a component of the state because it is encoded in c_t.
- Consumption is a random walk with innovation $(1-\beta) U(I - \beta A)^{-1} C w_{t+1}$.
  - This is a more explicit representation of the martingale result in (6).

35.4.2 Cointegration

Representation (18) reveals that the joint process $\{c_t, b_t\}$ possesses the property that Engle and Granger [27] called cointegration.

Cointegration is a tool that allows us to apply powerful results from the theory of stationary stochastic processes to (certain transformations of) nonstationary models.

To apply cointegration in the present context, suppose that z_t is asymptotically stationary Section **??**.

Despite this, both c_t and b_t will be non-stationary because they have unit roots (see (11) for b_t).

Nevertheless, there is a linear combination of c_t, b_t that *is* asymptotically stationary.

In particular, from the second equality in (18) we have

$$(1-\beta)b_t + c_t = (1-\beta)U(I-\beta A)^{-1}z_t \tag{19}$$

Hence the linear combination $(1-\beta)b_t + c_t$ is asymptotically stationary.

Accordingly, Granger and Engle would call $\begin{bmatrix}(1-\beta) & 1\end{bmatrix}$ a **cointegrating vector** for the state.

When applied to the nonstationary vector process $\begin{bmatrix}b_t & c_t\end{bmatrix}'$, it yields a process that is asymptotically stationary.

Equation (19) can be rearranged to take the form

$$(1-\beta)b_t + c_t = (1-\beta)\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j}. \tag{20}$$

Equation (20) asserts that the *cointegrating residual* on the left side equals the conditional expectation of the geometric sum of future incomes on the right Section **??**.

35.4.3 Cross-Sectional Implications

Consider again (18), this time in light of our discussion of distribution dynamics in the lecture on linear systems.

The dynamics of c_t are given by

$$c_{t+1} = c_t + (1-\beta)U(I-\beta A)^{-1}Cw_{t+1} \tag{21}$$

or

$$c_t = c_0 + \sum_{j=1}^{t} \hat{w}_j \quad \text{for} \quad \hat{w}_{t+1} := (1-\beta)U(I-\beta A)^{-1}Cw_{t+1}$$

The unit root affecting c_t causes the time t variance of c_t to grow linearly with t.

In particular, since $\{\hat{w}_t\}$ is iid, we have

$$\mathrm{Var}[c_t] = \mathrm{Var}[c_0] + t\,\hat{\sigma}^2 \tag{22}$$

where

$$\hat{\sigma}^2 := (1-\beta)^2 U(I-\beta A)^{-1}CC'(I-\beta A')^{-1}U'$$

When $\hat{\sigma} > 0$, $\{c_t\}$ has no asymptotic distribution.

Let's consider what this means for a cross-section of ex ante identical consumers born at time 0.

Let the distribution of c_0 represent the cross-section of initial consumption values.

Equation (22) tells us that the variance of c_t increases over time at a rate proportional to t.

A number of different studies have investigated this prediction and found some support for it (see, e.g., [21], [101]).

35.4.4 Impulse Response Functions

Impulse response functions measure responses to various impulses (i.e., temporary shocks).

The impulse response function of $\{c_t\}$ to the innovation $\{w_t\}$ is a box.

In particular, the response of c_{t+j} to a unit increase in the innovation w_{t+1} is $(1-\beta)U(I-\beta A)^{-1}C$ for all $j \geq 1$.

35.4.5 Moving Average Representation

It's useful to express the innovation to the expected present value of the endowment process in terms of a moving average representation for income y_t.

The endowment process defined by (3) has the moving average representation

$$y_{t+1} = d(L)w_{t+1} \tag{23}$$

where

- $d(L) = \sum_{j=0}^{\infty} d_j L^j$ for some sequence d_j, where L is the lag operator Section **??**
- at time t, the consumer has an information set Section **??** $w^t = [w_t, w_{t-1}, ...]$

Notice that

$$y_{t+j} - \mathbb{E}_t[y_{t+j}] = d_0 w_{t+j} + d_1 w_{t+j-1} + \cdots + d_{j-1} w_{t+1}$$

It follows that

$$\mathbb{E}_{t+1}[y_{t+j}] - \mathbb{E}_t[y_{t+j}] = d_{j-1} w_{t+1} \tag{24}$$

Using (24) in (16) gives

$$c_{t+1} - c_t = (1-\beta)d(\beta)w_{t+1} \tag{25}$$

The object $d(\beta)$ is the **present value of the moving average coefficients** in the representation for the endowment process y_t.

35.5 Two Classic Examples

We illustrate some of the preceding ideas with two examples.

In both examples, the endowment follows the process $y_t = z_{1t} + z_{2t}$ where

$$\begin{bmatrix} z_{1t+1} \\ z_{2t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} z_{1t} \\ z_{2t} \end{bmatrix} + \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \begin{bmatrix} w_{1t+1} \\ w_{2t+1} \end{bmatrix}$$

Here

- w_{t+1} is an iid 2×1 process distributed as $N(0, I)$
- z_{1t} is a permanent component of y_t
- z_{2t} is a purely transitory component of y_t

35.5.1 Example 1

Assume as before that the consumer observes the state z_t at time t.

In view of (18) we have

$$c_{t+1} - c_t = \sigma_1 w_{1t+1} + (1-\beta)\sigma_2 w_{2t+1} \tag{26}$$

Formula (26) shows how an increment $\sigma_1 w_{1t+1}$ to the permanent component of income z_{1t+1} leads to

- a permanent one-for-one increase in consumption and
- no increase in savings $-b_{t+1}$

But the purely transitory component of income $\sigma_2 w_{2t+1}$ leads to a permanent increment in consumption by a fraction $1-\beta$ of transitory income.

The remaining fraction β is saved, leading to a permanent increment in $-b_{t+1}$.

Application of the formula for debt in (11) to this example shows that

$$b_{t+1} - b_t = -z_{2t} = -\sigma_2 w_{2t} \tag{27}$$

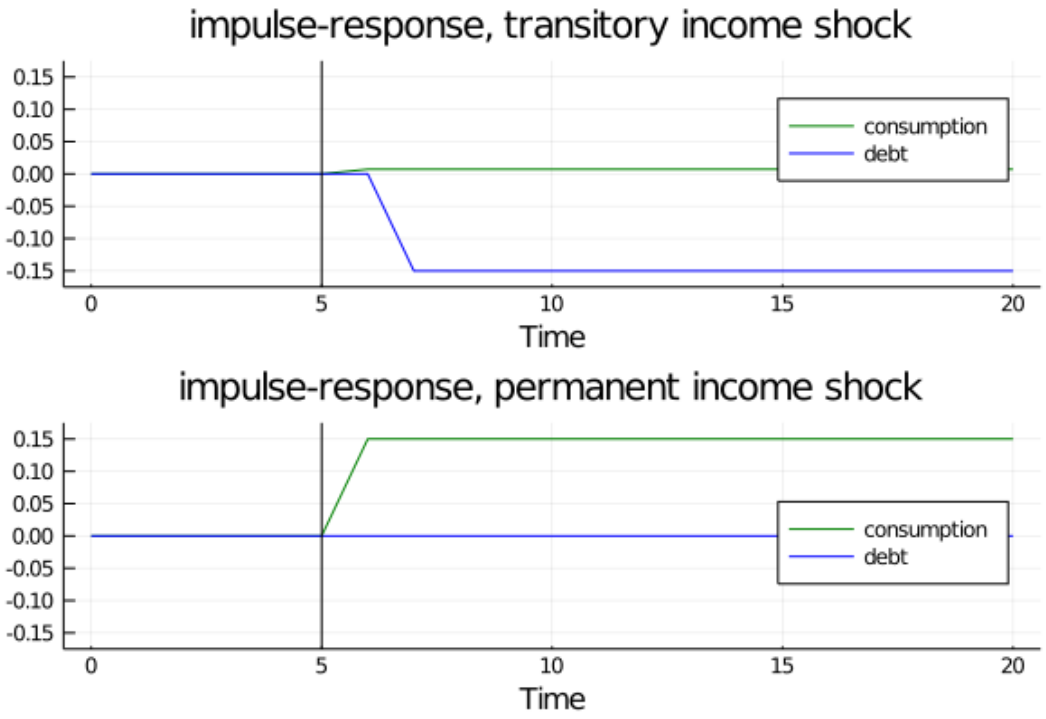
This confirms that none of $\sigma_1 w_{1t}$ is saved, while all of $\sigma_2 w_{2t}$ is saved.

The next figure illustrates these very different reactions to transitory and permanent income shocks using impulse-response functions

In [5]:
```
const r = 0.05
const β = 1.0 / (1.0 + r)
const T2 = 20  # Time horizon
const S = 5   # Impulse date
const σ1 = 0.15
const σ2 = 0.15


function time_path(permanent = false)
    w1 = zeros(T2+1)
    w2 = similar(w1)
    b = similar(w1)
    c = similar(w1)

    if permanent === false
        w2[S+2] = 1.0
    else
        w1[S+2] = 1.0
    end

    for t=2:T2
        b[t+1] = b[t] - σ2 * w2[t]
        c[t+1] = c[t] + σ1 * w1[t+1] + (1 - β) * σ2 * w2[t+1]
    end

    return b, c
end

L = 0.175
```

```
b1, c1 = time_path(false)
b2, c2 = time_path(true)
p = plot(0:T2, [c1 c2 b1 b2], layout = (2, 1),
        color = [:green :green :blue :blue],
        label = ["consumption" "consumption" "debt" "debt"])
t = ["impulse-response, transitory income shock"
     "impulse-response, permanent income shock"]
plot!(title = reshape(t, 1, length(t)), xlabel = "Time", ylims = (-L, L),
      legend = [:topright :bottomright])
vline!([S S], color = :black, layout = (2, 1), label = "")
```

Out[5]:



35.5.2 Example 2

Assume now that at time t the consumer observes y_t, and its history up to t, but not z_t.

Under this assumption, it is appropriate to use an *innovation representation* to form A, C, U in (18).

The discussion in sections 2.9.1 and 2.11.3 of [68] shows that the pertinent state space representation for y_t is

$$\begin{bmatrix} y_{t+1} \\ a_{t+1} \end{bmatrix} = \begin{bmatrix} 1 & -(1-K) \\ 0 & 0 \end{bmatrix} \begin{bmatrix} y_t \\ a_t \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} a_{t+1}$$

$$y_t = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} y_t \\ a_t \end{bmatrix}$$

where

- $K :=$ the stationary Kalman gain

- $a_t := y_t - E[y_t \mid y_{t-1}, \ldots, y_0]$

In the same discussion in [68] it is shown that $K \in [0, 1]$ and that K increases as σ_1/σ_2 does.

In other words, K increases as the ratio of the standard deviation of the permanent shock to that of the transitory shock increases.

Please see first look at the Kalman filter.

Applying formulas (18) implies

$$c_{t+1} - c_t = [1 - \beta(1 - K)]a_{t+1} \tag{28}$$

where the endowment process can now be represented in terms of the univariate innovation to y_t as

$$y_{t+1} - y_t = a_{t+1} - (1 - K)a_t \tag{29}$$

Equation (29) indicates that the consumer regards

- fraction K of an innovation a_{t+1} to y_{t+1} as *permanent*
- fraction $1 - K$ as purely transitory

The consumer permanently increases his consumption by the full amount of his estimate of the permanent part of a_{t+1}, but by only $(1 - \beta)$ times his estimate of the purely transitory part of a_{t+1}.

Therefore, in total he permanently increments his consumption by a fraction $K + (1 - \beta)(1 - K) = 1 - \beta(1 - K)$ of a_{t+1}.

He saves the remaining fraction $\beta(1 - K)$.

According to equation (29), the first difference of income is a first-order moving average.

Equation (28) asserts that the first difference of consumption is iid.

Application of formula to this example shows that

$$b_{t+1} - b_t = (K - 1)a_t \tag{30}$$

This indicates how the fraction K of the innovation to y_t that is regarded as permanent influences the fraction of the innovation that is saved.

35.6 Further Reading

The model described above significantly changed how economists think about consumption.

While Hall's model does a remarkably good job as a first approximation to consumption data, it's widely believed that it doesn't capture important aspects of some consumption/savings data.

For example, liquidity constraints and precautionary savings appear to be present sometimes.

Further discussion can be found in, e.g., [37], [84], [20], [15].

35.7 Appendix: the Euler Equation

Where does the first order condition (5) come from?

Here we'll give a proof for the two period case, which is representative of the general argument.

The finite horizon equivalent of the no-Ponzi condition is that the agent cannot end her life in debt, so $b_2 = 0$.

From the budget constraint (2) we then have

$$c_0 = \frac{b_1}{1+r} - b_0 + y_0 \quad \text{and} \quad c_1 = y_1 - b_1$$

Here b_0 and y_0 are given constants.

Substituting these constraints into our two period objective $u(c_0) + \beta \mathbb{E}_0[u(c_1)]$ gives

$$\max_{b_1} \left\{ u\left(\frac{b_1}{R} - b_0 + y_0\right) + \beta \, \mathbb{E}_0[u(y_1 - b_1)] \right\}$$

You will be able to verify that the first order condition is

$$u'(c_0) = \beta R \, \mathbb{E}_0[u'(c_1)]$$

Using $\beta R = 1$ gives (5) in the two period case.

The proof for the general case is similar.

Footnotes

[1] A linear marginal utility is essential for deriving (6) from (5). Suppose instead that we had imposed the following more standard assumptions on the utility function: $u'(c) > 0, u''(c) < 0, u'''(c) > 0$ and required that $c \geq 0$. The Euler equation remains (5). But the fact that $u''' < 0$ implies via Jensen's inequality that $\mathbb{E}_t[u'(c_{t+1})] > u'(\mathbb{E}_t[c_{t+1}])$. This inequality together with (5) implies that $\mathbb{E}_t[c_{t+1}] > c_t$ (consumption is said to be a 'submartingale'), so that consumption stochastically diverges to $+\infty$. The consumer's savings also diverge to $+\infty$.

[2] An optimal decision rule is a map from current state into current actions—in this case, consumption.

[3] Representation (3) implies that $d(L) = U(I - AL)^{-1}C$.

[4] This would be the case if, for example, the spectral radius of A is strictly less than one.

[5] A moving average representation for a process y_t is said to be **fundamental** if the linear space spanned by y^t is equal to the linear space spanned by w^t. A time-invariant innovations representation, attained via the Kalman filter, is by construction fundamental.

[6] See [58], [65], [66] for interesting applications of related ideas.

Chapter 36

Optimal Savings II: LQ Techniques

36.1 Contents

Co-authored with Chase Coleman.

36.2 Overview

This lecture continues our analysis of the linear-quadratic (LQ) permanent income model of savings and consumption.

As we saw in our previous lecture on this topic, Robert Hall [36] used the LQ permanent income model to restrict and interpret intertemporal comovements of nondurable consumption, nonfinancial income, and financial wealth.

For example, we saw how the model asserts that for any covariance stationary process for nonfinancial income

- consumption is a random walk
- financial wealth has a unit root and is cointegrated with consumption

Other applications use the same LQ framework.

For example, a model isomorphic to the LQ permanent income model has been used by Robert Barro [8] to interpret intertemporal comovements of a government's tax collections, its expenditures net of debt service, and its public debt.

This isomorphism means that in analyzing the LQ permanent income model, we are in effect also analyzing the Barro tax smoothing model.

It is just a matter of appropriately relabeling the variables in Hall's model.

In this lecture, we'll

- show how the solution to the LQ permanent income model can be obtained using LQ control methods

- represent the model as a linear state space system as in this lecture
- apply QuantEcon's LSS type to characterize statistical features of the consumer's optimal consumption and borrowing plans

We'll then use these characterizations to construct a simple model of cross-section wealth and consumption dynamics in the spirit of Truman Bewley [13].

(Later we'll study other Bewley models—see this lecture)

The model will prove useful for illustrating concepts such as

- stationarity
- ergodicity
- ensemble moments and cross section observations

36.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")

In [2]: using LinearAlgebra, Statistics
```

36.3 Introduction

Let's recall the basic features of the model discussed in permanent income model.

Consumer preferences are ordered by

$$E_0 \sum_{t=0}^{\infty} \beta^t u(c_t) \tag{1}$$

where $u(c) = -(c - \gamma)^2$.

The consumer maximizes (1) by choosing a consumption, borrowing plan $\{c_t, b_{t+1}\}_{t=0}^{\infty}$ subject to the sequence of budget constraints

$$c_t + b_t = \frac{1}{1+r} b_{t+1} + y_t, \quad t \geq 0 \tag{2}$$

and the no-Ponzi condition

$$E_0 \sum_{t=0}^{\infty} \beta^t b_t^2 < \infty \tag{3}$$

The interpretation of all variables and parameters are the same as in the previous lecture.

We continue to assume that $(1+r)\beta = 1$.

The dynamics of $\{y_t\}$ again follow the linear state space model

$$\begin{aligned} z_{t+1} &= A z_t + C w_{t+1} \\ y_t &= U z_t \end{aligned} \tag{4}$$

The restrictions on the shock process and parameters are the same as in our previous lecture.

36.3.1 Digression on a useful isomorphism

The LQ permanent income model of consumption is mathematically isomorphic with a version of Barro's [8] model of tax smoothing.

In the LQ permanent income model

- the household faces an exogenous process of nonfinancial income
- the household wants to smooth consumption across states and time

In the Barro tax smoothing model

- a government faces an exogenous sequence of government purchases (net of interest payments on its debt)
- a government wants to smooth tax collections across states and time

If we set

- T_t, total tax collections in Barro's model to consumption c_t in the LQ permanent income model
- G_t, exogenous government expenditures in Barro's model to nonfinancial income y_t in the permanent income model
- B_t, government risk-free one-period assets falling due in Barro's model to risk-free one period consumer debt b_t falling due in the LQ permanent income model
- R, the gross rate of return on risk-free one-period government debt in Barro's model to the gross rate of return $1 + r$ on financial assets in the permanent income model of consumption

then the two models are mathematically equivalent.

All characterizations of a $\{c_t, y_t, b_t\}$ in the LQ permanent income model automatically apply to a $\{T_t, G_t, B_t\}$ process in the Barro model of tax smoothing.

See consumption and tax smoothing models for further exploitation of an isomorphism between consumption and tax smoothing models.

36.3.2 A specification of the nonfinancial income process

For the purposes of this lecture, let's assume $\{y_t\}$ is a second-order univariate autoregressive process:

$$y_{t+1} = \alpha + \rho_1 y_t + \rho_2 y_{t-1} + \sigma w_{t+1}$$

We can map this into the linear state space framework in (4), as discussed in our lecture on linear models.

To do so we take

$$z_t = \begin{bmatrix} 1 \\ y_t \\ y_{t-1} \end{bmatrix}, \quad A = \begin{bmatrix} 1 & 0 & 0 \\ \alpha & \rho_1 & \rho_2 \\ 0 & 1 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ \sigma \\ 0 \end{bmatrix}, \quad \text{and} \quad U = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$$

36.4 The LQ Approach

Previously we solved the permanent income model by solving a system of linear expectational difference equations subject to two boundary conditions.

Here we solve the same model using LQ methods based on dynamic programming.

After confirming that answers produced by the two methods agree, we apply QuantEcon's LSS type to illustrate features of the model.

Why solve a model in two distinct ways?

Because by doing so we gather insights about the structure of the model.

Our earlier approach based on solving a system of expectational difference equations brought to the fore the role of the consumer's expectations about future nonfinancial income.

On the other hand, formulating the model in terms of an LQ dynamic programming problem reminds us that

- finding the state (of a dynamic programming problem) is an art, and
- iterations on a Bellman equation implicitly jointly solve both a forecasting problem and a control problem

36.4.1 The LQ Problem

Recall from our lecture on LQ theory that the optimal linear regulator problem is to choose a decision rule for u_t to minimize

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t \{x_t' R x_t + u_t' Q u_t\},$$

subject to x_0 given and the law of motion

$$x_{t+1} = \tilde{A} x_t + \tilde{B} u_t + \tilde{C} w_{t+1}, \qquad t \geq 0, \tag{5}$$

where w_{t+1} is iid with mean vector zero and $\mathbb{E} w_t w_t' = I$.

The tildes in $\tilde{A}, \tilde{B}, \tilde{C}$ are to avoid clashing with notation in (4).

The value function for this problem is $v(x) = -x' P x - d$, where

- P is the unique positive semidefinite solution of the corresponding matrix Riccati equation.
- The scalar d is given by $d = \beta(1-\beta)^{-1} \text{trace}(P \tilde{C} \tilde{C}')$.

The optimal policy is $u_t = -F x_t$, where $F := \beta(Q + \beta \tilde{B}' P \tilde{B})^{-1} \tilde{B}' P \tilde{A}$.

Under an optimal decision rule F, the state vector x_t evolves according to $x_{t+1} = (\tilde{A} - \tilde{B}F) x_t + \tilde{C} w_{t+1}$.

36.4.2 Mapping into the LQ framework

To map into the LQ framework, we'll use

$$x_t := \begin{bmatrix} z_t \\ b_t \end{bmatrix} = \begin{bmatrix} 1 \\ y_t \\ y_{t-1} \\ b_t \end{bmatrix}$$

as the state vector and $u_t := c_t - \gamma$ as the control.

With this notation and $U_\gamma := \begin{bmatrix} \gamma & 0 & 0 \end{bmatrix}$, we can write the state dynamics as in (5) when

$$\tilde{A} := \begin{bmatrix} A & 0 \\ (1+r)(U_\gamma - U) & 1+r \end{bmatrix} \quad \tilde{B} := \begin{bmatrix} 0 \\ 1+r \end{bmatrix} \quad \text{and} \quad \tilde{C} := \begin{bmatrix} C \\ 0 \end{bmatrix} w_{t+1}$$

Please confirm for yourself that, with these definitions, the LQ dynamics (5) match the dynamics of z_t and b_t described above.

To map utility into the quadratic form $x_t' R x_t + u_t' Q u_t$ we can set

- $Q := 1$ (remember that we are minimizing) and
- $R :=$ a 4×4 matrix of zeros

However, there is one problem remaining.

We have no direct way to capture the non-recursive restriction (3) on the debt sequence $\{b_t\}$ from within the LQ framework.

To try to enforce it, we're going to use a trick: put a small penalty on b_t^2 in the criterion function.

In the present setting, this means adding a small entry $\epsilon > 0$ in the $(4, 4)$ position of R.

That will induce a (hopefully) small approximation error in the decision rule.

We'll check whether it really is small numerically soon.

36.5 Implementation

Let's write some code to solve the model.

One comment before we start is that the bliss level of consumption γ in the utility function has no effect on the optimal decision rule.

We saw this in the previous lecture permanent income.

The reason is that it drops out of the Euler equation for consumption.

In what follows we set it equal to unity.

36.5.1 The exogenous noinfinancial income process

First we create the objects for the optimal linear regulator

In [3]:
```
using QuantEcon, LinearAlgebra
using Plots
gr(fmt=:png);

# Set parameters
```

```
α, β, ρ1, ρ2, σ = 10.0, 0.95, 0.9, 0.0, 1.0

R = 1 / β
A = [1.0 0.0 0.0;
       α  ρ1  ρ2;
     0.0 1.0 0.0]
C = [0.0; σ; 0.0]''
G = [0.0 1.0 0.0]

# Form LinearStateSpace system and pull off steady state moments
μ_z0 = [1.0, 0.0, 0.0]
Σ_z0 = zeros(3, 3)
Lz = LSS(A, C, G, mu_0=μ_z0, Sigma_0=Σ_z0)
μ_z, μ_y, Σ_z, Σ_y = stationary_distributions(Lz)

# Mean vector of state for the savings problem
mxo = [μ_z; 0.0]

# Create stationary covariance matrix of x -- start everyone off at b=0
a1 = zeros(3, 1)
aa = hcat(Σ_z, a1)
bb = zeros(1, 4)
sxo = vcat(aa, bb)

# These choices will initialize the state vector of an individual at zero
↪debt
# and the ergodic distribution of the endowment process. Use these to create
# the Bewley economy.
mxbewley = mxo
sxbewley = sxo
```

```
Out[3]: 4×4 Array{Float64,2}:
 0.0  0.0      0.0      0.0
 0.0  5.26316  4.73684  0.0
 0.0  4.73684  5.26316  0.0
 0.0  0.0      0.0      0.0
```

The next step is to create the matrices for the LQ system

```
In [4]: A12 = zeros(3,1)
ALQ_l = hcat(A, A12)
ALQ_r = [0 -R 0 R]
ALQ = vcat(ALQ_l, ALQ_r)

RLQ = [0.0 0.0 0.0 0.0;
       0.0 0.0 0.0 0.0;
       0.0 0.0 0.0 0.0;
       0.0 0.0 0.0 1e-9]

QLQ = 1.0
BLQ = [0.0; 0.0; 0.0; R]
CLQ = [0.0; σ; 0.0; 0.0]
β_LQ = β
```

```
Out[4]: 0.95
```

Let's print these out and have a look at them

```
In [5]: println("A = $ALQ")
        println("B = $BLQ")
        println("R = $RLQ")
        println("Q = $QLQ")
```

```
A = [1.0 0.0 0.0 0.0; 10.0 0.9 0.0 0.0; 0.0 1.0 0.0 0.0; 0.0 -1.
↪0526315789473684 0.0
1.0526315789473684]
B = [0.0, 0.0, 0.0, 1.0526315789473684]
R = [0.0 0.0 0.0 0.0; 0.0 0.0 0.0 0.0; 0.0 0.0 0.0 0.0; 0.0 0.0 0.0 1.0e-9]
Q = 1.0
```

Now create the appropriate instance of an LQ model

```
In [6]: LQPI = QuantEcon.LQ(QLQ, RLQ, ALQ, BLQ, CLQ, bet=β_LQ);
```

We'll save the implied optimal policy function soon and compare with what we get by employing an alternative solution method.

```
In [7]: P, F, d = stationary_values(LQPI)    #  compute value function and
↪decision rule
        ABF = ALQ - BLQ * F    #  form closed loop system
```

```
Out[7]: 4×4 Array{Float64,2}:
          1.0      0.0       0.0  0.0
         10.0      0.9       0.0  0.0
          0.0      1.0       0.0  0.0
         68.9655  -0.689655  0.0  1.0
```

36.5.2 Comparison with the difference equation approach

In our first lecture on the infinite horizon permanent income problem we used a different solution method.

The method was based around

- deducing the Euler equations that are the first-order conditions with respect to consumption and savings
- using the budget constraints and boundary condition to complete a system of expectational linear difference equations
- solving those equations to obtain the solution

Expressed in state space notation, the solution took the form

$$
\begin{aligned}
z_{t+1} &= Az_t + Cw_{t+1} \\
b_{t+1} &= b_t + U[(I - \beta A)^{-1}(A - I)]z_t \\
y_t &= Uz_t \\
c_t &= (1 - \beta)[U(I - \beta A)^{-1}z_t - b_t]
\end{aligned}
$$

Now we'll apply the formulas in this system

```
In [8]: # Use the above formulas to create the optimal policies for b_{t+1} and c_t
        b_pol = G * (inv(I - β * A)) * (A - I)
        c_pol = (1 - β) * (G * inv(I - β * A))

        # Create the A matrix for a LinearStateSpace instance
        A_LSS1 = vcat(A, b_pol)
        A_LSS2 = [0, 0, 0, 1]
        A_LSS = hcat(A_LSS1, A_LSS2)

        # Create the C matrix for LSS methods
        C_LSS = vcat(C, 0)

        # Create the G matrix for LSS methods
        G_LSS1 = vcat(G, c_pol)
        G_LSS2 = vcat(0, -(1 - β))
        G_LSS = hcat(G_LSS1, G_LSS2)

       # Use the following values to start everyone off at b=0, initial incomes zero
        μ_0 = [1.0, 0.0, 0.0, 0.0]
        Σ_0 = zeros(4, 4)
```

```
Out[8]: 4×4 Array{Float64,2}:
         0.0  0.0  0.0  0.0
         0.0  0.0  0.0  0.0
         0.0  0.0  0.0  0.0
         0.0  0.0  0.0  0.0
```

A_LSS calculated as we have here should equal ABF calculated above using the LQ model

```
In [9]: ABF - A_LSS
```

```
Out[9]: 4×4 Array{Float64,2}:
           0.0         0.0         0.0   0.0
           0.0         0.0         0.0   0.0
           0.0         0.0         0.0   0.0
          -9.51248e-6  9.51248e-8  0.0  -2.0e-8
```

Now compare pertinent elements of c_pol and F

```
In [10]: println(c_pol, -F)
```

```
[65.51724137931033 0.34482758620689685 0.0][65.51723234245394 0.344827676575457
↪-0.0
-0.050000018999992145]
```

We have verified that the two methods give the same solution.

Now let's create instances of the LSS type and use it to do some interesting experiments.

To do this, we'll use the outcomes from our second method.

36.6 Two Example Economies

In the spirit of Bewley models [13], we'll generate panels of consumers.

The examples differ only in the initial states with which we endow the consumers.

All other parameter values are kept the same in the two examples

- In the first example, all consumers begin with zero nonfinancial income and zero debt.
  - The consumers are thus *ex ante* identical.
- In the second example, while all begin with zero debt, we draw their initial income levels from the invariant distribution of financial income.
  - Consumers are *ex ante* heterogeneous.

In the first example, consumers' nonfinancial income paths display pronounced transients early in the sample

- these will affect outcomes in striking ways.

Those transient effects will not be present in the second example.

We use methods affiliated with the LSS type to simulate the model.

36.6.1 First set of initial conditions

We generate 25 paths of the exogenous non-financial income process and the associated optimal consumption and debt paths.

In a first set of graphs, darker lines depict a particular sample path, while the lighter lines describe 24 other paths.

A second graph plots a collection of simulations against the population distribution that we extract from the LSS instance LSS.

Comparing sample paths with population distributions at each date t is a useful exercise—see our discussion of the laws of large numbers.

```
In [11]: lss = LSS(A_LSS, C_LSS, G_LSS, mu_0=μ_0, Sigma_0=Σ_0);
```

36.6.2 Population and sample panels

In the code below, we use the LSS type to

- compute and plot population quantiles of the distributions of consumption and debt for a population of consumers
- simulate a group of 25 consumers and plot sample paths on the same graph as the population distribution

```
In [12]: function income_consumption_debt_series(A, C, G, μ_0, Σ_0, T = 150,
  ↪npaths = 25)

             lss = LSS(A, C, G, mu_0=μ_0, Sigma_0=Σ_0)

             # simulation/Moment Parameters
             moment_generator = moment_sequence(lss)
```

```
    # simulate various paths
    bsim = zeros(npaths, T)
    csim = zeros(npaths, T)
    ysim = zeros(npaths, T)

    for i in 1:npaths
        sims = simulate(lss,T)
        bsim[i, :] = sims[1][end, :]
        csim[i, :] = sims[2][2, :]
        ysim[i, :] = sims[2][1, :]
    end

    # get the moments
    cons_mean = zeros(T)
    cons_var = similar(cons_mean)
    debt_mean = similar(cons_mean)
    debt_var = similar(cons_mean)
    for (idx, t) = enumerate(moment_generator)
        (μ_x, μ_y, Σ_x, Σ_y) = t
        cons_mean[idx], cons_var[idx] = μ_y[2], Σ_y[2, 2]
        debt_mean[idx], debt_var[idx] = μ_x[4], Σ_x[4, 4]
        idx == T && break
    end
    return bsim, csim, ysim, cons_mean, cons_var, debt_mean, debt_var
end

function consumption_income_debt_figure(bsim, csim, ysim)

    # get T
    T =  size(bsim, 2)

    # create first figure
    xvals = 1:T

    # plot consumption and income
    plt_1 = plot(csim[1,:], label="c", color=:blue, lw=2)
    plot!(plt_1, ysim[1, :], label="y", color=:green, lw=2)
    plot!(plt_1, csim', alpha=0.1, color=:blue, label="")
    plot!(plt_1, ysim', alpha=0.1, color=:green, label="")
    plot!(plt_1, title="Nonfinancial Income, Consumption, and Debt",
          xlabel="t", ylabel="y and c",legend=:bottomright)

    # plot debt
    plt_2 = plot(bsim[1,: ], label="b", color=:red, lw=2)
    plot!(plt_2, bsim', alpha=0.1, color=:red,label="")
    plot!(plt_2, xlabel="t", ylabel="debt",legend=:bottomright)

    plot(plt_1, plt_2, layout=(2,1), size=(800,600))
end

function consumption_debt_fanchart(csim, cons_mean, cons_var,
                                   bsim, debt_mean, debt_var)
    # get T
    T =  size(bsim, 2)

    # create percentiles of cross-section distributions
    cmean = mean(cons_mean)
    c90 = 1.65 * sqrt.(cons_var)
```

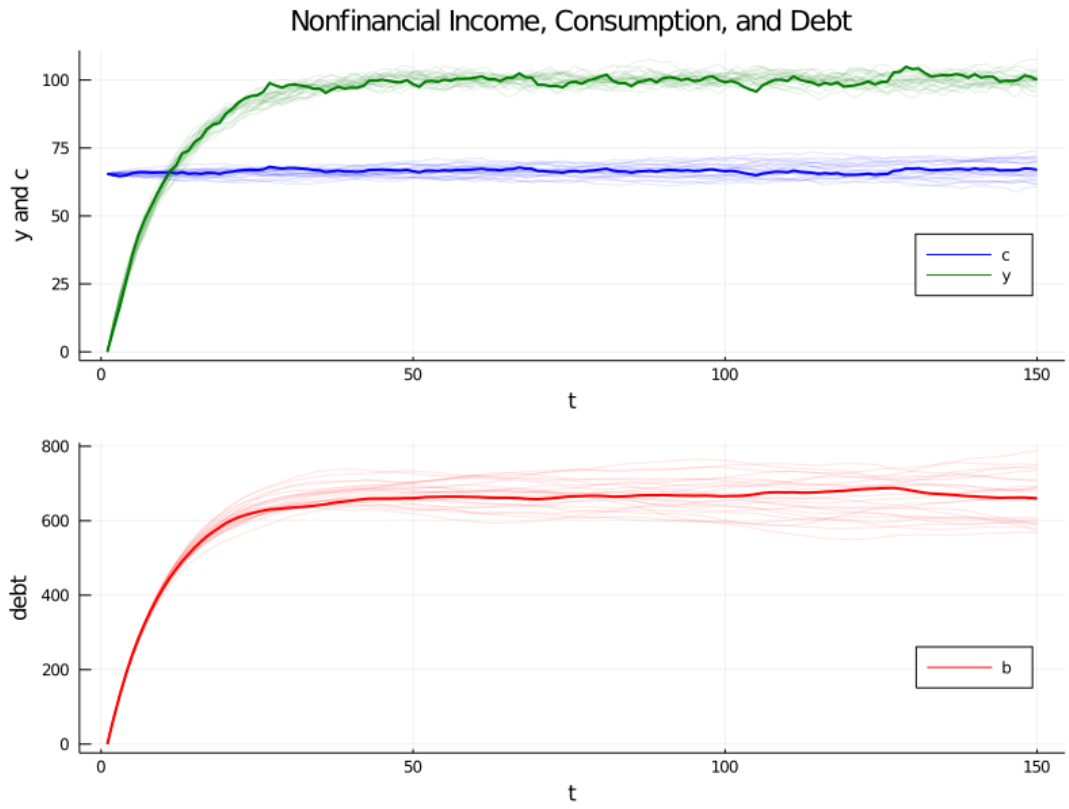
```
            c95 = 1.96 * sqrt.(cons_var)
            c_perc_95p, c_perc_95m = cons_mean + c95, cons_mean - c95
            c_perc_90p, c_perc_90m = cons_mean + c90, cons_mean - c90

            # create percentiles of cross-section distributions
            dmean = mean(debt_mean)
            d90 = 1.65 * sqrt.(debt_var)
            d95 = 1.96 * sqrt.(debt_var)
            d_perc_95p, d_perc_95m = debt_mean + d95, debt_mean - d95
            d_perc_90p, d_perc_90m = debt_mean + d90, debt_mean - d90

            xvals = 1:T

            # first fanchart
            plt_1=plot(xvals, cons_mean, color=:black, lw=2, label="")
            plot!(plt_1, xvals, Array(csim'), color=:black, alpha=0.25, label="")
            plot!(xvals, fillrange=[c_perc_95m, c_perc_95p], alpha=0.25, color=:
↪blue, label="")
            plot!(xvals, fillrange=[c_perc_90m, c_perc_90p], alpha=0.25, color=:
↪red, label="")
            plot!(plt_1, title="Consumption/Debt over time",
                  ylim=(cmean-15, cmean+15), ylabel="consumption")

            # second fanchart
            plt_2=plot(xvals, debt_mean, color=:black, lw=2,label="")
            plot!(plt_2, xvals, Array(bsim'), color=:black, alpha=0.25,label="")
            plot!(xvals, fillrange=[d_perc_95m, d_perc_95p], alpha=0.25, color=:
↪blue,label="")
            plot!(xvals, fillrange=[d_perc_90m, d_perc_90p], alpha=0.25, color=:
↪red,label="")
            plot!(plt_2, ylabel="debt", xlabel="t")

            plot(plt_1, plt_2, layout=(2,1), size=(800,600))
        end
```

```
Out[12]: consumption_debt_fanchart (generic function with 1 method)
```

Now let's create figures with initial conditions of zero for y_0 and b_0

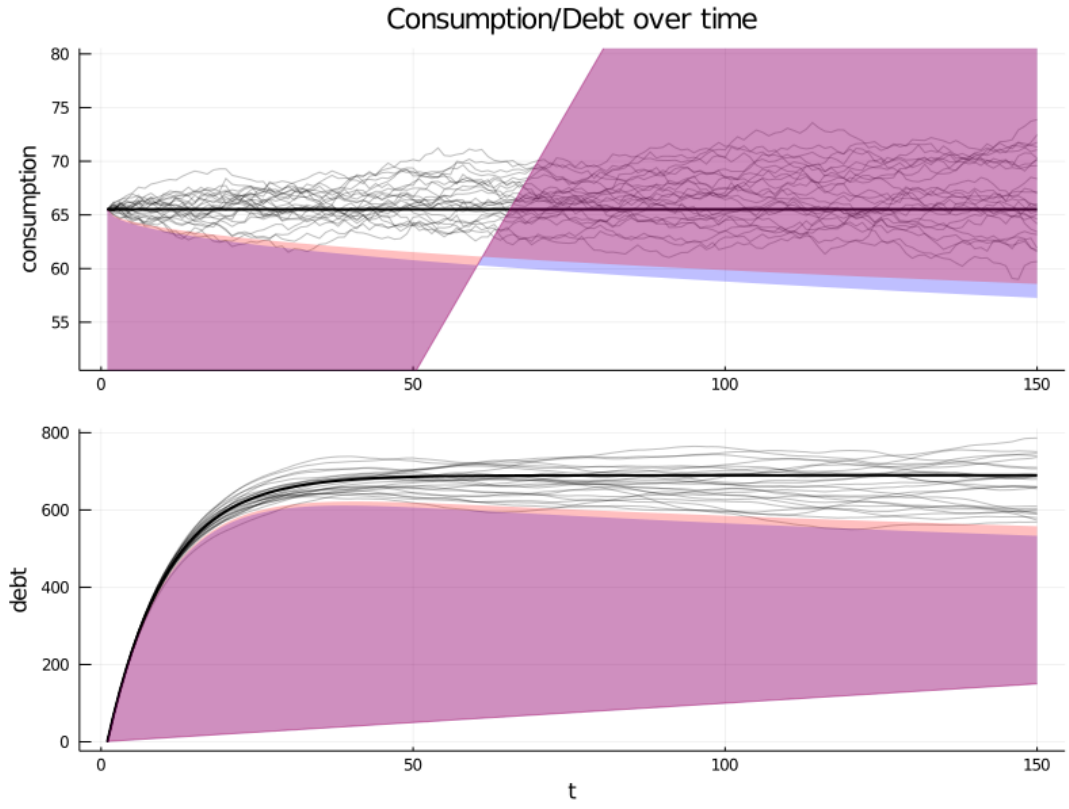
```
In [13]: out = income_consumption_debt_series(A_LSS, C_LSS, G_LSS, μ_0, Σ_0)
         bsim0, csim0, ysim0 = out[1:3]
         cons_mean0, cons_var0, debt_mean0, debt_var0 = out[4:end]

         consumption_income_debt_figure(bsim0, csim0, ysim0)
```

```
Out[13]:
```




```
In [14]: consumption_debt_fanchart(csim0, cons_mean0, cons_var0,
                                   bsim0, debt_mean0, debt_var0)
```

Out[14]:



Here is what is going on in the above graphs.

For our simulation, we have set initial conditions $b_0 = y_{-1} = y_{-2} = 0$.

Because $y_{-1} = y_{-2} = 0$, nonfinancial income y_t starts far below its stationary mean $\mu_{y,\infty}$ and rises early in each simulation.

Recall from the previous lecture that we can represent the optimal decision rule for consumption in terms of the **co-integrating relationship**.

$$(1-\beta)b_t + c_t = (1-\beta)E_t \sum_{j=0}^{\infty} \beta^j y_{t+j} \tag{6}$$

So at time 0 we have

$$c_0 = (1-\beta)E_0 \sum_{t=0}^{\infty} \beta^j y_t$$

This tells us that consumption starts at the income that would be paid by an annuity whose value equals the expected discounted value of nonfinancial income at time $t = 0$.

To support that level of consumption, the consumer borrows a lot early and consequently builds up substantial debt.

In fact, he or she incurs so much debt that eventually, in the stochastic steady state, he consumes less each period than his nonfinancial income.

He uses the gap between consumption and nonfinancial income mostly to service the interest payments due on his debt.

Thus, when we look at the panel of debt in the accompanying graph, we see that this is a group of *ex ante* identical people each of whom starts with zero debt.

All of them accumulate debt in anticipation of rising nonfinancial income.

They expect their nonfinancial income to rise toward the invariant distribution of income, a consequence of our having started them at $y_{-1} = y_{-2} = 0$.

Cointegration residual

The following figure plots realizations of the left side of (6), which, as discussed in our last lecture, is called the **cointegrating residual**.

As mentioned above, the right side can be thought of as an annuity payment on the expected present value of future income $E_t \sum_{j=0}^{\infty} \beta^j y_{t+j}$.

Early along a realization, c_t is approximately constant while $(1-\beta)b_t$ and $(1-\beta)E_t \sum_{j=0}^{\infty} \beta^j y_{t+j}$ both rise markedly as the household's present value of income and borrowing rise pretty much together.

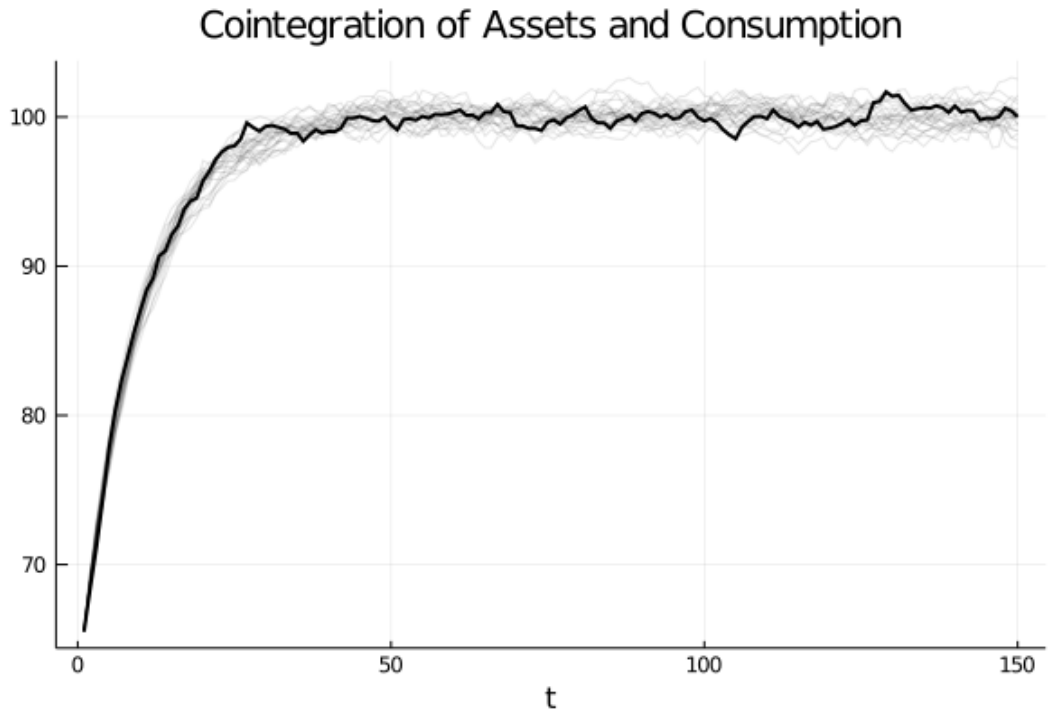
This example illustrates the following point: the definition of cointegration implies that the cointegrating residual is *asymptotically* covariance stationary, not *covariance stationary*.

The cointegrating residual for the specification with zero income and zero debt initially has a notable transient component that dominates its behavior early in the sample.

By altering initial conditions, we shall remove this transient in our second example to be presented below

In [15]:
```
function cointegration_figure(bsim, csim)
    # create figure
    plot((1 - β) * bsim[1, :] + csim[1, :], color=:black,lw=2,label="")
    plot!((1 - β) * bsim' + csim', color=:black, alpha=.1,label="")
    plot!(title="Cointegration of Assets and Consumption", xlabel="t")
end

cointegration_figure(bsim0, csim0)
```

Out[15]:



36.6.3 A "borrowers and lenders" closed economy

When we set $y_{-1} = y_{-2} = 0$ and $b_0 = 0$ in the preceding exercise, we make debt "head north" early in the sample.

Average debt in the cross-section rises and approaches asymptote.

We can regard these as outcomes of a "small open economy" that borrows from abroad at the fixed gross interest rate $R = r + 1$ in anticipation of rising incomes.

So with the economic primitives set as above, the economy converges to a steady state in which there is an excess aggregate supply of risk-free loans at a gross interest rate of R.

This excess supply is filled by "foreigner lenders" willing to make those loans.

We can use virtually the same code to rig a "poor man's Bewley [13] model" in the following way

- as before, we start everyone at $b_0 = 0$

- But instead of starting everyone at $y_{-1} = y_{-2} = 0$, we draw $\begin{bmatrix} y_{-1} \\ y_{-2} \end{bmatrix}$ from the invariant distribution of the $\{y_t\}$ process

This rigs a closed economy in which people are borrowing and lending with each other at a gross risk-free interest rate of $R = \beta^{-1}$.

Across the group of people being analyzed, risk-free loans are in zero excess supply.

We have arranged primitives so that $R = \beta^{-1}$ clears the market for risk-free loans at zero aggregate excess supply.

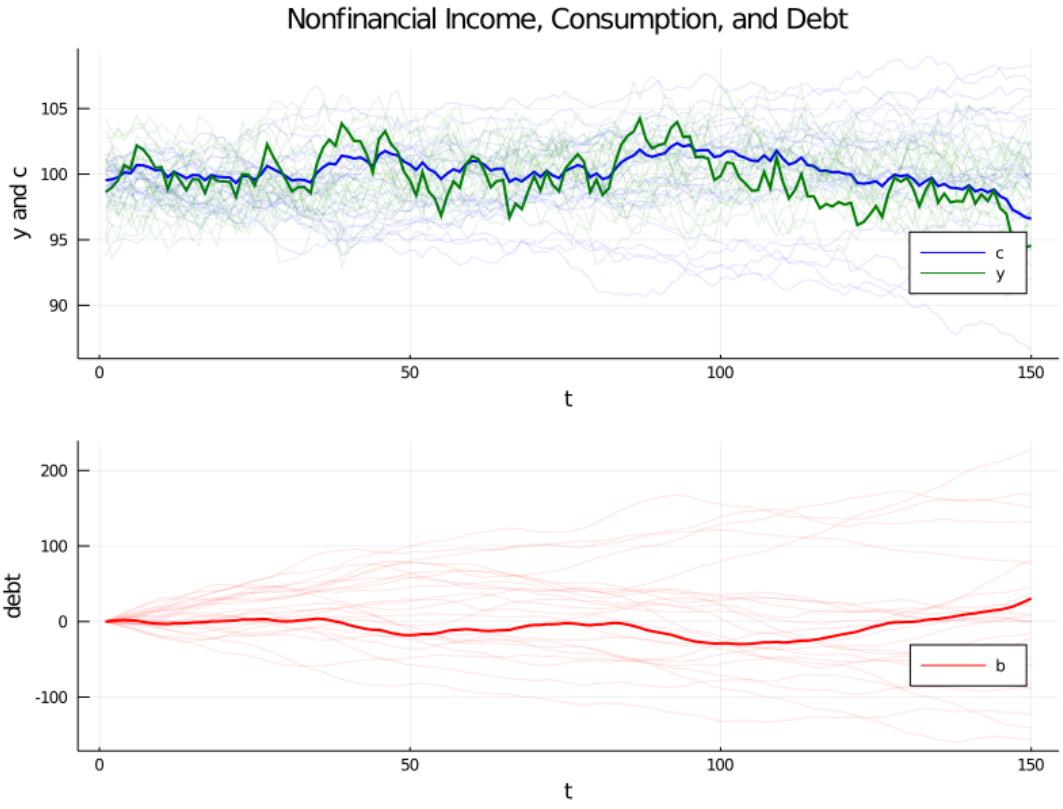
So the risk-free loans are being made from one person to another within our closed set of agent.

There is no need for foreigners to lend to our group.

Let's have a look at the corresponding figures

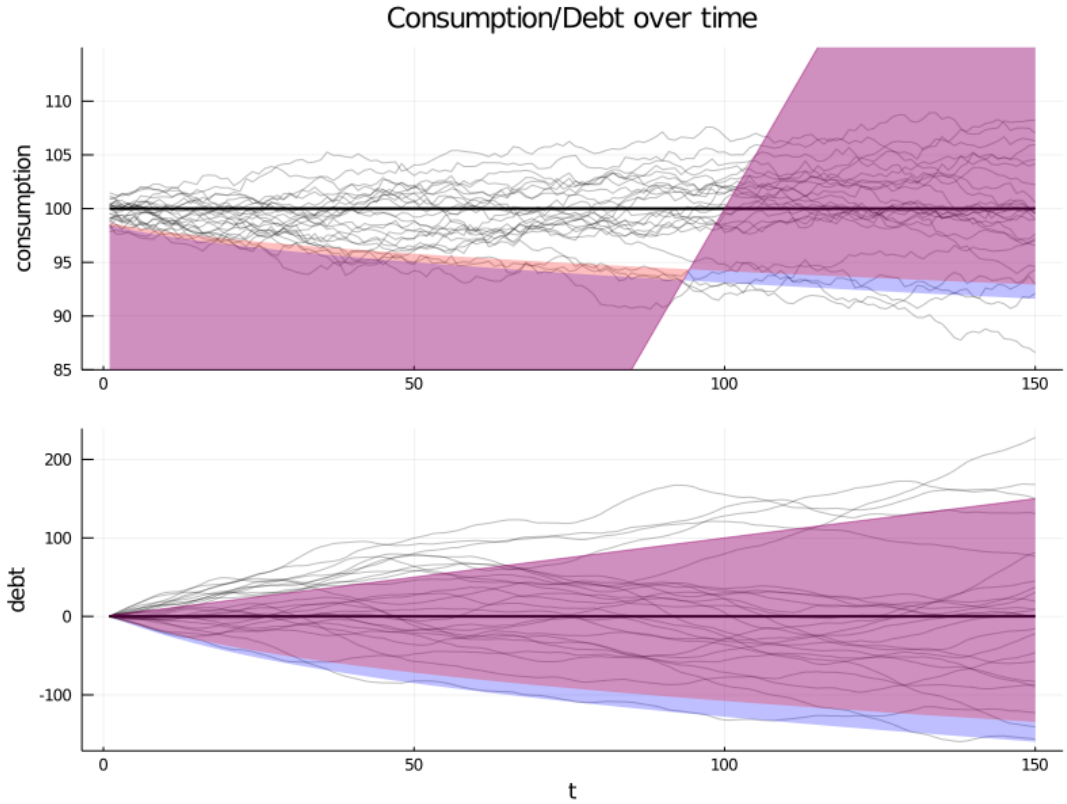
```
In [16]: out = income_consumption_debt_series(A_LSS, C_LSS, G_LSS, mxbewley,
  ↪sxbewley)
         bsimb, csimb, ysimb = out[1:3]
         cons_meanb, cons_varb, debt_meanb, debt_varb = out[4:end]

         consumption_income_debt_figure(bsimb, csimb, ysimb)
```

Out[16]:




```
In [17]: consumption_debt_fanchart(csimb, cons_meanb, cons_varb,
                                   bsimb, debt_meanb, debt_varb)
```

Out[17]:



The graphs confirm the following outcomes:

- As before, the consumption distribution spreads out over time.

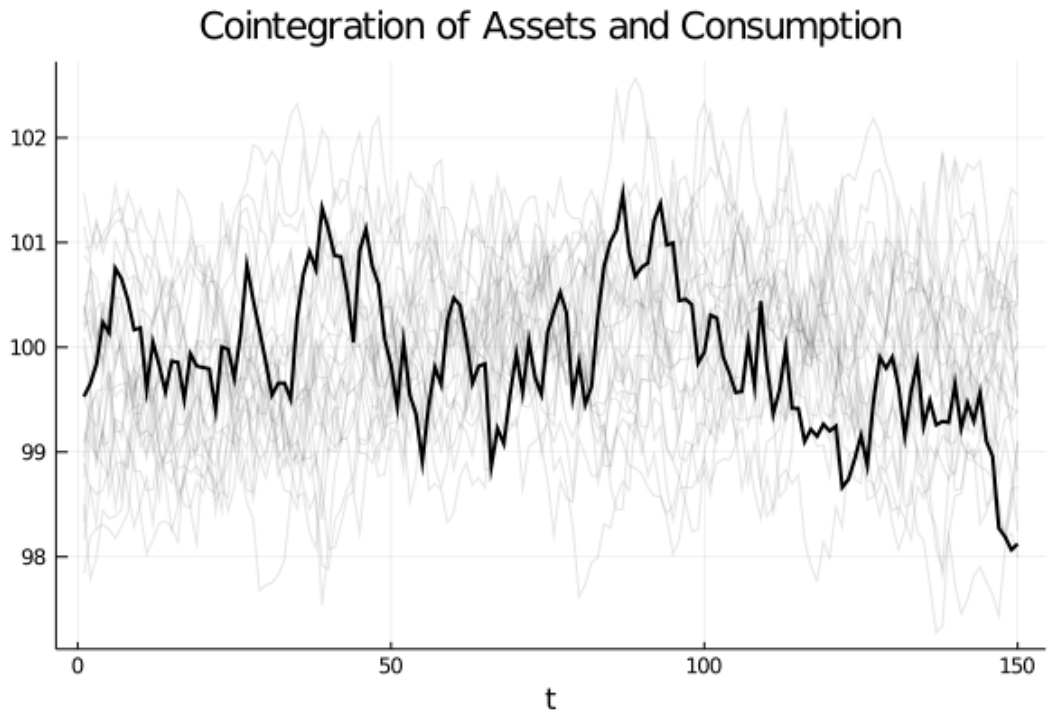
But now there is some initial dispersion because there is *ex ante* heterogeneity in the initial draws of $\begin{bmatrix} y_{-1} \\ y_{-2} \end{bmatrix}$.

- As before, the cross-section distribution of debt spreads out over time.
- Unlike before, the average level of debt stays at zero, confirming that this is a closed borrower-and-lender economy.
- Now the cointegrating residual seems stationary, and not just asymptotically stationary.

Let's have a look at the cointegration figure

In [18]:
```
cointegration_figure(bsimb, csimb)
```

Out[18]:


Cointegration of Assets and Consumption
102
101
100
99
98
0
50
100
150
t

Chapter 37

Consumption and Tax Smoothing with Complete and Incomplete Markets

37.1 Contents

37.2 Overview

This lecture describes two types of consumption-smoothing and tax-smoothing models

- One is in the **complete markets** tradition of Lucas and Stokey [72].
- The other is in the **incomplete markets** tradition of Hall [36] and Barro [8].
- Complete markets* allow a consumer or government to buy or sell claims contingent on all possible states of the world.
- Incomplete markets* allow a consumer or government to buy or sell only a limited set of securities, often only a single risk-free security.

Hall [36] and Barro [8] both assumed that the only asset that can be traded is a risk-free one period bond.

Hall assumed an exogenous stochastic process of nonfinancial income and an exogenous gross interest rate on one period risk-free debt that equals β^{-1}, where $\beta \in (0, 1)$ is also a consumer's intertemporal discount factor.

Barro [8] made an analogous assumption about the risk-free interest rate in a tax-smoothing model that we regard as isomorphic to Hall's consumption-smoothing model.

We maintain Hall and Barro's assumption about the interest rate when we describe an incomplete markets version of our model.

In addition, we extend their assumption about the interest rate to an appropriate counterpart

that we use in a "complete markets" model in the style of Lucas and Stokey [72].

While we are equally interested in consumption-smoothing and tax-smoothing models, for the most part we focus explicitly on consumption-smoothing versions of these models.

But for each version of the consumption-smoothing model there is a natural tax-smoothing counterpart obtained simply by

- relabeling consumption as tax collections and nonfinancial income as government expenditures
- relabeling the consumer's debt as the government's *assets*

For elaborations on this theme, please see Optimal Savings II: LQ Techniques and later parts of this lecture.

We'll consider two closely related alternative assumptions about the consumer's exogenous nonfinancial income process (or in the tax-smoothing interpretation, the government's exogenous expenditure process):

- that it obeys a finite N state Markov chain (setting $N = 2$ most of the time)
- that it is described by a linear state space model with a continuous state vector in $\mathbb{R}^n$ driven by a Gaussian vector iid shock process

We'll spend most of this lecture studying the finite-state Markov specification, but will briefly treat the linear state space specification before concluding.

37.2.1 Relationship to Other Lectures

This lecture can be viewed as a followup to Optimal Savings II: LQ Techniques and a warm up for a model of tax smoothing described in opt_tax_recur.

Linear-quadratic versions of the Lucas-Stokey tax-smoothing model are described in lqramsey.

The key differences between those lectures and this one are

- Here the decision maker takes all prices as exogenous, meaning that his decisions do not affect them.
- In lqramsey and opt_tax_recur, the decision maker – the government in the case of these lectures – recognizes that his decisions affect prices.

So these later lectures are partly about how the government should manipulate prices of government debt.

37.3 Background

Outcomes in consumption-smoothing (or tax-smoothing) models emerge from two sources:

- a decision maker – a consumer in the consumption-smoothing model or a government in the tax-smoothing model – who wants to maximize an intertemporal objective function that expresses its preference for paths of consumption (or tax collections) that are *smooth* in the sense of not varying across time and Markov states
- a set of trading opportunities that allow the optimizer to transform a possibly erratic nonfinancial income (or government expenditure) process into a smoother consumption (or tax collections) process by purchasing or selling financial securities

In the complete markets version of the model, each period the consumer can buy or sell one-period ahead state-contingent securities whose payoffs depend on next period's realization of the Markov state.

In the two-state Markov chain case, there are two such securities each period.

In an N state Markov state version of the model, N such securities are traded each period.

These state-contingent securities are commonly called Arrow securities, after Kenneth Arrow who first theorized about them.

In the incomplete markets version of the model, the consumer can buy and sell only one security each period, a risk-free bond with gross return β^{-1}.

37.3.1 Finite State Markov Income Process

In each version of the consumption-smoothing model, nonfinancial income is governed by a two-state Markov chain (it's easy to generalize this to an N state Markov chain).

In particular, the *state of the world* is given by s_t that follows a Markov chain with transition probability matrix

$$P_{ij} = \mathbb{P}\{s_{t+1} = \bar{s}_j \,|\, s_t = \bar{s}_i\}$$

Nonfinancial income $\{y_t\}$ obeys

$$y_t = \begin{cases} \bar{y}_1 & \text{if } s_t = \bar{s}_1 \\ \bar{y}_2 & \text{if } s_t = \bar{s}_2 \end{cases}$$

A consumer wishes to maximize

$$\mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t u(c_t)\right] \quad \text{where} \quad u(c_t) = -(c_t - \gamma)^2 \quad \text{and} \quad 0 < \beta < 1 \tag{1}$$

Remark About Isomorphism

We can regard these as Barro [8] tax-smoothing models if we set $c_t = T_t$ and $G_t = y_t$, where T_t is total tax collections and $\{G_t\}$ is an exogenous government expenditures process.

37.3.2 Market Structure

The two models differ in how effectively the market structure allows the consumer to transfer resources across time and Markov states, there being more transfer opportunities in the complete markets setting than in the incomplete markets setting.

Watch how these differences in opportunities affect

- how smooth consumption is across time and Markov states
- how the consumer chooses to make his levels of indebtedness behave over time and across Markov states

37.4 Model 1 (Complete Markets)

At each date $t \geq 0$, the consumer trades **one-period ahead Arrow securities**.

We assume that prices of these securities are exogenous to the consumer (or in the tax-smoothing version of the model, to the government).

Exogenous means that they are unaffected by the decision maker.

In Markov state s_t at time t, one unit of consumption in state s_{t+1} at time $t+1$ costs $q(s_{t+1} \mid s_t)$ units of the time t consumption good.

At time $t = 0$, the consumer starts with an inherited level of debt due at time 0 of b_0 units of time 0 consumption goods.

The consumer's budget constraint at $t \geq 0$ in Markov state s_t is

$$c_t + b_t \leq y(s_t) + \sum_j q(\bar{s}_j \mid s_t)\, b_{t+1}(\bar{s}_j \mid s_t)$$

where b_t is the consumer's one-period debt that falls due at time t and $b_{t+1}(\bar{s}_j \mid s_t)$ are the consumer's time t sales of the time $t+1$ consumption good in Markov state $\bar{s}_j$, a source of time t revenues.

An analogue of Hall's assumption that the one-period risk-free gross interest rate is β^{-1} is

$$q(\bar{s}_j \mid \bar{s}_i) = \beta P_{ij} \tag{2}$$

To understand this, observe that in state $\bar{s}_i$ it costs $\sum_j q(\bar{s}_j \mid \bar{s}_i)$ to purchase one unit of consumption next period *for sure*, i.e., meaning no matter what state of the world occurs at $t+1$.

Hence the implied price of a risk-free claim on one unit of consumption next period is

$$\sum_j q(\bar{s}_j \mid \bar{s}_i) = \sum_j \beta P_{ij} = \beta$$

This confirms that (2) is a natural analogue of Hall's assumption about the risk-free one-period interest rate.

First-order necessary conditions for maximizing the consumer's expected utility are

$$\beta \frac{u'(c_{t+1})}{u'(c_t)} \mathbb{P}\{s_{t+1} \mid s_t\} = q(s_{t+1} \mid s_t)$$

or, under our assumption (2) on Arrow security prices,

$$c_{t+1} = c_t \tag{3}$$

Thus, our consumer sets $c_t = \bar{c}$ for all $t \geq 0$ for some value $\bar{c}$ that it is our job now to determine.

Guess: We'll make the plausible guess that

$$b_{t+1}(\bar{s}_j \mid s_t = \bar{s}_i) = b(\bar{s}_j), \quad i = 1, 2; \;\; j = 1, 2 \tag{4}$$

so that the amount borrowed today turns out to depend only on *tomorrow's* Markov state. (Why is this is a plausible guess?).

To determine $\bar{c}$, we shall pursue the implications of the consumer's budget constraints in each Markov state today and our guess (4) about the consumer's debt level choices.

For $t \geq 1$, these imply

$$\begin{aligned} \bar{c} + b(\bar{s}_1) &= y(\bar{s}_1) + q(\bar{s}_1 \mid \bar{s}_1) b(\bar{s}_1) + q(\bar{s}_2 \mid \bar{s}_1) b(\bar{s}_2) \\ \bar{c} + b(\bar{s}_2) &= y(\bar{s}_2) + q(\bar{s}_1 \mid \bar{s}_2) b(\bar{s}_1) + q(\bar{s}_2 \mid \bar{s}_2) b(\bar{s}_2), \end{aligned} \tag{5}$$

or

$$\begin{bmatrix} b(\bar{s}_1) \\ b(\bar{s}_2) \end{bmatrix} + \begin{bmatrix} \bar{c} \\ \bar{c} \end{bmatrix} = \begin{bmatrix} y(\bar{s}_1) \\ y(\bar{s}_2) \end{bmatrix} + \beta \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} b(\bar{s}_1) \\ b(\bar{s}_2) \end{bmatrix}$$

These are 2 equations in the 3 unknowns $\bar{c}, b(\bar{s}_1), b(\bar{s}_2)$.

To get a third equation, we assume that at time $t = 0$, b_0 is the debt due; and we assume that at time $t = 0$, the Markov state is $\bar{s}_1$.

Then the budget constraint at time $t = 0$ is

$$\bar{c} + b_0 = y(\bar{s}_1) + q(\bar{s}_1 \mid \bar{s}_1) b(\bar{s}_1) + q(\bar{s}_2 \mid \bar{s}_1) b(\bar{s}_2) \tag{6}$$

If we substitute (6) into the first equation of (5) and rearrange, we discover that

$$b(\bar{s}_1) = b_0 \tag{7}$$

We can then use the second equation of (5) to deduce the restriction

$$y(\bar{s}_1) - y(\bar{s}_2) + [q(\bar{s}_1 \mid \bar{s}_1) - q(\bar{s}_1 \mid \bar{s}_2) - 1] b_0 + [q(\bar{s}_2 \mid \bar{s}_1) + 1 - q(\bar{s}_2 \mid \bar{s}_2)] b(\bar{s}_2) = 0, \tag{8}$$

an equation in the unknown $b(\bar{s}_2)$.

Knowing $b(\bar{s}_1)$ and $b(\bar{s}_2)$, we can solve equation (6) for the constant level of consumption $\bar{c}$.

37.4.1 Key outcomes

The preceding calculations indicate that in the complete markets version of our model, we obtain the following striking results:

- The consumer chooses to make consumption perfectly constant across time and Markov states.

We computed the constant level of consumption $\bar{c}$ and indicated how that level depends on the underlying specifications of preferences, Arrow securities prices, the stochastic process of exogenous nonfinancial income, and the initial debt level b_0

- The consumer's debt neither accumulates, nor decumulates, nor drifts. Instead the debt level each period is an exact function of the Markov state, so in the two-state Markov case, it switches between two values.
- We have verified guess (4).

We computed how one of those debt levels depends entirely on initial debt – it equals it – and how the other value depends on virtually all remaining parameters of the model.

37.4.2 Code

Here's some code that, among other things, contains a function called consumption_complete().

This function computes $b(\bar{s}_1), b(\bar{s}_2), \bar{c}$ as outcomes given a set of parameters, under the assumption of complete markets.

37.4.3 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Parameters, Plots, QuantEcon, Random
        gr(fmt = :png);
```

```
In [3]: ConsumptionProblem = @with_kw (β = 0.96,
                                       y = [2.0, 1.5],
                                       b0 = 3.0,
                                       P = [0.8 0.2
                                            0.4 0.6])

        function consumption_complete(cp)

            @unpack β, P, y, b0 = cp   # Unpack

            y1, y2 = y                                  # extract income levels
            b1 = b0                                     # b1 is known to be equal to b0
            Q = β * P                                   # assumed price system

            # Using equation (7) calculate b2
            b2 = (y2 - y1 - (Q[1, 1] - Q[2, 1] - 1) * b1) / (Q[1, 2] + 1 - Q[2, 2])

            # Using equation (5) calculae c̄
            c̄ = y1 - b0 + ([b1 b2] * Q[1, :])[1]

            return c̄, b1, b2
        end

        function consumption_incomplete(cp; N_simul = 150)

            @unpack β, P, y, b0 = cp  # unpack

            # for the simulation use the MarkovChain type
            mc = MarkovChain(P)

            # useful variables
```

```
    y = y
    v = inv(I - β * P) * y

    # simulate state path
    s_path = simulate(mc, N_simul, init=1)

    # store consumption and debt path
    b_path, c_path = ones(N_simul + 1), ones(N_simul)
    b_path[1] = b0

    # optimal decisions from (12) and (13)
    db = ((1 - β) * v - y) / β

    for (i, s) in enumerate(s_path)
        c_path[i] = (1 - β) * (v[s, 1] - b_path[i])
        b_path[i + 1] = b_path[i] + db[s, 1]
    end

    return c_path, b_path[1:end - 1], y[s_path], s_path
end
```

```
Out[3]: consumption_incomplete (generic function with 1 method)
```

Let's test by checking that $\bar{c}$ and b_2 satisfy the budget constraint

```
In [4]: cp = ConsumptionProblem()
        c̄, b1, b2 = consumption_complete(cp)
        debt_complete = [b1, b2]
        isapprox((c̄ + b2 - cp.y[2] - debt_complete' * (cp.β * cp.P)[2, :])[1], 0)
```

```
Out[4]: true
```

Below, we'll take the outcomes produced by this code – in particular the implied consumption and debt paths – and compare them with outcomes from an incomplete markets model in the spirit of Hall [36] and Barro [8] (and also, for those who love history, Gallatin (1807) [34]).

37.5 Model 2 (One-Period Risk Free Debt Only)

This is a version of the original models of Hall (1978) and Barro (1979) in which the decision maker's ability to substitute intertemporally is constrained by his ability to buy or sell only one security, a risk-free one-period bond bearing a constant gross interest rate that equals β^{-1}.

Given an initial debt b_0 at time 0, the consumer faces a sequence of budget constraints

$$c_t + b_t = y_t + \beta b_{t+1}, \quad t \geq 0$$

where β is the price at time t of a risk-free claim on one unit of time consumption at time $t+1$.

First-order conditions for the consumer's problem are

$$\sum_j u'(c_{t+1,j})P_{ij} = u'(c_{t,i})$$

For our assumed quadratic utility function this implies

$$\sum_j c_{t+1,j}P_{ij} = c_{t,i}, \tag{9}$$

which is Hall's (1978) conclusion that consumption follows a random walk.

As we saw in our first lecture on the permanent income model, this leads to

$$b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} - (1-\beta)^{-1} c_t \tag{10}$$

and

$$c_t = (1-\beta)\left[\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} - b_t\right]. \tag{11}$$

Equation (11) expresses c_t as a net interest rate factor $1-\beta$ times the sum of the expected present value of nonfinancial income $\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j}$ and financial wealth $-b_t$.

Substituting (11) into the one-period budget constraint and rearranging leads to

$$b_{t+1} - b_t = \beta^{-1}\left[(1-\beta)\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} - y_t\right] \tag{12}$$

Now let's do a useful calculation that will yield a convenient expression for the key term $\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j}$ in our finite Markov chain setting.

Define

$$v_t := \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j}$$

In our finite Markov chain setting, $v_t = v(1)$ when $s_t = \bar{s}_1$ and $v_t = v(2)$ when $s_t = \bar{s}_2$.

Therefore, we can write

$$\begin{aligned} v(1) &= y(1) + \beta P_{11} v(1) + \beta P_{12} v(2) \\ v(2) &= y(2) + \beta P_{21} v(1) + \beta P_{22} v(2) \end{aligned}$$

or

$$\vec{v} = \vec{y} + \beta P \vec{v}$$

where $\vec{v} = \begin{bmatrix} v(1) \\ v(2) \end{bmatrix}$ and $\vec{y} = \begin{bmatrix} y(1) \\ y(2) \end{bmatrix}$.

We can also write the last expression as

$$\vec{v} = (I - \beta P)^{-1}\vec{y}$$

In our finite Markov chain setting, from expression (11), consumption at date t when debt is b_t and the Markov state today is $s_t = i$ is evidently

$$c(b_t, i) = (1 - \beta)\left([(I - \beta P)^{-1}\vec{y}]_i - b_t\right) \tag{13}$$

and the increment in debt is

$$b_{t+1} - b_t = \beta^{-1}[(1 - \beta)v(i) - y(i)] \tag{14}$$

37.5.1 Summary of Outcomes

In contrast to outcomes in the complete markets model, in the incomplete markets model

- consumption drifts over time as a random walk; the level of consumption at time t depends on the level of debt that the consumer brings into the period as well as the expected discounted present value of nonfinancial income at t
- the consumer's debt drifts upward over time in response to low realizations of nonfinancial income and drifts downward over time in response to high realizations of nonfinancial income
- the drift over time in the consumer's debt and the dependence of current consumption on today's debt level account for the drift over time in consumption

37.5.2 The Incomplete Markets Model

The code above also contains a function called consumption_incomplete() that uses (13) and (14) to

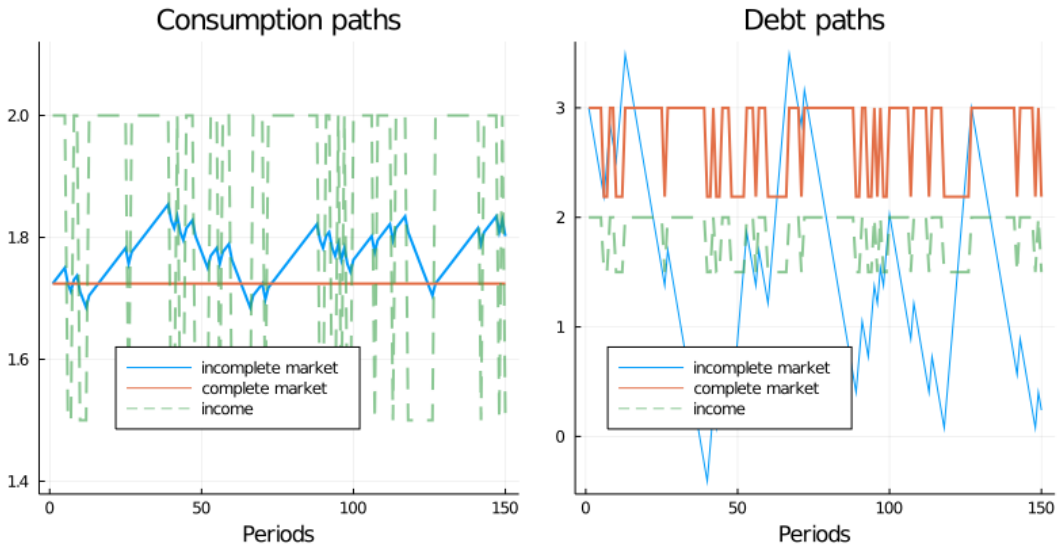
- simulate paths of y_t, c_t, b_{t+1}
- plot these against values of of $\bar{c}, b(s_1), b(s_2)$ found in a corresponding complete markets economy

Let's try this, using the same parameters in both complete and incomplete markets economies

```
In [5]: Random.seed!(42)
        N_simul = 150
        cp = ConsumptionProblem()

        c, b1, b2 = consumption_complete(cp)
        debt_complete = [b1, b2]

        c_path, debt_path, y_path, s_path = consumption_incomplete(cp,
      ↪N_simul=N_simul)

        plt_cons = plot(title = "Consumption paths", xlabel = "Periods", ylim = [1.
      ↪4,2.1])
        plot!(plt_cons, 1:N_simul, c_path, label = "incomplete market", lw = 2)
        plot!(plt_cons, 1:N_simul, fill(c, N_simul), label = "complete market", lw
      ↪= 2)
```

```
        plot!(plt_cons, 1:N_simul, y_path, label = "income", lw = 2, alpha = 0.6,
↪linestyle =
        :dash)
        plot!(plt_cons, legend = :bottom)

        plt_debt = plot(title = "Debt paths", xlabel = "Periods")
        plot!(plt_debt, 1:N_simul, debt_path, label = "incomplete market")
        plot!(plt_debt, 1:N_simul, debt_complete[s_path], label = "complete
↪market", lw = 2)
        plot!(plt_debt, 1:N_simul, y_path, label = "income", lw = 2, alpha = 0.6,
↪linestyle =
        :dash)
        plot!(plt_debt, legend = :bottomleft)

        plot(plt_cons, plt_debt, layout = (1,2), size = (800, 400))
```

Out[5]:



In the graph on the left, for the same sample path of nonfinancial income y_t, notice that

- consumption is constant when there are complete markets, but it takes a random walk in the incomplete markets version of the model
- the consumer's debt oscillates between two values that are functions of the Markov state in the complete markets model, while the consumer's debt drifts in a "unit root" fashion in the incomplete markets economy

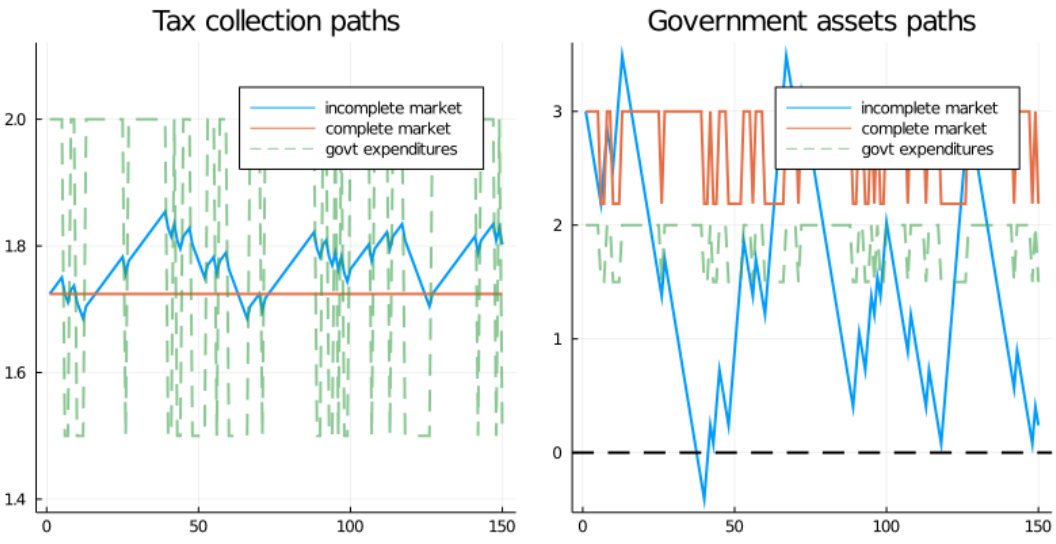
Using the Isomorphism

We can simply relabel variables to acquire tax-smoothing interpretations of our two models

```
In [6]: plt_tax = plot(title = "Tax collection paths", x_label = "Periods", ylim =
↪[1.4,2.1])
        plot!(plt_tax, 1:N_simul, c_path, label = "incomplete market", lw = 2)
        plot!(plt_tax, 1:N_simul, fill(c, N_simul), label = "complete market", lw
↪= 2)
```

```
        plot!(plt_tax, 1:N_simul, y_path, label = "govt expenditures", alpha = .6,
↪linestyle =
        :dash,
              lw = 2)

        plt_gov = plot(title = "Government assets paths", x_label = "Periods")
        plot!(plt_gov, 1:N_simul, debt_path, label = "incomplete market", lw = 2)
        plot!(plt_gov, 1:N_simul, debt_complete[s_path], label = "complete
↪market", lw = 2)
        plot!(plt_gov, 1:N_simul, y_path, label = "govt expenditures", alpha = .6,
↪linestyle =
        :dash,
              lw = 2)
        hline!(plt_gov, [0], linestyle = :dash, color = :black, lw = 2, label = "")
        plot(plt_tax, plt_gov, layout = (1,2), size = (800, 400))
```

Out[6]:



37.6 Example: Tax Smoothing with Complete Markets

It is useful to focus on a simple tax-smoothing example with complete markets.

This example will illustrate how, in a complete markets model like that of Lucas and Stokey [72], the government purchases insurance from the private sector.

- Purchasing insurance protects the government against the need to raise taxes too high or issue too much debt in the high government expenditure event.

We assume that government expenditures move between two values $G_1 < G_2$, where Markov state 1 means "peace" and Markov state 2 means "war".

The government budget constraint in Markov state i is

$$T_i + b_i = G_i + \sum_j Q_{ij} b_j$$

where

$$Q_{ij} = \beta P_{ij}$$

is the price of one unit of output next period in state j when today's Markov state is i and b_i is the government's level of *assets* in Markov state i.

That is, b_i is the amount of the one-period loans owned by the government that fall due at time t.

As above, we'll assume that the initial Markov state is state 1.

In addition, to simplify our example, we'll set the government's initial asset level to 0, so that $b_1 = 0$.

Here's our code to compute a quantitative example with zero debt in peace time:

In [7]:
```
# Parameters

β = .96
y = [1.0, 2.0]
b0 = 0.0
P = [0.8 0.2;
     0.4 0.6]

cp = ConsumptionProblem(β, y, b0, P)
Q = β * P
N_simul = 150

c, b1, b2 = consumption_complete(cp)
debt_complete = [b1, b2]

println("P = $P")
println("Q = $Q")
println("Govt expenditures in peace and war = $y")
println("Constant tax collections = $c")
println("Govt assets in two states = $debt_complete")

msg = """
Now let's check the government's budget constraint in peace and war.
Our assumptions imply that the government always purchases 0 units of the
Arrow peace security.
"""
println(msg)

AS1 = Q[1, 2] * b2
println("Spending on Arrow war security in peace = $AS1")
AS2 = Q[2, 2] * b2
println("Spending on Arrow war security in war = $AS2")

println("\n")
println("Government tax collections plus asset levels in peace and war")
TB1 = c + b1
println("T+b in peace = $TB1")
TB2 = c + b2
println("T+b in war = $TB2")
```

```
println("\n")
println("Total government spending in peace and war")
G1= y[1] + AS1
G2 = y[2] + AS2
println("total govt spending in peace = $G1")
println("total govt spending in war = $G2")

println("\n")
println("Let's see ex post and ex ante returns on Arrow securities")

Π = 1 ./ Q    # reciprocal(Q)
exret = Π
println("Ex post returns to purchase of Arrow securities = $exret")
exant = Π .* P
println("Ex ante returns to purchase of Arrow securities = $exant")
```

```
    P = [0.8 0.2; 0.4 0.6]
Q = [0.768 0.192; 0.384 0.576]
Govt expenditures in peace and war = [1.0, 2.0]
Constant tax collections = 1.3116883116883118
Govt assets in two states = [0.0, 1.6233766233766234]
Now let's check the government's budget constraint in peace and war.
Our assumptions imply that the government always purchases 0 units of the
Arrow peace security.

Spending on Arrow war security in peace = 0.3116883116883117
Spending on Arrow war security in war = 0.9350649350649349


Government tax collections plus asset levels in peace and war
T+b in peace = 1.3116883116883118
T+b in war = 2.9350649350649354


Total government spending in peace and war
total govt spending in peace = 1.3116883116883118
total govt spending in war = 2.935064935064935


Let's see ex post and ex ante returns on Arrow securities
Ex post returns to purchase of Arrow securities = [1.3020833333333333
5.208333333333333; 2.6041666666666665 1.7361111111111112]
Ex ante returns to purchase of Arrow securities = [1.0416666666666667
1.0416666666666667; 1.0416666666666667 1.0416666666666667]
```

37.6.1 Explanation

In this example, the government always purchase 0 units of the Arrow security that pays off in peace time (Markov state 1).

But it purchases a positive amount of the security that pays off in war time (Markov state 2).

We recommend plugging the quantities computed above into the government budget constraints in the two Markov states and staring.

This is an example in which the government purchases *insurance* against the possibility that war breaks out or continues

- the insurance does not pay off so long as peace continues
- the insurance pays off when there is war

Exercise: try changing the Markov transition matrix so that

$$P = \begin{bmatrix} 1 & 0 \\ .2 & .8 \end{bmatrix}$$

Also, start the system in Markov state 2 (war) with initial government assets -10, so that the government starts the war in debt and $b_2 = -10$.

37.7 Linear State Space Version of Complete Markets Model

Now we'll use a setting like that in first lecture on the permanent income model.

In that model, there were

- incomplete markets: the consumer could trade only a single risk-free one-period bond bearing gross one-period risk-free interest rate equal to β^{-1}
- the consumer's exogenous nonfinancial income was governed by a linear state space model driven by Gaussian shocks, the kind of model studied in an earlier lecture about linear state space models

We'll write down a complete markets counterpart of that model.

So now we'll suppose that nonfinancial income is governed by the state space system

$$\begin{aligned} x_{t+1} &= Ax_t + Cw_{t+1} \\ y_t &= S_y x_t \end{aligned}$$

where x_t is an $n \times 1$ vector and $w_{t+1} \sim N(0, I)$ is IID over time.

Again, as a counterpart of the Hall-Barro assumption that the risk-free gross interest rate is β^{-1}, we assume the scaled prices of one-period ahead Arrow securities are

$$p_{t+1}(x_{t+1} \,|\, x_t) = \beta \phi(x_{t+1} \,|\, Ax_t, CC') \tag{15}$$

where $\phi(\cdot \,|\, \mu, \Sigma)$ is a multivariate Gaussian distribution with mean vector μ and covariance matrix Σ.

Let $b(x_{t+1})$ be a vector of state-contingent debt due at $t+1$ as a function of the $t+1$ state x_{t+1}.

Using the pricing function assumed in (15), the value at t of $b(x_{t+1})$ is

$$\beta \int b(x_{t+1}) \phi(x_{t+1} \,|\, Ax_t, CC') dx_{t+1} = \beta \mathbb{E}_t b_{t+1}$$

In the complete markets setting, the consumer faces a sequence of budget constraints

$$c_t + b_t = y_t + \beta \mathbb{E}_t b_{t+1}, t \geq 0$$

We can solve the time t budget constraint forward to obtain

$$b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j (y_{t+j} - c_{t+j})$$

We assume as before that the consumer cares about the expected value of

$$\sum_{t=0}^{\infty} \beta^t u(c_t), \quad 0 < \beta < 1$$

In the incomplete markets version of the model, we assumed that $u(c_t) = -(c_t - \gamma)^2$, so that the above utility functional became

$$-\sum_{t=0}^{\infty} \beta^t (c_t - \gamma)^2, \quad 0 < \beta < 1$$

But in the complete markets version, we can assume a more general form of utility function that satisfies $u' > 0$ and $u'' < 0$.

The first-order condition for the consumer's problem with complete markets and our assumption about Arrow securities prices is

$$u'(c_{t+1}) = u'(c_t) \quad \text{for all } t \geq 0$$

which again implies $c_t = \bar{c}$ for some $\bar{c}$.

So it follows that

$$b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j (y_{t+j} - \bar{c})$$

or

$$b_t = S_y (I - \beta A)^{-1} x_t - \frac{1}{1-\beta} \bar{c} \tag{16}$$

where the value of $\bar{c}$ satisfies

$$\bar{b}_0 = S_y (I - \beta A)^{-1} x_0 - \frac{1}{1-\beta} \bar{c} \tag{17}$$

where $\bar{b}_0$ is an initial level of the consumer's debt, specified as a parameter of the problem.

Thus, in the complete markets version of the consumption-smoothing model, $c_t = \bar{c}, \forall t \geq 0$ is determined by (17) and the consumer's debt is a fixed function of the state x_t described by (16).

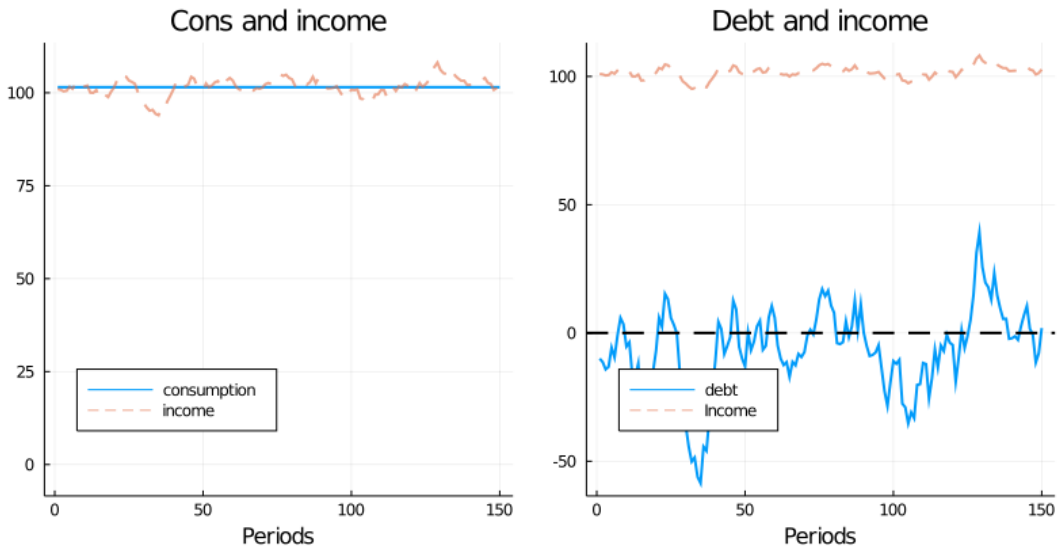
Here's an example that shows how in this setting the availability of insurance against fluctuating nonfinancial income allows the consumer completely to smooth consumption across time and across states of the world.

```
In [8]: function complete_ss(β, b0, x0, A, C, S_y, T = 12)
```

```
        # Create a linear state space for simulation purposes
        # This adds "b" as a state to the linear state space system
        # so that setting the seed places shocks in same place for
        # both the complete and incomplete markets economy
        # Atilde = vcat(hcat(A, zeros(size(A,1), 1)),
        #               zeros(1, size(A,2) + 1))
        # Ctilde = vcat(C, zeros(1, 1))
        # S_ytilde = hcat(S_y, zeros(1, 1))

        lss = LSS(A, C, S_y, mu_0=x0)

        # Add extra state to initial condition
        # x0 = hcat(x0, 0)

        # Compute the (I - β*A)^{-1}
        rm = inv(I - β * A)

        # Constant level of consumption
        cbar = (1 - β) * (S_y * rm * x0 .- b0)
        c_hist = ones(T) * cbar[1]

        # Debt
        x_hist, y_hist = simulate(lss, T)
        b_hist = (S_y * rm * x_hist .- cbar[1] / (1.0 - β))

        return c_hist, vec(b_hist), vec(y_hist), x_hist
    end

    N_simul = 150

    # Define parameters
    α, ρ1, ρ2 = 10.0, 0.9, 0.0
    σ = 1.0
    # N_simul = 1
    # T = N_simul
    A = [1.0 0.0 0.0;
         α    ρ1  ρ2;
         0.0 1.0 0.0]
    C = [0.0, σ, 0.0]
    S_y = [1.0 1.0 0.0]
    β, b0 = 0.95, -10.0
    x0 = [1.0, α / (1 - ρ1), α / (1 - ρ1)]

    # Do simulation for complete markets
    out = complete_ss(β, b0, x0, A, C, S_y, 150)
    c_hist_com, b_hist_com, y_hist_com, x_hist_com = out

    # Consumption plots
    plt_cons = plot(title = "Cons and income", xlabel = "Periods", ylim = [-5.
↪0, 110])
    plot!(plt_cons, 1:N_simul, c_hist_com, label = "consumption", lw = 2)
    plot!(plt_cons, 1:N_simul, y_hist_com, label = "income",
          lw = 2, alpha = 0.6, linestyle = :dash)

    # Debt plots
    plt_debt = plot(title = "Debt and income", xlabel = "Periods")
    plot!(plt_debt, 1:N_simul, b_hist_com, label = "debt", lw = 2)
    plot!(plt_debt, 1:N_simul, y_hist_com, label = "Income",
```

```
        lw = 2, alpha = 0.6, linestyle = :dash)
hline!(plt_debt, [0], color = :black, linestyle = :dash, lw = 2, label = "")
plot(plt_cons, plt_debt, layout = (1,2), size = (800, 400))
plot!(legend = :bottomleft)
```

Out[8]:



37.7.1 Interpretation of Graph

In the above graph, please note that:

- nonfinancial income fluctuates in a stationary manner
- consumption is completely constant
- the consumer's debt fluctuates in a stationary manner; in fact, in this case because nonfinancial income is a first-order autoregressive process, the consumer's debt is an exact affine function (meaning linear plus a constant) of the consumer's nonfinancial income

37.7.2 Incomplete Markets Version

The incomplete markets version of the model with nonfinancial income being governed by a linear state space system is described in the first lecture on the permanent income model and the followup lecture on the permanent income model.

In that version, consumption follows a random walk and the consumer's debt follows a process with a unit root.

We leave it to the reader to apply the usual isomorphism to deduce the corresponding implications for a tax-smoothing model like Barro's [8].

37.7.3 Government Manipulation of Arrow Securities Prices

In optimal taxation in an LQ economy and recursive optimal taxation, we study **complete-markets** models in which the government recognizes that it can manipulate Arrow securities prices.

In optimal taxation with incomplete markets, we study an **incomplete-markets** model in which the government manipulates asset prices.

Chapter 38

Optimal Savings III: Occasionally Binding Constraints

38.1 Contents

38.2 Overview

Next we study an optimal savings problem for an infinitely lived consumer—the "common ancestor" described in [68], section 1.3.

This is an essential sub-problem for many representative macroeconomic models

- [1]
- [56]
- etc.

It is related to the decision problem in the stochastic optimal growth model and yet differs in important ways.

For example, the choice problem for the agent includes an additive income term that leads to an occasionally binding constraint.

Our presentation of the model will be relatively brief.

- For further details on economic intuition, implication and models, see [68]
- Proofs of all mathematical results stated below can be found in this paper

To solve the model we will use Euler equation based time iteration, similar to this lecture.

This method turns out to be

- Globally convergent under mild assumptions, even when utility is unbounded (both above and below).
- More efficient numerically than value function iteration.

38.2.1 References

Other useful references include [20], [22], [63], [87], [89] and [95].

38.3 The Optimal Savings Problem

Let's write down the model and then discuss how to solve it.

38.3.1 Set Up

Consider a household that chooses a state-contingent consumption plan $\{c_t\}_{t \geq 0}$ to maximize

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t u(c_t)$$

subject to

$$c_t + a_{t+1} \leq R a_t + z_t, \qquad c_t \geq 0, \qquad a_t \geq -b \qquad t = 0, 1, ... \tag{1}$$

Here

- $\beta \in (0, 1)$ is the discount factor
- a_t is asset holdings at time t, with ad-hoc borrowing constraint $a_t \geq -b$
- c_t is consumption
- z_t is non-capital income (wages, unemployment compensation, etc.)
- $R := 1 + r$, where $r > 0$ is the interest rate on savings

Non-capital income $\{z_t\}$ is assumed to be a Markov process taking values in $Z \subset (0, \infty)$ with stochastic kernel Π.

This means that $\Pi(z, B)$ is the probability that $z_{t+1} \in B$ given $z_t = z$.

The expectation of $f(z_{t+1})$ given $z_t = z$ is written as

$$\int f(\acute{z}) \, \Pi(z, d\acute{z})$$

We further assume that

1. $r > 0$ and $\beta R < 1$
2. u is smooth, strictly increasing and strictly concave with $\lim_{c \to 0} u'(c) = \infty$ and $\lim_{c \to \infty} u'(c) = 0$

The asset space is $[-b, \infty)$ and the state is the pair $(a, z) \in S := [-b, \infty) \times Z$.

A *feasible consumption path* from $(a, z) \in S$ is a consumption sequence $\{c_t\}$ such that $\{c_t\}$ and its induced asset path $\{a_t\}$ satisfy

1. $(a_0, z_0) = (a, z)$

2. the feasibility constraints in (1), and
3. measurability of c_t w.r.t. the filtration generated by $\{z_1, \ldots, z_t\}$

The meaning of the third point is just that consumption at time t can only be a function of outcomes that have already been observed.

38.3.2 Value Function and Euler Equation

The *value function* $V \colon S \to \mathbb{R}$ is defined by

$$V(a, z) := \sup \mathbb{E} \left\{ \sum_{t=0}^{\infty} \beta^t u(c_t) \right\} \tag{2}$$

where the supremum is over all feasible consumption paths from (a, z).

An *optimal consumption path* from (a, z) is a feasible consumption path from (a, z) that attains the supremum in (2).

To pin down such paths we can use a version of the Euler equation, which in the present setting is

$$u'(c_t) \geq \beta R \, \mathbb{E}_t[u'(c_{t+1})] \tag{3}$$

and

$$u'(c_t) = \beta R \, \mathbb{E}_t[u'(c_{t+1})] \quad \text{whenever } c_t < R a_t + z_t + b \tag{4}$$

In essence, this says that the natural "arbitrage" relation $u'(c_t) = \beta R \, \mathbb{E}_t[u'(c_{t+1})]$ holds when the choice of current consumption is interior.

Interiority means that c_t is strictly less than its upper bound $R a_t + z_t + b$.

(The lower boundary case $c_t = 0$ never arises at the optimum because $u'(0) = \infty$)

When c_t does hit the upper bound $R a_t + z_t + b$, the strict inequality $u'(c_t) > \beta R \, \mathbb{E}_t[u'(c_{t+1})]$ can occur because c_t cannot increase sufficiently to attain equality.

With some thought and effort, one can show that (3) and (4) are equivalent to

$$u'(c_t) = \max \left\{ \beta R \, \mathbb{E}_t[u'(c_{t+1})] \,, \; u'(R a_t + z_t + b) \right\} \tag{5}$$

38.3.3 Optimality Results

Given our assumptions, it is known that

1. For each $(a, z) \in S$, a unique optimal consumption path from (a, z) exists.
2. This path is the unique feasible path from (a, z) satisfying the Euler equality (5) and the transversality condition

$$\lim_{t \to \infty} \beta^t \, \mathbb{E} \left[u'(c_t) a_{t+1} \right] = 0. \tag{6}$$

Moreover, there exists an *optimal consumption function* $c^* \colon S \to [0, \infty)$ such that the path from (a, z) generated by

$$(a_0, z_0) = (a, z), \quad z_{t+1} \sim \Pi(z_t, dy), \quad c_t = c^*(a_t, z_t) \quad \text{and} \quad a_{t+1} = R a_t + z_t - c_t$$

satisfies both (5) and (6), and hence is the unique optimal path from (a, z).

In summary, to solve the optimization problem, we need to compute c^*.

38.4 Computation

There are two standard ways to solve for c^*

1. Time iteration (TI) using the Euler equality
2. Value function iteration (VFI)

Let's look at these in turn.

38.4.1 Time Iteration

We can rewrite (5) to make it a statement about functions rather than random variables.

In particular, consider the functional equation

$$u' \circ c \, (a, z) = \max \left\{ \gamma \int u' \circ c \, \{R a + z - c(a, z), \, \acute{z}\} \, \Pi(z, d\acute{z}) \, , \; u'(R a + z + b) \right\} \tag{7}$$

where $\gamma := \beta R$ and $u' \circ c(s) := u'(c(s))$.

Equation (7) is a functional equation in c.

In order to identify a solution, let $\mathcal{C}$ be the set of candidate consumption functions $c \colon S \to \mathbb{R}$ such that

- each $c \in \mathcal{C}$ is continuous and (weakly) increasing
- $\min Z \leq c(a, z) \leq R a + z + b$ for all $(a, z) \in S$

In addition, let $K \colon \mathcal{C} \to \mathcal{C}$ be defined as follows:

For given $c \in \mathcal{C}$, the value $Kc(a, z)$ is the unique $t \in J(a, z)$ that solves

$$u'(t) = \max \left\{ \gamma \int u' \circ c \, \{R a + z - t, \, \acute{z}\} \, \Pi(z, d\acute{z}) \, , \; u'(R a + z + b) \right\} \tag{8}$$

where

$$J(a, z) := \{ t \in \mathbb{R} \, : \, \min Z \leq t \leq R a + z + b \} \tag{9}$$

We refer to K as Coleman's policy function operator [17].

It is known that

- K is a contraction mapping on $\mathcal{C}$ under the metric

$$\rho(c, d) := \| u' \circ c - u' \circ d \| := \sup_{s \in S} | u'(c(s)) - u'(d(s)) | \qquad (c, d \in \mathcal{C})$$

- The metric ρ is complete on $\mathcal{C}$
- Convergence in ρ implies uniform convergence on compacts

In consequence, K has a unique fixed point $c^* \in \mathcal{C}$ and $K^n c \to c^*$ as $n \to \infty$ for any $c \in \mathcal{C}$.

By the definition of K, the fixed points of K in $\mathcal{C}$ coincide with the solutions to (7) in $\mathcal{C}$.

In particular, it can be shown that the path $\{c_t\}$ generated from $(a_0, z_0) \in S$ using policy function c^* is the unique optimal path from $(a_0, z_0) \in S$.

TL;DR The unique optimal policy can be computed by picking any $c \in \mathcal{C}$ and iterating with the operator K defined in (8).

38.4.2 Value Function Iteration

The Bellman operator for this problem is given by

$$Tv(a, z) = \max_{0 \leq c \leq Ra+z+b} \left\{ u(c) + \beta \int v(Ra + z - c, \hat{z}) \Pi(z, d\hat{z}) \right\} \tag{10}$$

We have to be careful with VFI (i.e., iterating with T) in this setting because u is not assumed to be bounded

- In fact typically unbounded both above and below — e.g. $u(c) = \log c$.
- In which case, the standard DP theory does not apply.
- $T^n v$ is not guaranteed to converge to the value function for arbitrary continous bounded v.

Nonetheless, we can always try the popular strategy "iterate and hope".

We can then check the outcome by comparing with that produced by TI.

The latter is known to converge, as described above.

38.4.3 Implementation

Here's the code for a named-tuple constructor called `ConsumerProblem` that stores primitives, as well as

- a `T` function, which implements the Bellman operator T specified above
- a `K` function, which implements the Coleman operator K specified above
- an `initialize`, which generates suitable initial conditions for iteration

38.4.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
```

```
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

In [2]:
```
using LinearAlgebra, Statistics
using BenchmarkTools, Optim, Parameters, Plots, QuantEcon, Random
using Optim: converged, maximum, maximizer, minimizer, iterations
gr(fmt = :png);
```

In [3]:
```
# utility and marginal utility functions
u(x) = log(x)
du(x) = 1 / x

# model
function ConsumerProblem(;r = 0.01,
                          β = 0.96,
                          Π = [0.6 0.4; 0.05 0.95],
                          z_vals = [0.5, 1.0],
                          b = 0.0,
                          grid_max = 16,
                          grid_size = 50)
    R = 1 + r
    asset_grid = range(-b, grid_max, length = grid_size)

    return (r = r, R = R, β = β, b = b, Π = Π, z_vals = z_vals, asset_grid
↪= asset_grid)
end

function T!(cp, V, out; ret_policy = false)

    # unpack input, set up arrays
    @unpack R, Π, β, b, asset_grid, z_vals = cp
    z_idx = 1:length(z_vals)

    # value function when the shock index is z_i
    vf = interp(asset_grid, V)

    opt_lb = 1e-8

    # solve for RHS of Bellman equation
    for (i_z, z) in enumerate(z_vals)
        for (i_a, a) in enumerate(asset_grid)

            function obj(c)
                EV = dot(vf.(R * a + z - c, z_idx), Π[i_z, :]) # compute
↪expectation
                return u(c) +  β * EV
            end
            res = maximize(obj, opt_lb, R .* a .+ z .+ b)
            converged(res) || error("Didn't converge") # important to check

            if ret_policy
                out[i_a, i_z] = maximizer(res)
            else
                out[i_a, i_z] = maximum(res)
            end

        end
    end
```

```
    out
end

T(cp, V; ret_policy = false) =
    T!(cp, V, similar(V); ret_policy = ret_policy)

get_greedy!(cp, V, out) =
    update_bellman!(cp, V, out, ret_policy = true)

get_greedy(cp, V) =
    update_bellman(cp, V, ret_policy = true)

function K!(cp, c, out)
    # simplify names, set up arrays
    @unpack R, Π, β, b, asset_grid, z_vals = cp
    z_idx = 1:length(z_vals)
    gam = R * β

    # policy function when the shock index is z_i
    cf = interp(asset_grid, c)

    # compute lower_bound for optimization
    opt_lb = 1e-8

    for (i_z, z) in enumerate(z_vals)
        for (i_a, a) in enumerate(asset_grid)
            function h(t)
                cps = cf.(R * a + z - t, z_idx) # c' for each z'
                expectation = dot(du.(cps), Π[i_z, :])
              return abs(du(t) - max(gam * expectation, du(R * a + z + b)))
            end
            opt_ub = R*a + z + b  # addresses issue #8 on github
            res = optimize(h, min(opt_lb, opt_ub - 1e-2), opt_ub,
                           method = Optim.Brent())
            out[i_a, i_z] = minimizer(res)
        end
    end
    return out
end

K(cp, c) = K!(cp, c, similar(c))

function initialize(cp)
    # simplify names, set up arrays
    @unpack R, β, b, asset_grid, z_vals = cp
    shape = length(asset_grid), length(z_vals)
    V, c = zeros(shape...), zeros(shape...)

    # populate V and c
    for (i_z, z) in enumerate(z_vals)
        for (i_a, a) in enumerate(asset_grid)
            c_max = R * a + z + b
            c[i_a, i_z] = c_max
            V[i_a, i_z] = u(c_max) / (1 - β)
        end
    end

    return V, c
```

```
    end
```

```
Out[3]: initialize (generic function with 1 method)
```

Both `T` and `K` use linear interpolation along the asset grid to approximate the value and consumption functions.

The following exercises walk you through several applications where policy functions are computed.

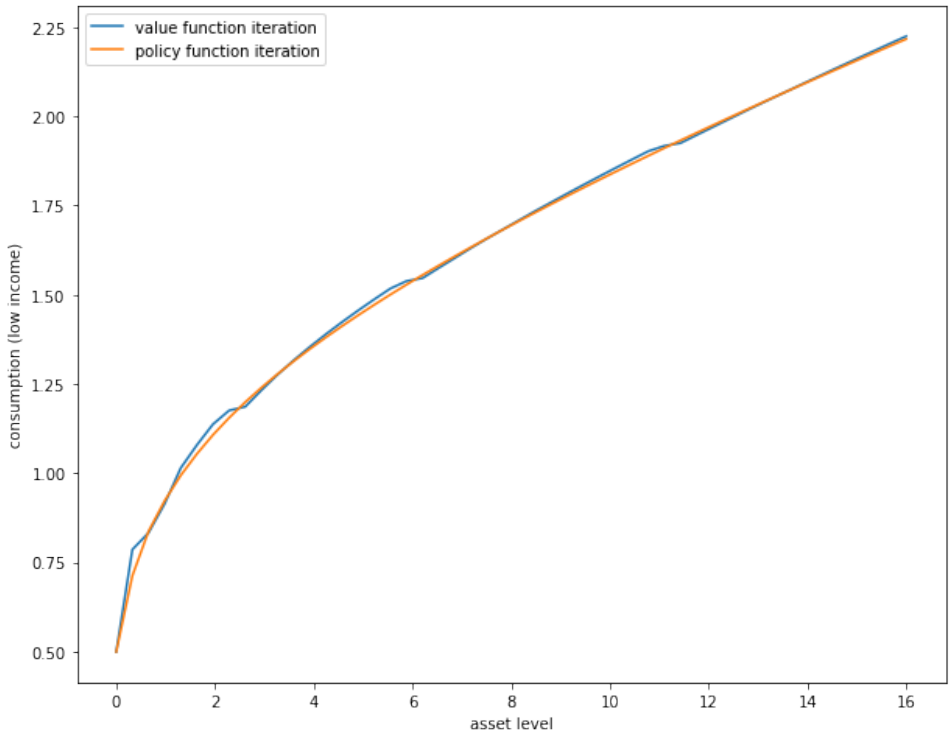
In exercise 1 you will see that while VFI and TI produce similar results, the latter is much faster.

Intuition behind this fact was provided in a previous lecture on time iteration.

38.5 Exercises

38.5.1 Exercise 1

The first exercise is to replicate the following figure, which compares TI and VFI as solution methods



The figure shows consumption policies computed by iteration of K and T respectively

- In the case of iteration with T, the final value function is used to compute the observed policy.

Consumption is shown as a function of assets with income z held fixed at its smallest value.

The following details are needed to replicate the figure

- The parameters are the default parameters in the definition of `consumerProblem`.
- The initial conditions are the default ones from `initialize(cp)`.
- Both operators are iterated 80 times.

When you run your code you will observe that iteration with K is faster than iteration with T.

In the Julia console, a comparison of the operators can be made as follows

```
In [4]: cp = ConsumerProblem()
        v, c, = initialize(cp)
```

```
Out[4]: ([-17.328679513998615 0.0; -4.664387247760648 7.125637140580436; … ; 69.
  ↪82541010621486
        70.57937835479346; 70.32526591846735 71.06452735149534], [0.5 1.0; 0.
  ↪8297959183673469
        1.329795918367347; … ; 16.33020408163265 16.83020408163265; 16.66 17.16])
```

```
In [5]: @btime T(cp, v);
```

```
  530.441 μs (4676 allocations: 428.20 KiB)
```

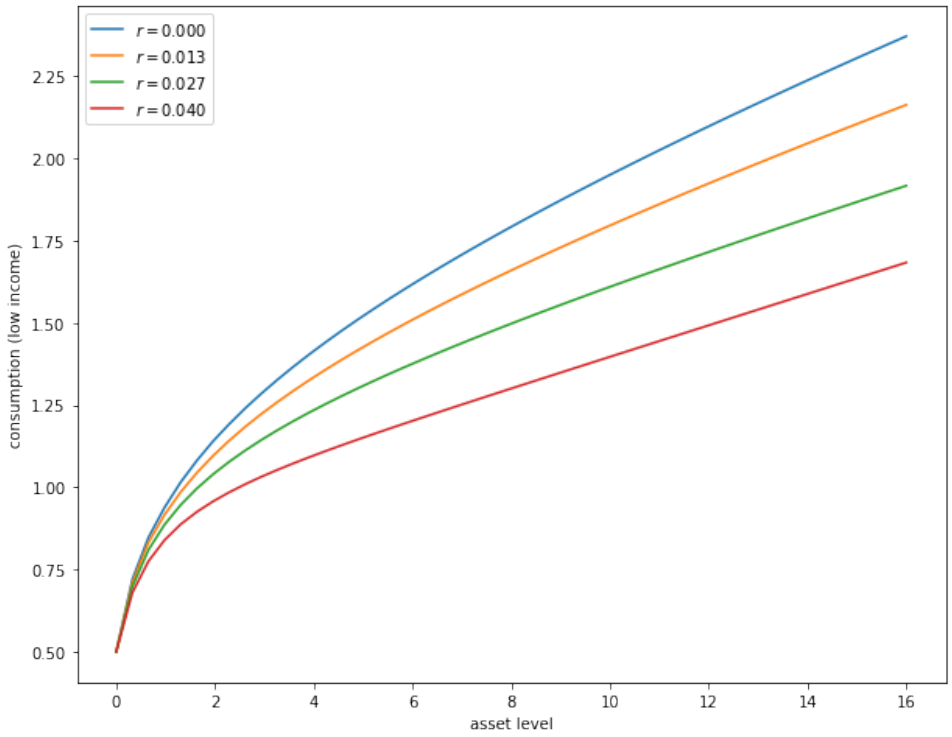
```
In [6]: @btime K(cp, c);
```

```
  768.181 μs (7925 allocations: 742.17 KiB)
```

38.5.2 Exercise 2

Next let's consider how the interest rate affects consumption.

Reproduce the following figure, which shows (approximately) optimal consumption policies for different interest rates



- Other than r, all parameters are at their default values
- r steps through range(0, 0.04, length = 4)
- Consumption is plotted against assets for income shock fixed at the smallest value

The figure shows that higher interest rates boost savings and hence suppress consumption.

38.5.3 Exercise 3

Now let's consider the long run asset levels held by households.

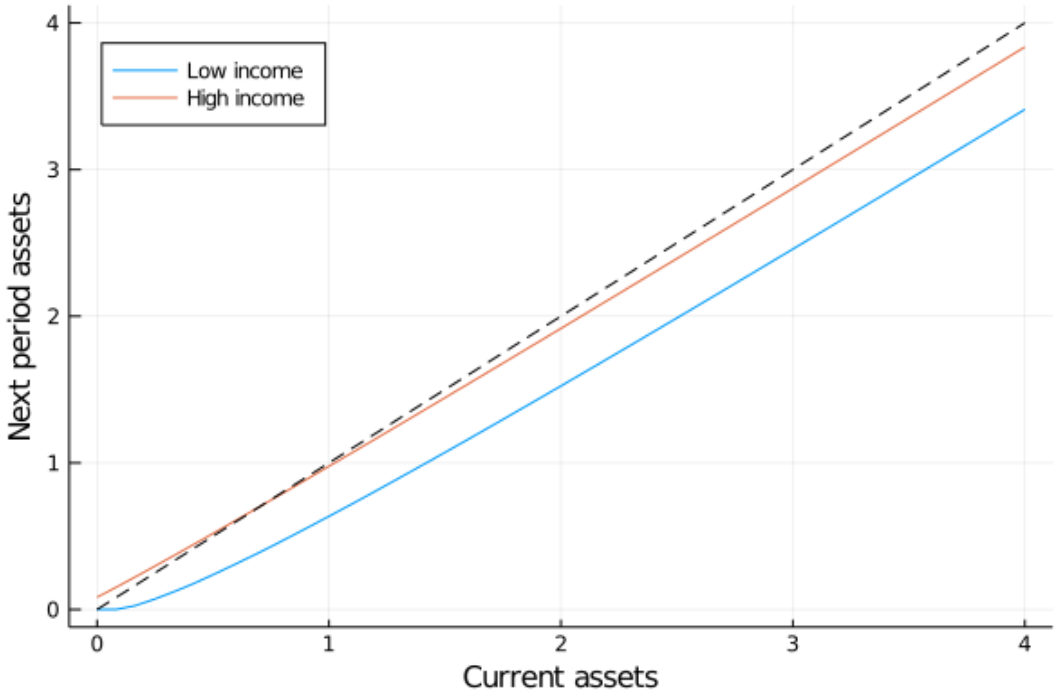
We'll take r = 0.03 and otherwise use default parameters.

The following figure is a 45 degree diagram showing the law of motion for assets when consumption is optimal

In [7]:
```
# solve for optimal consumption
m = ConsumerProblem(r = 0.03, grid_max = 4)
v_init, c_init = initialize(m)

c = compute_fixed_point(c -> K(m, c),
                        c_init,
                        max_iter = 150,
                        verbose = false)
a = m.asset_grid
R, z_vals = m.R, m.z_vals

# generate savings plot
plot(a, R * a .+ z_vals[1] - c[:, 1], label = "Low income")
plot!(xlabel = "Current assets", ylabel = "Next period assets")
plot!(a, R * a .+ z_vals[2] - c[:, 2], label = "High income")
plot!(xlabel = "Current assets", ylabel = "Next period assets")
```

```
plot!(a, a, linestyle = :dash, color = "black", label = "")
plot!(xlabel = "Current assets", ylabel = "Next period assets")
plot!(legend = :topleft)
```

Out[7]:



The blue line and orange line represent the function

$$a' = h(a, z) := Ra + z - c^*(a, z)$$

when income z takes its high and low values respectively.

The dashed line is the 45 degree line.

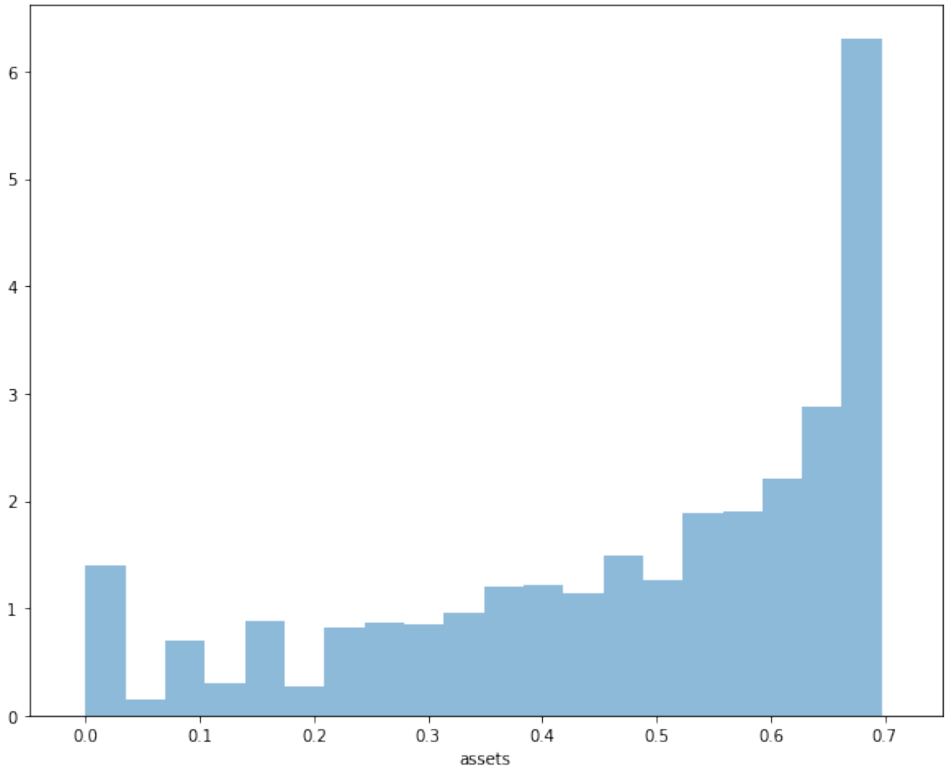
We can see from the figure that the dynamics will be stable — assets do not diverge.

In fact there is a unique stationary distribution of assets that we can calculate by simulation

- Can be proved via theorem 2 of [54].
- Represents the long run dispersion of assets across households when households have idiosyncratic shocks.

Ergodicity is valid here, so stationary probabilities can be calculated by averaging over a single long time series.

- Hence to approximate the stationary distribution we can simulate a long time series for assets and histogram, as in the following figure



Your task is to replicate the figure

- Parameters are as discussed above
- The histogram in the figure used a single time series $\{a_t\}$ of length 500,000
- Given the length of this time series, the initial condition (a_0, z_0) will not matter
- You might find it helpful to use the `MarkovChain` type from `quantecon`

38.5.4 Exercise 4

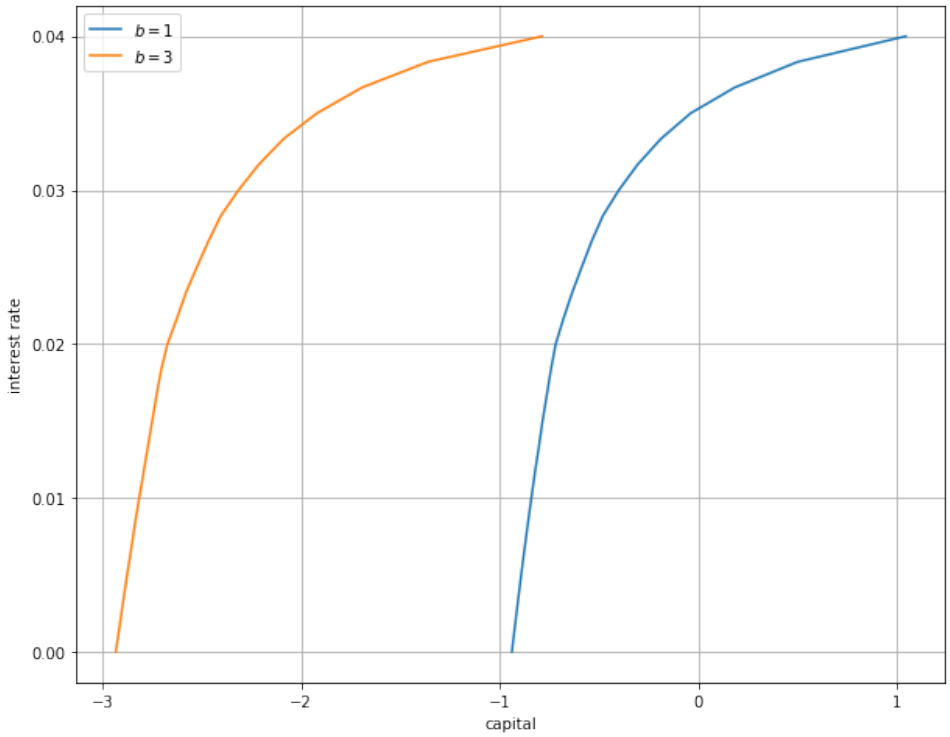
Following on from exercises 2 and 3, let's look at how savings and aggregate asset holdings vary with the interest rate

- Note: [68] section 18.6 can be consulted for more background on the topic treated in this exercise

For a given parameterization of the model, the mean of the stationary distribution can be interpreted as aggregate capital in an economy with a unit mass of *ex-ante* identical households facing idiosyncratic shocks.

Let's look at how this measure of aggregate capital varies with the interest rate and borrowing constraint.

The next figure plots aggregate capital against the interest rate for b in (1, 3)



As is traditional, the price (interest rate) is on the vertical axis.

The horizontal axis is aggregate capital computed as the mean of the stationary distribution.

Exercise 4 is to replicate the figure, making use of code from previous exercises.

Try to explain why the measure of aggregate capital is equal to $-b$ when $r = 0$ for both cases shown here.

38.6 Solutions

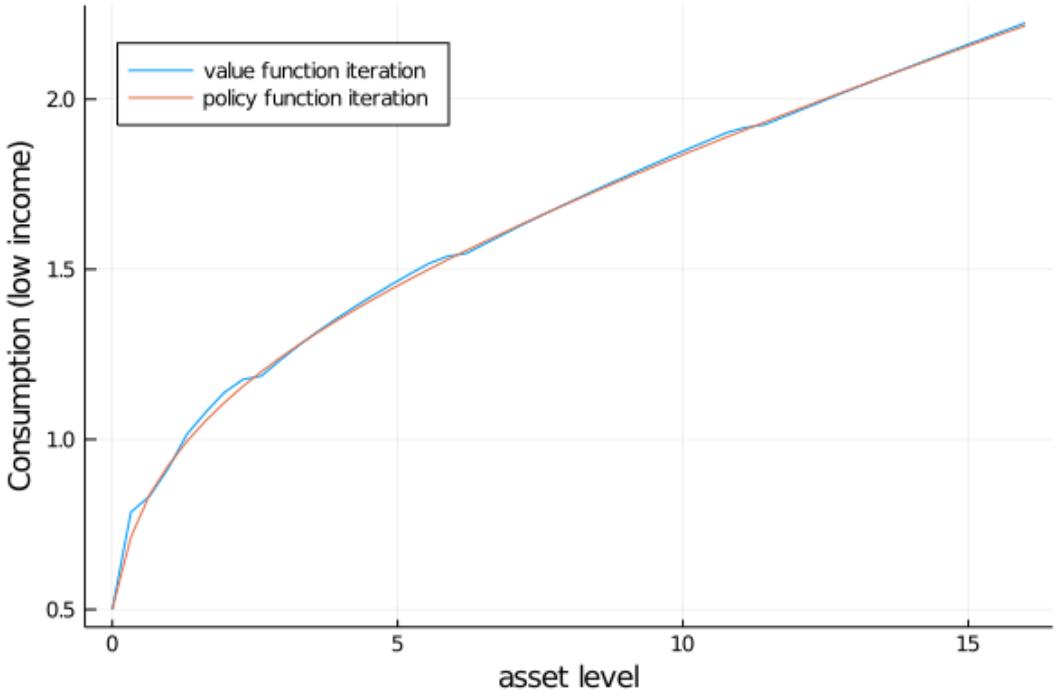
38.6.1 Exercise 1

In [8]:
```
cp = ConsumerProblem()
N = 80

V, c = initialize(cp)
println("Starting value function iteration")
for i in 1:N
    V = T(cp, V)
end
c1 = T(cp, V, ret_policy=true)

V2, c2 = initialize(cp)
println("Starting policy function iteration")
for i in 1:N
    c2 = K(cp, c2)
end

plot(cp.asset_grid, c1[:, 1], label = "value function iteration")
plot!(cp.asset_grid, c2[:, 1], label = "policy function iteration")
```

```
plot!(xlabel = "asset level", ylabel = "Consumption (low income)")
plot!(legend = :topleft)
```

```
   Starting value function iteration
Starting policy function iteration
```

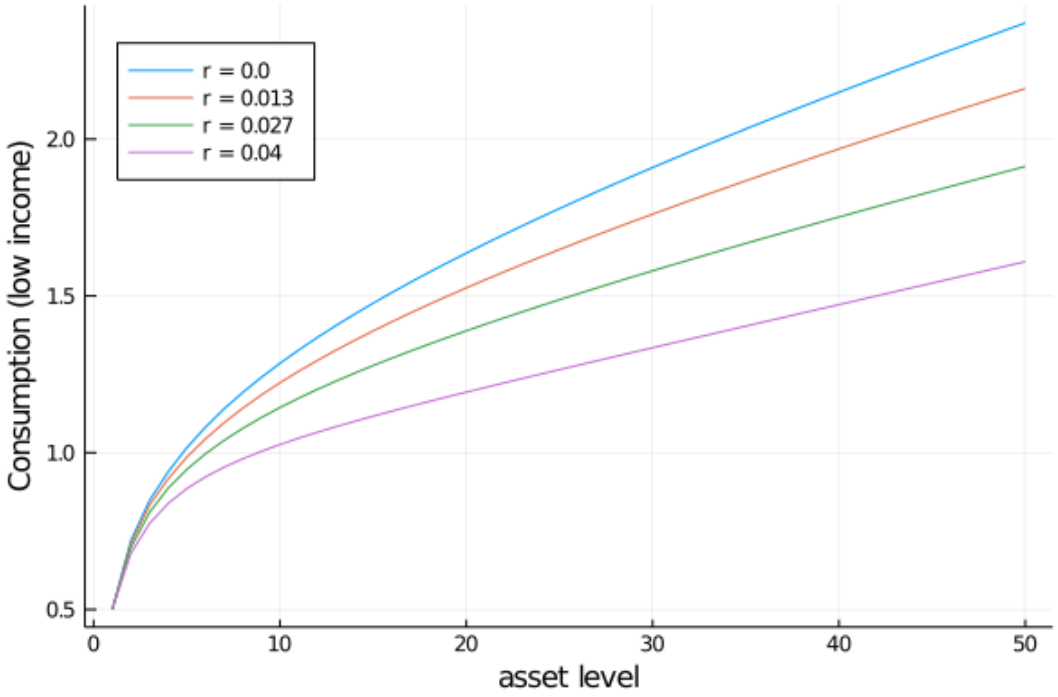
Out[8]:



38.6.2 Exercise 2

In [9]:
```
r_vals = range(0, 0.04, length = 4)
traces = []
legends = []

for r_val in r_vals
    cp = ConsumerProblem(r = r_val)
    v_init, c_init = initialize(cp)
    c = compute_fixed_point(x -> K(cp, x),
                            c_init,
                            max_iter = 150,
                            verbose = false)
    traces = push!(traces, c[:, 1])
    legends = push!(legends, "r = $(round(r_val, digits = 3))")
end

plot(traces, label = reshape(legends, 1, length(legends)))
plot!(xlabel = "asset level", ylabel = "Consumption (low income)")
plot!(legend = :topleft)
```

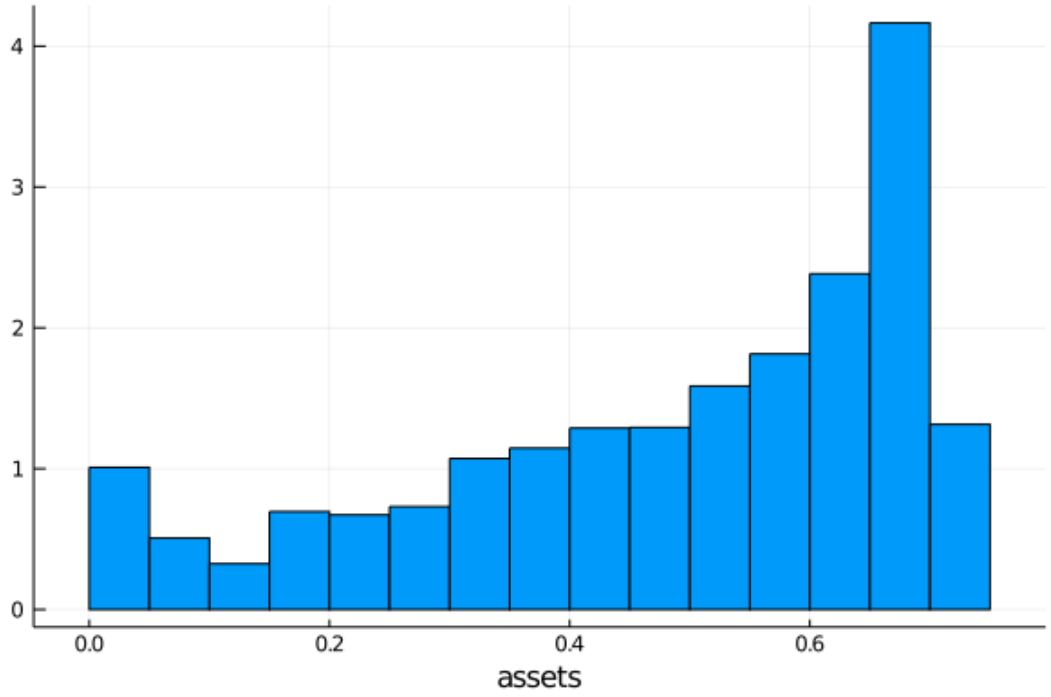
Out[9]:



38.6.3 Exercise 3

In [10]:
```
function compute_asset_series(cp, T = 500_000; verbose = false)
    @unpack Π, z_vals, R = cp  # simplify names
    z_idx = 1:length(z_vals)
    v_init, c_init = initialize(cp)
    c = compute_fixed_point(x -> K(cp, x), c_init,
                            max_iter = 150, verbose = false)

    cf = interp(cp.asset_grid, c)

    a = zeros(T + 1)
    z_seq = simulate(MarkovChain(Π), T)
    for t in 1:T
        i_z = z_seq[t]
        a[t+1] = R * a[t] + z_vals[i_z] - cf(a[t], i_z)
    end
    return a
end

cp = ConsumerProblem(r = 0.03, grid_max = 4)
Random.seed!(42) # for reproducibility
a = compute_asset_series(cp)
histogram(a, nbins = 20, leg = false, normed = true, xlabel = "assets")
```

Out[10]:

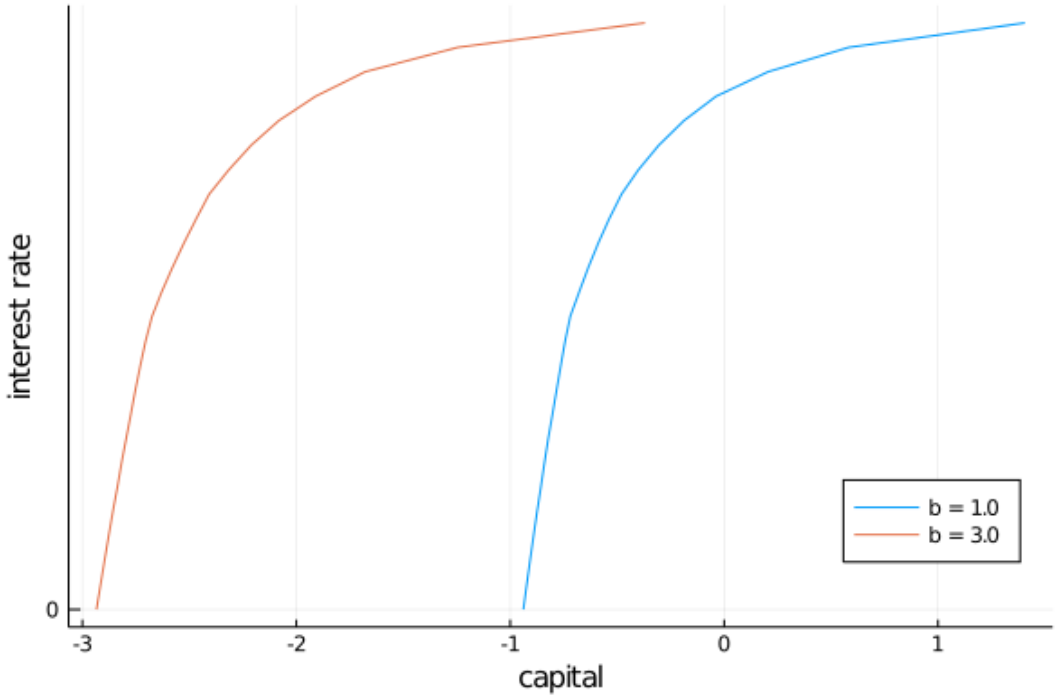


38.6.4 Exercise 4

In [11]:
```
M = 25
r_vals = range(0, 0.04, length = M)

xs = []
ys = []
legends = []
for b in [1.0, 3.0]
    asset_mean = zeros(M)
    for (i, r_val) in enumerate(r_vals)
        cp = ConsumerProblem(r = r_val, b = b)
        the_mean = mean(compute_asset_series(cp, 250_000))
        asset_mean[i] = the_mean
    end
    xs = push!(xs, asset_mean)
    ys = push!(ys, r_vals)
    legends = push!(legends, "b = $b")
    println("Finished iteration b = $b")
end
plot(xs, ys, label = reshape(legends, 1, length(legends)))
plot!(xlabel = "capital", ylabel = "interest rate", yticks = ([0, 0.045]))
plot!(legend = :bottomright)
```

```
Finished iteration b = 1.0
Finished iteration b = 3.0
```

Out[11]:


interest rate
0
-3
-2
-1
0
1
capital
b = 1.0
b = 3.0

Chapter 39

Robustness

39.1 Contents

39.2 Overview

This lecture modifies a Bellman equation to express a decision maker's doubts about transition dynamics.

His specification doubts make the decision maker want a *robust* decision rule.

Robust means insensitive to misspecification of transition dynamics.

The decision maker has a single *approximating model*.

He calls it *approximating* to acknowledge that he doesn't completely trust it.

He fears that outcomes will actually be determined by another model that he cannot describe explicitly.

All that he knows is that the actual data-generating model is in some (uncountable) set of models that surrounds his approximating model.

He quantifies the discrepancy between his approximating model and the genuine data-generating model by using a quantity called *entropy*.

(We'll explain what entropy means below)

He wants a decision rule that will work well enough no matter which of those other models actually governs outcomes.

This is what it means for his decision rule to be "robust to misspecification of an approximating model".

This may sound like too much to ask for, but ....

... a *secret weapon* is available to design robust decision rules.

The secret weapon is max-min control theory.

A value-maximizing decision maker enlists the aid of an (imaginary) value-minimizing model chooser to construct *bounds* on the value attained by a given decision rule under different models of the transition dynamics.

The original decision maker uses those bounds to construct a decision rule with an assured performance level, no matter which model actually governs outcomes.

> **Note**
>
> In reading this lecture, please don't think that our decision maker is paranoid when he conducts a worst-case analysis. By designing a rule that works well against a worst-case, his intention is to construct a rule that will work well across a *set* of models.

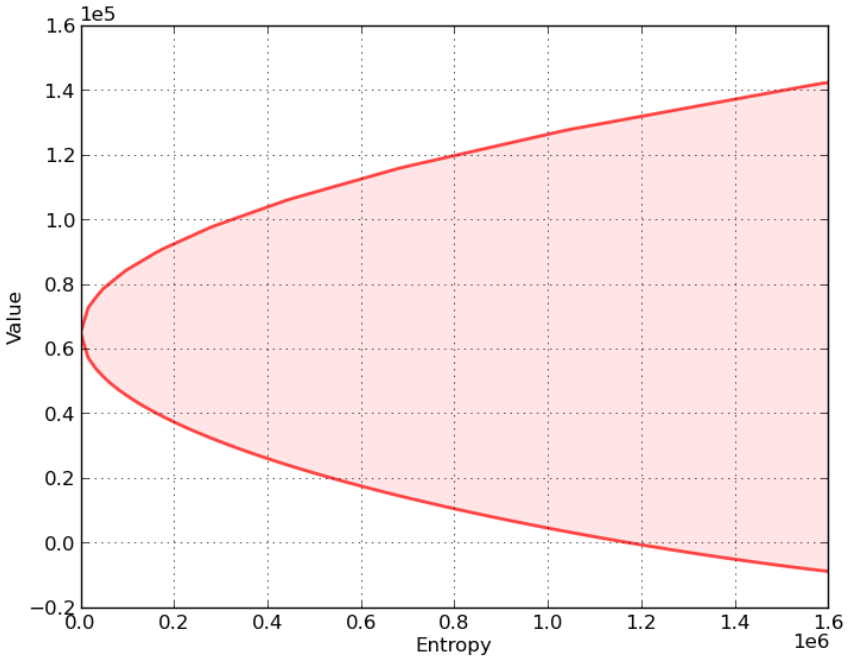
39.2.1 Sets of Models Imply Sets Of Values

Our "robust" decision maker wants to know how well a given rule will work when he does not *know* a single transition law ....

... he wants to know *sets* of values that will be attained by a given decision rule F under a *set* of transition laws.

Ultimately, he wants to design a decision rule F that shapes these *sets* of values in ways that he prefers.

With this in mind, consider the following graph, which relates to a particular decision problem to be explained below



The figure shows a *value-entropy correspondence* for a particular decision rule F.

The shaded set is the graph of the correspondence, which maps entropy to a set of values associated with a set of models that surround the decision maker's approximating model.

Here

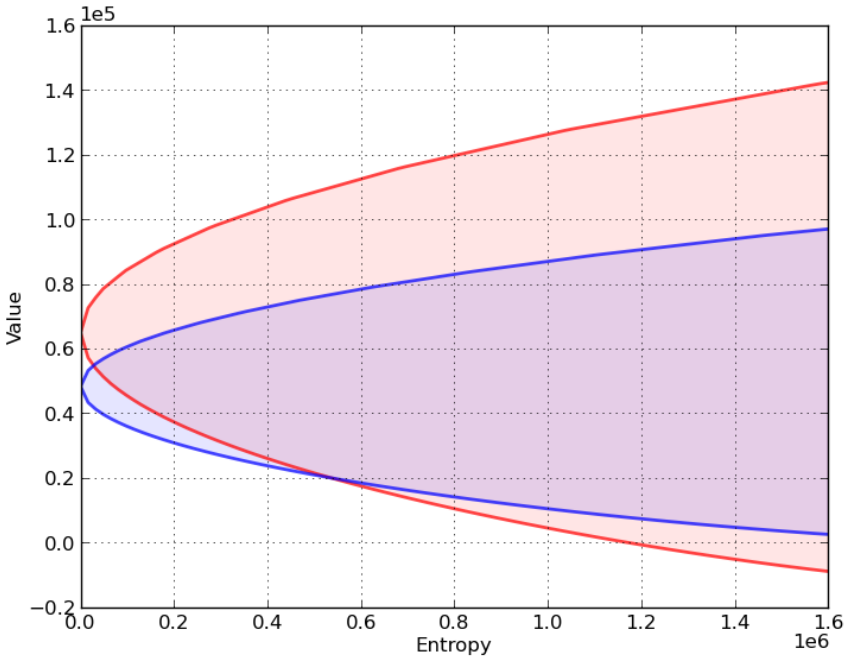
- *Value* refers to a sum of discounted rewards obtained by applying the decision rule F when the state starts at some fixed initial state x_0.
- *Entropy* is a nonnegative number that measures the size of a set of models surrounding the decision maker's approximating model.
  - Entropy is zero when the set includes only the approximating model, indicating that the decision maker completely trusts the approximating model.
  - Entropy is bigger, and the set of surrounding models is bigger, the less the decision maker trusts the approximating model.

The shaded region indicates that for **all** models having entropy less than or equal to the number on the horizontal axis, the value obtained will be somewhere within the indicated set of values.

Now let's compare sets of values associated with two different decision rules, F_r and F_b.

In the next figure,

- The red set shows the value-entropy correspondence for decision rule F_r.
- The blue set shows the value-entropy correspondence for decision rule F_b.



The blue correspondence is skinnier than the red correspondence.

This conveys the sense in which the decision rule F_b is *more robust* than the decision rule F_r.

- *more robust* means that the set of values is less sensitive to *increasing misspecification* as measured by entropy.

Notice that the less robust rule F_r promises higher values for small misspecifications (small entropy).

(But it is more fragile in the sense that it is more sensitive to perturbations of the approximating model)

Below we'll explain in detail how to construct these sets of values for a given F, but for now ....

Here is a hint about the *secret weapons* we'll use to construct these sets

- We'll use some min problems to construct the lower bounds.
- We'll use some max problems to construct the upper bounds.

We will also describe how to choose F to shape the sets of values.

This will involve crafting a *skinnier* set at the cost of a lower *level* (at least for low values of entropy).

39.2.2 Inspiring Video

If you want to understand more about why one serious quantitative researcher is interested in this approach, we recommend Lars Peter Hansen's Nobel lecture.

39.2.3 Other References

Our discussion in this lecture is based on

- [45]
- [39]

39.2.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

39.3 The Model

For simplicity, we present ideas in the context of a class of problems with linear transition laws and quadratic objective functions.

To fit in with our earlier lecture on LQ control, we will treat loss minimization rather than value maximization.

To begin, recall the infinite horizon LQ problem, where an agent chooses a sequence of controls $\{u_t\}$ to minimize

$$\sum_{t=0}^{\infty} \beta^t \{x_t' R x_t + u_t' Q u_t\} \tag{1}$$

subject to the linear law of motion

$$x_{t+1} = Ax_t + Bu_t + Cw_{t+1}, \qquad t = 0, 1, 2, ... \tag{2}$$

As before,

- x_t is $n \times 1$, A is $n \times n$
- u_t is $k \times 1$, B is $n \times k$
- w_t is $j \times 1$, C is $n \times j$
- R is $n \times n$ and Q is $k \times k$

Here x_t is the state, u_t is the control, and w_t is a shock vector.

For now we take $\{w_t\} := \{w_t\}_{t=1}^{\infty}$ to be deterministic — a single fixed sequence.

We also allow for *model uncertainty* on the part of the agent solving this optimization problem.

In particular, the agent takes $w_t = 0$ for all $t \geq 0$ as a benchmark model, but admits the possibility that this model might be wrong.

As a consequence, she also considers a set of alternative models expressed in terms of sequences $\{w_t\}$ that are "close" to the zero sequence.

She seeks a policy that will do well enough for a set of alternative models whose members are pinned down by sequences $\{w_t\}$.

Soon we'll quantify the quality of a model specification in terms of the maximal size of the expression $\sum_{t=0}^{\infty} \beta^{t+1} w_{t+1}' w_{t+1}$.

39.4 Constructing More Robust Policies

If our agent takes $\{w_t\}$ as a given deterministic sequence, then, drawing on intuition from earlier lectures on dynamic programming, we can anticipate Bellman equations such as

$$J_{t-1}(x) = \min_u \{x' R x + u' Q u + \beta J_t(Ax + Bu + Cw_t)\}$$

(Here J depends on t because the sequence $\{w_t\}$ is not recursive)

Our tool for studying robustness is to construct a rule that works well even if an adverse sequence $\{w_t\}$ occurs.

In our framework, "adverse" means "loss increasing".

As we'll see, this will eventually lead us to construct the Bellman equation.

$$J(x) = \min_u \max_w \{x' R x + u' Q u + \beta [J(Ax + Bu + Cw) - \theta w' w]\} \tag{3}$$

Notice that we've added the penalty term $-\theta w' w$.

Since $w' w = \|w\|^2$, this term becomes influential when w moves away from the origin.

The penalty parameter θ controls how much we penalize the maximizing agent for "harming" the minimizing agent.

By raising θ more and more, we more and more limit the ability of maximizing agent to distort outcomes relative to the approximating model.

So bigger θ is implicitly associated with smaller distortion sequences $\{w_t\}$.

39.4.1 Analyzing the Bellman equation

So what does J in (3) look like?

As with the ordinary LQ control model, J takes the form $J(x) = x'Px$ for some symmetric positive definite matrix P.

One of our main tasks will be to analyze and compute the matrix P.

Related tasks will be to study associated feedback rules for u_t and w_{t+1}.

First, using matrix calculus, you will be able to verify that

$$\begin{aligned} \max_w \{(Ax + Bu + Cw)'P(Ax + Bu + Cw) - \theta w'w\} \\ = (Ax + Bu)'\mathcal{D}(P)(Ax + Bu) \end{aligned} \tag{4}$$

where

$$\mathcal{D}(P) := P + PC(\theta I - C'PC)^{-1}C'P \tag{5}$$

and I is a $j \times j$ identity matrix. Substituting this expression for the maximum into (3) yields

$$x'Px = \min_u \{x'Rx + u'Qu + \beta\,(Ax + Bu)'\mathcal{D}(P)(Ax + Bu)\} \tag{6}$$

Using similar mathematics, the solution to this minimization problem is $u = -Fx$ where $F := (Q + \beta B'\mathcal{D}(P)B)^{-1}\beta B'\mathcal{D}(P)A$.

Substituting this minimizer back into (6) and working through the algebra gives $x'Px = x'\mathcal{B}(\mathcal{D}(P))x$ for all x, or, equivalently,

$$P = \mathcal{B}(\mathcal{D}(P))$$

where $\mathcal{D}$ is the operator defined in (5) and

$$\mathcal{B}(P) := R - \beta^2 A'PB(Q + \beta B'PB)^{-1}B'PA + \beta A'PA$$

The operator $\mathcal{B}$ is the standard (i.e., non-robust) LQ Bellman operator, and $P = \mathcal{B}(P)$ is the standard matrix Riccati equation coming from the Bellman equation — see this discussion.

Under some regularity conditions (see [39]), the operator $\mathcal{B} \circ \mathcal{D}$ has a unique positive definite fixed point, which we denote below by $\hat{P}$.

A robust policy, indexed by θ, is $u = -\hat{F}x$ where

$$\hat{F} := (Q + \beta B'\mathcal{D}(\hat{P})B)^{-1}\beta B'\mathcal{D}(\hat{P})A \tag{7}$$

We also define

$$\hat{K} := (\theta I - C'\hat{P}C)^{-1}C'\hat{P}(A - B\hat{F}) \tag{8}$$

The interpretation of $\hat{K}$ is that $w_{t+1} = \hat{K}x_t$ on the worst-case path of $\{x_t\}$, in the sense that this vector is the maximizer of (4) evaluated at the fixed rule $u = -\hat{F}x$.

Note that $\hat{P}, \hat{F}, \hat{K}$ are all determined by the primitives and θ.

Note also that if θ is very large, then $\mathcal{D}$ is approximately equal to the identity mapping.

Hence, when θ is large, $\hat{P}$ and $\hat{F}$ are approximately equal to their standard LQ values.

Furthermore, when θ is large, $\hat{K}$ is approximately equal to zero.

Conversely, smaller θ is associated with greater fear of model misspecification, and greater concern for robustness.

39.5 Robustness as Outcome of a Two-Person Zero-Sum Game

What we have done above can be interpreted in terms of a two-person zero-sum game in which $\hat{F}, \hat{K}$ are Nash equilibrium objects.

Agent 1 is our original agent, who seeks to minimize loss in the LQ program while admitting the possibility of misspecification.

Agent 2 is an imaginary malevolent player.

Agent 2's malevolence helps the original agent to compute bounds on his value function across a set of models.

We begin with agent 2's problem.

39.5.1 Agent 2's Problem

Agent 2

1. knows a fixed policy F specifying the behavior of agent 1, in the sense that $u_t = -Fx_t$ for all t
2. responds by choosing a shock sequence $\{w_t\}$ from a set of paths sufficiently close to the benchmark sequence $\{0, 0, 0, ...\}$

A natural way to say "sufficiently close to the zero sequence" is to restrict the summed inner product $\sum_{t=1}^{\infty} w_t' w_t$ to be small.

However, to obtain a time-invariant recursive formulation, it turns out to be convenient to restrict a discounted inner product

$$\sum_{t=1}^{\infty} \beta^t w_t' w_t \leq \eta \tag{9}$$

Now let F be a fixed policy, and let $J_F(x_0, \mathbf{w})$ be the present-value cost of that policy given sequence $\mathbf{w} := \{w_t\}$ and initial condition $x_0 \in \mathbb{R}^n$.

Substituting $-Fx_t$ for u_t in (1), this value can be written as

$$J_F(x_0, \mathbf{w}) := \sum_{t=0}^{\infty} \beta^t x_t'(R + F'QF)x_t \tag{10}$$

where

$$x_{t+1} = (A - BF)x_t + Cw_{t+1} \tag{11}$$

and the initial condition x_0 is as specified in the left side of (10).

Agent 2 chooses $\mathbf{w}$ to maximize agent 1's loss $J_F(x_0, \mathbf{w})$ subject to (9).

Using a Lagrangian formulation, we can express this problem as

$$\max_{\mathbf{w}} \sum_{t=0}^{\infty} \beta^t \left\{ x_t'(R + F'QF)x_t - \beta\theta(w_{t+1}'w_{t+1} - \eta) \right\}$$

where $\{x_t\}$ satisfied (11) and θ is a Lagrange multiplier on constraint (9).

For the moment, let's take θ as fixed, allowing us to drop the constant $\beta\theta\eta$ term in the objective function, and hence write the problem as

$$\max_{\mathbf{w}} \sum_{t=0}^{\infty} \beta^t \left\{ x_t'(R + F'QF)x_t - \beta\theta w_{t+1}'w_{t+1} \right\}$$

or, equivalently,

$$\min_{\mathbf{w}} \sum_{t=0}^{\infty} \beta^t \left\{ -x_t'(R + F'QF)x_t + \beta\theta w_{t+1}'w_{t+1} \right\} \tag{12}$$

subject to (11).

What's striking about this optimization problem is that it is once again an LQ discounted dynamic programming problem, with $\mathbf{w} = \{w_t\}$ as the sequence of controls.

The expression for the optimal policy can be found by applying the usual LQ formula (see here).

We denote it by $K(F, \theta)$, with the interpretation $w_{t+1} = K(F, \theta)x_t$.

The remaining step for agent 2's problem is to set θ to enforce the constraint (9), which can be done by choosing $\theta = \theta_\eta$ such that

$$\beta \sum_{t=0}^{\infty} \beta^t x_t' K(F, \theta_\eta)' K(F, \theta_\eta) x_t = \eta \tag{13}$$

Here x_t is given by (11) — which in this case becomes $x_{t+1} = (A - BF + CK(F, \theta))x_t$.

39.5.2 Using Agent 2's Problem to Construct Bounds on the Value Sets

The Lower Bound

Define the minimized object on the right side of problem (12) as $R_\theta(x_0, F)$.

Because "minimizers minimize" we have

$$R_\theta(x_0, F) \leq \sum_{t=0}^{\infty} \beta^t \{-x_t'(R + F'QF)x_t\} + \beta\theta \sum_{t=0}^{\infty} \beta^t w_{t+1}' w_{t+1},$$

where $x_{t+1} = (A - BF + CK(F, \theta))x_t$ and x_0 is a given initial condition.

This inequality in turn implies the inequality

$$R_\theta(x_0, F) - \theta \text{ ent} \leq \sum_{t=0}^{\infty} \beta^t \{-x_t'(R + F'QF)x_t\} \tag{14}$$

where

$$\text{ent} := \beta \sum_{t=0}^{\infty} \beta^t w_{t+1}' w_{t+1}$$

The left side of inequality (14) is a straight line with slope $-\theta$.

Technically, it is a "separating hyperplane".

At a particular value of entropy, the line is tangent to the lower bound of values as a function of entropy.

In particular, the lower bound on the left side of (14) is attained when

$$\text{ent} = \beta \sum_{t=0}^{\infty} \beta^t x_t' K(F, \theta)' K(F, \theta) x_t \tag{15}$$

To construct the *lower bound* on the set of values associated with all perturbations $\mathbf{w}$ satisfying the entropy constraint (9) at a given entropy level, we proceed as follows:

- For a given θ, solve the minimization problem (12).
- Compute the minimizer $R_\theta(x_0, F)$ and the associated entropy using (15).
- Compute the lower bound on the value function $R_\theta(x_0, F) - \theta$ ent and plot it against ent.
- Repeat the preceding three steps for a range of values of θ to trace out the lower bound.

Note

This procedure sweeps out a set of separating hyperplanes indexed by different values for the Lagrange multiplier θ.

The Upper Bound

To construct an *upper bound* we use a very similar procedure.

We simply replace the *minimization* problem (12) with the *maximization* problem.

$$V_{\tilde{\theta}}(x_0, F) = \max_{\mathbf{w}} \sum_{t=0}^{\infty} \beta^t \left\{ -x_t'(R + F'QF)x_t - \beta\tilde{\theta} w_{t+1}' w_{t+1} \right\} \tag{16}$$

where now $\tilde{\theta} > 0$ penalizes the choice of $\mathbf{w}$ with larger entropy.

(Notice that $\tilde{\theta} = -\theta$ in problem (12))

Because "maximizers maximize" we have

$$V_{\tilde{\theta}}(x_0, F) \geq \sum_{t=0}^{\infty} \beta^t \left\{ -x_t'(R + F'QF)x_t \right\} - \beta\tilde{\theta} \sum_{t=0}^{\infty} \beta^t w_{t+1}' w_{t+1}$$

which in turn implies the inequality

$$V_{\tilde{\theta}}(x_0, F) + \tilde{\theta} \text{ ent} \geq \sum_{t=0}^{\infty} \beta^t \left\{ -x_t'(R + F'QF)x_t \right\} \tag{17}$$

where

$$\text{ent} \equiv \beta \sum_{t=0}^{\infty} \beta^t w_{t+1}' w_{t+1}$$

The left side of inequality (17) is a straight line with slope $\tilde{\theta}$.

The upper bound on the left side of (17) is attained when

$$\text{ent} = \beta \sum_{t=0}^{\infty} \beta^t x_t' K(F, \tilde{\theta})' K(F, \tilde{\theta}) x_t \tag{18}$$

To construct the *upper bound* on the set of values associated all perturbations $\mathbf{w}$ with a given entropy we proceed much as we did for the lower bound.

- For a given $\tilde{\theta}$, solve the maximization problem (16).

- Compute the maximizer $V_{\tilde{\theta}}(x_0, F)$ and the associated entropy using (18).
- Compute the upper bound on the value function $V_{\tilde{\theta}}(x_0, F) + \tilde{\theta}$ ent and plot it against ent.
- Repeat the preceding three steps for a range of values of $\tilde{\theta}$ to trace out the upper bound.

Reshaping the set of values

Now in the interest of *reshaping* these sets of values by choosing F, we turn to agent 1's problem.

39.5.3 Agent 1's Problem

Now we turn to agent 1, who solves

$$\min_{\{u_t\}} \sum_{t=0}^{\infty} \beta^t \left\{ x_t' R x_t + u_t' Q u_t - \beta \theta w_{t+1}' w_{t+1} \right\} \tag{19}$$

where $\{w_{t+1}\}$ satisfies $w_{t+1} = K x_t$.

In other words, agent 1 minimizes

$$\sum_{t=0}^{\infty} \beta^t \left\{ x_t' (R - \beta \theta K' K) x_t + u_t' Q u_t \right\} \tag{20}$$

subject to

$$x_{t+1} = (A + CK) x_t + B u_t \tag{21}$$

Once again, the expression for the optimal policy can be found here — we denote it by $\tilde{F}$.

39.5.4 Nash Equilibrium

Clearly the $\tilde{F}$ we have obtained depends on K, which, in agent 2's problem, depended on an initial policy F.

Holding all other parameters fixed, we can represent this relationship as a mapping Φ, where

$$\tilde{F} = \Phi(K(F, \theta))$$

The map $F \mapsto \Phi(K(F, \theta))$ corresponds to a situation in which

1. agent 1 uses an arbitrary initial policy F
2. agent 2 best responds to agent 1 by choosing $K(F, \theta)$
3. agent 1 best responds to agent 2 by choosing $\tilde{F} = \Phi(K(F, \theta))$

As you may have already guessed, the robust policy $\hat{F}$ defined in (7) is a fixed point of the mapping Φ.

In particular, for any given θ,

1. $K(\hat{F}, \theta) = \hat{K}$, where $\hat{K}$ is as given in (8)
2. $\Phi(\hat{K}) = \hat{F}$

A sketch of the proof is given in the appendix.

39.6 The Stochastic Case

Now we turn to the stochastic case, where the sequence $\{w_t\}$ is treated as an iid sequence of random vectors.

In this setting, we suppose that our agent is uncertain about the *conditional probability distribution* of w_{t+1}.

The agent takes the standard normal distribution $N(0, I)$ as the baseline conditional distribution, while admitting the possibility that other "nearby" distributions prevail.

These alternative conditional distributions of w_{t+1} might depend nonlinearly on the history $x_s, s \leq t$.

To implement this idea, we need a notion of what it means for one distribution to be near another one.

Here we adopt a very useful measure of closeness for distributions known as the *relative entropy*, or Kullback-Leibler divergence.

For densities p, q, the Kullback-Leibler divergence of q from p is defined as

$$D_{KL}(p, q) := \int \ln\left[\frac{p(x)}{q(x)}\right] p(x)\, dx$$

Using this notation, we replace (3) with the stochastic analogue

$$J(x) = \min_u \max_{\psi \in \mathcal{P}} \left\{ x'Rx + u'Qu + \beta \left[\int J(Ax + Bu + Cw)\, \psi(dw) - \theta D_{KL}(\psi, \phi) \right] \right\} \tag{22}$$

Here $\mathcal{P}$ represents the set of all densities on $\mathbb{R}^n$ and ϕ is the benchmark distribution $N(0, I)$.

The distribution ϕ is chosen as the least desirable conditional distribution in terms of next period outcomes, while taking into account the penalty term $\theta D_{KL}(\psi, \phi)$.

This penalty term plays a role analogous to the one played by the deterministic penalty $\theta w'w$ in (3), since it discourages large deviations from the benchmark.

39.6.1 Solving the Model

The maximization problem in (22) appears highly nontrivial — after all, we are maximizing over an infinite dimensional space consisting of the entire set of densities.

However, it turns out that the solution is tractable, and in fact also falls within the class of normal distributions.

First, we note that J has the form $J(x) = x'Px + d$ for some positive definite matrix P and constant real number d.

Moreover, it turns out that if $(I - \theta^{-1} C'PC)^{-1}$ is nonsingular, then

$$\begin{aligned} &\max_{\psi \in \mathcal{P}} \left\{ \int (Ax + Bu + Cw)' P (Ax + Bu + Cw)\, \psi(dw) - \theta D_{KL}(\psi, \phi) \right\} \\ &\qquad = (Ax + Bu)' \mathcal{D}(P)(Ax + Bu) + \kappa(\theta, P) \end{aligned} \tag{23}$$

where

$$\kappa(\theta, P) := \theta \ln[\det(I - \theta^{-1} C' P C)^{-1}]$$

and the maximizer is the Gaussian distribution

$$\psi = N\left((\theta I - C' P C)^{-1} C' P (Ax + Bu), (I - \theta^{-1} C' P C)^{-1}\right) \tag{24}$$

Substituting the expression for the maximum into Bellman equation (22) and using $J(x) = x' P x + d$ gives

$$x' P x + d = \min_u \left\{ x' R x + u' Q u + \beta (Ax + Bu)' \mathcal{D}(P)(Ax + Bu) + \beta \left[d + \kappa(\theta, P) \right] \right\} \tag{25}$$

Since constant terms do not affect minimizers, the solution is the same as (6), leading to

$$x' P x + d = x' \mathcal{B}(\mathcal{D}(P)) x + \beta \left[d + \kappa(\theta, P) \right]$$

To solve this Bellman equation, we take $\hat{P}$ to be the positive definite fixed point of $\mathcal{B} \circ \mathcal{D}$.

In addition, we take $\hat{d}$ as the real number solving $d = \beta \left[d + \kappa(\theta, P) \right]$, which is

$$\hat{d} := \frac{\beta}{1 - \beta} \kappa(\theta, P) \tag{26}$$

The robust policy in this stochastic case is the minimizer in (25), which is once again $u = -\hat{F} x$ for $\hat{F}$ given by (7).

Substituting the robust policy into (24) we obtain the worst case shock distribution:

$$w_{t+1} \sim N(\hat{K} x_t, (I - \theta^{-1} C' \hat{P} C)^{-1})$$

where $\hat{K}$ is given by (8).

Note that the mean of the worst-case shock distribution is equal to the same worst-case w_{t+1} as in the earlier deterministic setting.

39.6.2 Computing Other Quantities

Before turning to implementation, we briefly outline how to compute several other quantities of interest.

Worst-Case Value of a Policy

One thing we will be interested in doing is holding a policy fixed and computing the discounted loss associated with that policy.

So let F be a given policy and let $J_F(x)$ be the associated loss, which, by analogy with (22), satisfies

$$J_F(x) = \max_{\psi \in \mathcal{P}} \left\{ x'(R + F'QF)x + \beta \left[\int J_F((A - BF)x + Cw)\, \psi(dw) - \theta D_{KL}(\psi, \phi) \right] \right\}$$

Writing $J_F(x) = x' P_F x + d_F$ and applying the same argument used to derive (23) we get

$$x' P_F x + d_F = x'(R + F'QF)x + \beta \left[x'(A - BF)' \mathcal{D}(P_F)(A - BF)x + d_F + \kappa(\theta, P_F) \right]$$

To solve this we take P_F to be the fixed point

$$P_F = R + F'QF + \beta(A - BF)' \mathcal{D}(P_F)(A - BF)$$

and

$$d_F := \frac{\beta}{1 - \beta} \kappa(\theta, P_F) = \frac{\beta}{1 - \beta} \theta \ln[\det(I - \theta^{-1} C' P_F C)^{-1}] \tag{27}$$

If you skip ahead to the appendix, you will be able to verify that $-P_F$ is the solution to the Bellman equation in agent 2's problem discussed above — we use this in our computations.

39.7 Implementation

The QuantEcon.jl package provides a type called `RBLQ` for implementation of robust LQ optimal control.

The code can be found on GitHub.

Here is a brief description of the methods of the type

- `d_operator()` and `b_operator()` implement $\mathcal{D}$ and $\mathcal{B}$ respectively
- `robust_rule()` and `robust_rule_simple()` both solve for the triple $\hat{F}, \hat{K}, \hat{P}$, as described in equations (7) – (8) and the surrounding discussion
  - `robust_rule()` is more efficient
  - `robust_rule_simple()` is more transparent and easier to follow
- `K_to_F()` and `F_to_K()` solve the decision problems of agent 1 and agent 2 respectively
- `compute_deterministic_entropy()` computes the left-hand side of (13)
- `evaluate_F()` computes the loss and entropy associated with a given policy — see this discussion

39.8 Application

Let us consider a monopolist similar to this one, but now facing model uncertainty.

The inverse demand function is $p_t = a_0 - a_1 y_t + d_t$

where

$$d_{t+1} = \rho d_t + \sigma_d w_{t+1}, \quad \{w_t\} \overset{\text{iid}}{\sim} N(0, 1)$$

and all parameters are strictly positive.

The period return function for the monopolist is

$$r_t = p_t y_t - \gamma \frac{(y_{t+1} - y_t)^2}{2} - c y_t$$

Its objective is to maximize expected discounted profits, or, equivalently, to minimize $\mathbb{E} \sum_{t=0}^{\infty} \beta^t (-r_t)$.

To form a linear regulator problem, we take the state and control to be

$$x_t = \begin{bmatrix} 1 \\ y_t \\ d_t \end{bmatrix} \quad \text{and} \quad u_t = y_{t+1} - y_t$$

Setting $b := (a_0 - c)/2$ we define

$$R = - \begin{bmatrix} 0 & b & 0 \\ b & -a_1 & 1/2 \\ 0 & 1/2 & 0 \end{bmatrix} \quad \text{and} \quad Q = \gamma/2$$

For the transition matrices we set

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \rho \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \qquad C = \begin{bmatrix} 0 \\ 0 \\ \sigma_d \end{bmatrix}$$

Our aim is to compute the value-entropy correspondences shown above.

The parameters are

$$a_0 = 100, a_1 = 0.5, \rho = 0.9, \sigma_d = 0.05, \beta = 0.95, c = 2, \gamma = 50.0$$

The standard normal distribution for w_t is understood as the agent's baseline, with uncertainty parameterized by θ.

We compute value-entropy correspondences for two policies.

1. The no concern for robustness policy F_0, which is the ordinary LQ loss minimizer.
2. A "moderate" concern for robustness policy F_b, with $\theta = 0.02$.

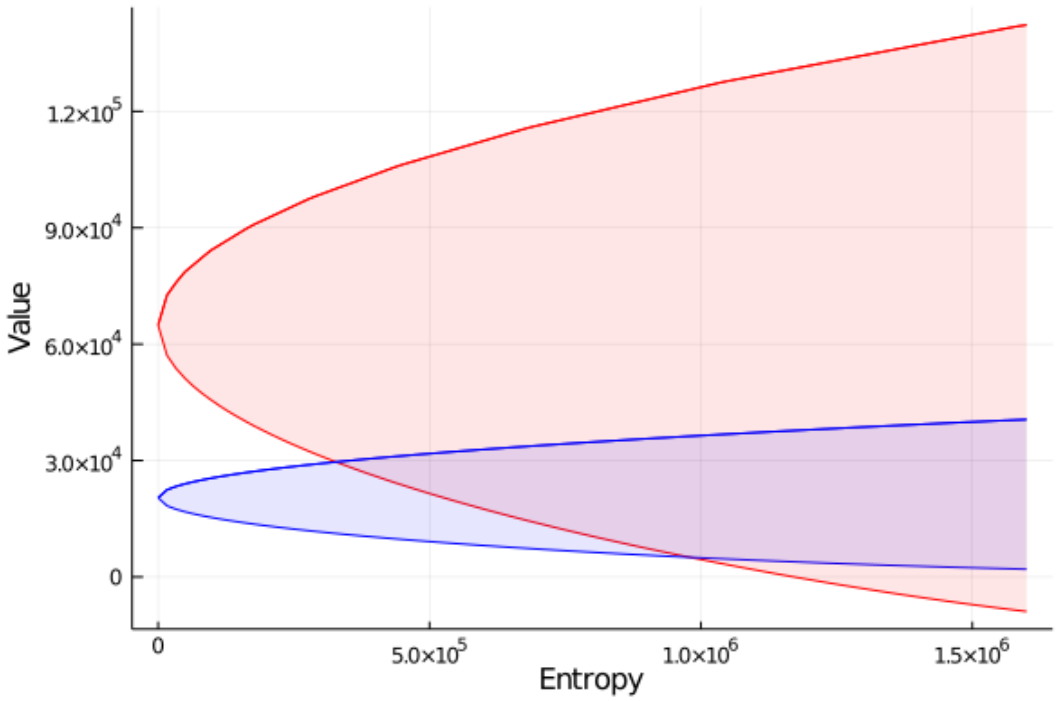
The code for producing the graph shown above, with blue being for the robust policy, is as follows

In [3]:
```
using QuantEcon, Plots, LinearAlgebra, Interpolations
gr(fmt = :png);

# model parameters
a_0 = 100
a_1 = 0.5
ρ = 0.9
σ_d = 0.05
β = 0.95
```

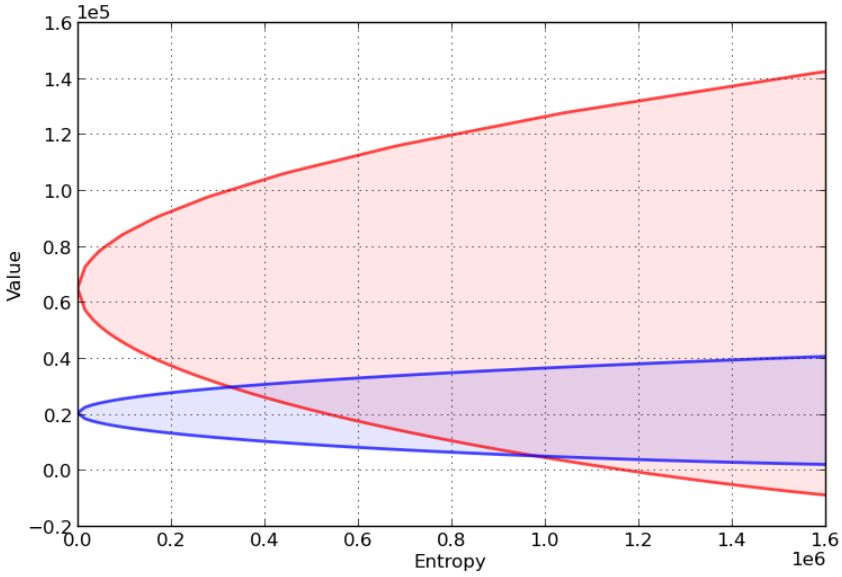
```
c = 2
γ = 50.0
θ = 0.002
ac = (a_0 - c) / 2.0

# Define LQ matrices
R = [ 0   ac    0;
    ac -a_1  0.5;
    0.  0.5    0]
R = -R  # For minimization
Q = Matrix([γ / 2.0]')
A = [1. 0. 0.;
    0. 1. 0.;
    0. 0.  ρ]
B = [0. 1. 0.]'
C = [0. 0. σ_d]'

## Functions

function evaluate_policy(θ, F)
    rlq = RBLQ(Q, R, A, B, C, β, θ)
    K_F, P_F, d_F, O_F, o_F = evaluate_F(rlq, F)
    x0 = [1.0 0.0 0.0]'
    value = - x0' * P_F * x0 .- d_F
    entropy = x0' * O_F * x0 .+ o_F
    return value[1], entropy[1]    # return scalars
end

function value_and_entropy(emax, F, bw, grid_size = 1000)
    if lowercase(bw) == "worst"
        θs = 1 ./ range(1e-8,  1000, length = grid_size)
    else
        θs = -1 ./ range(1e-8,  1000, length = grid_size)
    end

    data = zeros(grid_size, 2)

    for (i, θ) in enumerate(θs)
        data[i, :] = collect(evaluate_policy(θ, F))
        if data[i, 2] ≥ emax      # stop at this entropy level
            data = data[1:i, :]
            break
        end
    end
    return data
end

## Main

# compute optimal rule
optimal_lq = QuantEcon.LQ(Q, R, A, B, C, zero(B'A), bet=β)
Po, Fo, Do = stationary_values(optimal_lq)

# compute robust rule for our ϑ
baseline_robust = RBLQ(Q, R, A, B, C, β, θ)
Fb, Kb, Pb = robust_rule(baseline_robust)

# Check the positive definiteness of worst-case covariance matrix to
```

```
# ensure that θ exceeds the breakdown point
test_matrix = I - (C' * Pb * C ./ θ)[1]
eigenvals, eigenvecs = eigen(test_matrix)
@assert all(x -> x ≥ 0, eigenvals)

emax = 1.6e6

# compute values and entropies
optimal_best_case = value_and_entropy(emax, Fo, "best")
robust_best_case = value_and_entropy(emax, Fb, "best")
optimal_worst_case = value_and_entropy(emax, Fo, "worst")
robust_worst_case = value_and_entropy(emax, Fb, "worst")

# we reverse order of "worst_case"s so values are ascending
data_pairs = ((optimal_best_case, optimal_worst_case),
              (robust_best_case, robust_worst_case))

egrid = range(0,  emax, length = 100)
egrid_data = []
for data_pair in data_pairs
    for data in data_pair
        x, y = data[:, 2], data[:, 1]
        curve = LinearInterpolation(x, y, extrapolation_bc = Line())
        push!(egrid_data, curve.(egrid))
    end
end
plot(egrid, egrid_data, color=[:red :red :blue :blue])
plot!(egrid, egrid_data[1], fillrange=egrid_data[2],
    fillcolor=:red, fillalpha=0.1, color=:red, legend=:none)
plot!(egrid, egrid_data[3], fillrange=egrid_data[4],
    fillcolor=:blue, fillalpha=0.1, color=:blue, legend=:none)
plot!(xlabel="Entropy", ylabel="Value")
```

Out[3]:



Here's another such figure, with $\theta = 0.002$ instead of 0.02



Can you explain the different shape of the value-entropy correspondence for the robust policy?

39.9 Appendix

We sketch the proof only of the first claim in this section, which is that, for any given θ, $K(\hat{F}, \theta) = \hat{K}$, where $\hat{K}$ is as given in (8).

This is the content of the next lemma.

Lemma. If $\hat{P}$ is the fixed point of the map $\mathcal{B} \circ \mathcal{D}$ and $\hat{F}$ is the robust policy as given in (7), then

$$K(\hat{F}, \theta) = (\theta I - C' \hat{P} C)^{-1} C' \hat{P} (A - B\hat{F}) \tag{28}$$

Proof: As a first step, observe that when $F = \hat{F}$, the Bellman equation associated with the LQ problem (11) – (12) is

$$\tilde{P} = -R - \hat{F}' Q \hat{F} - \beta^2 (A - B\hat{F})' \tilde{P} C (\beta\theta I + \beta C' \tilde{P} C)^{-1} C' \tilde{P} (A - B\hat{F}) + \beta (A - B\hat{F})' \tilde{P} (A - B\hat{F}) \tag{29}$$

(revisit this discussion if you don't know where (29) comes from) and the optimal policy is

$$w_{t+1} = -\beta (\beta\theta I + \beta C' \tilde{P} C)^{-1} C' \tilde{P} (A - B\hat{F}) x_t$$

Suppose for a moment that $-\hat{P}$ solves the Bellman equation (29).

In this case the policy becomes

$$w_{t+1} = (\theta I - C'\hat{P}C)^{-1}C'\hat{P}(A - B\hat{F})x_t$$

which is exactly the claim in (28).

Hence it remains only to show that $-\hat{P}$ solves (29), or, in other words,

$$\hat{P} = R + \hat{F}'Q\hat{F} + \beta(A - B\hat{F})'\hat{P}C(\theta I - C'\hat{P}C)^{-1}C'\hat{P}(A - B\hat{F}) + \beta(A - B\hat{F})'\hat{P}(A - B\hat{F})$$

Using the definition of $\mathcal{D}$, we can rewrite the right-hand side more simply as

$$R + \hat{F}'Q\hat{F} + \beta(A - B\hat{F})'\mathcal{D}(\hat{P})(A - B\hat{F})$$

Although it involves a substantial amount of algebra, it can be shown that the latter is just $\hat{P}$.

(Hint: Use the fact that $\hat{P} = \mathcal{B}(\mathcal{D}(\hat{P}))$)

Chapter 40

Discrete State Dynamic Programming

40.1 Contents

40.2 Overview

In this lecture we discuss a family of dynamic programming problems with the following features:

1. a discrete state space and discrete choices (actions)
2. an infinite horizon
3. discounted rewards
4. Markov state transitions

We call such problems discrete dynamic programs, or discrete DPs.

Discrete DPs are the workhorses in much of modern quantitative economics, including

- monetary economics
- search and labor economics
- household savings and consumption theory
- investment theory
- asset pricing
- industrial organization, etc.

When a given model is not inherently discrete, it is common to replace it with a discretized version in order to use discrete DP techniques.

This lecture covers

- the theory of dynamic programming in a discrete setting, plus examples and applications
- a powerful set of routines for solving discrete DPs from the QuantEcon code libary

40.2.1 How to Read this Lecture

We use dynamic programming many applied lectures, such as

- The shortest path lecture
- The McCall search model lecture
- The optimal growth lecture

The objective of this lecture is to provide a more systematic and theoretical treatment, including algorithms and implementation, while focusing on the discrete case.

40.2.2 References

For background reading on dynamic programming and additional applications, see, for example,

- [68]
- [53], section 3.5
- [86]
- [100]
- [92]
- [78]
- EDTC, chapter 5

40.3 Discrete DPs

Loosely speaking, a discrete DP is a maximization problem with an objective function of the form

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t r(s_t, a_t) \tag{1}$$

where

- s_t is the state variable
- a_t is the action
- β is a discount factor
- $r(s_t, a_t)$ is interpreted as a current reward when the state is s_t and the action chosen is a_t

Each pair (s_t, a_t) pins down transition probabilities $Q(s_t, a_t, s_{t+1})$ for the next period state s_{t+1}.

Thus, actions influence not only current rewards but also the future time path of the state.

The essence of dynamic programming problems is to trade off current rewards vs favorable positioning of the future state (modulo randomness).

Examples:

- consuming today vs saving and accumulating assets
- accepting a job offer today vs seeking a better one in the future
- exercising an option now vs waiting

40.3.1 Policies

The most fruitful way to think about solutions to discrete DP problems is to compare *policies*.

In general, a policy is a randomized map from past actions and states to current action.

In the setting formalized below, it suffices to consider so-called *stationary Markov policies*, which consider only the current state.

In particular, a stationary Markov policy is a map σ from states to actions

- $a_t = \sigma(s_t)$ indicates that a_t is the action to be taken in state s_t

It is known that, for any arbitrary policy, there exists a stationary Markov policy that dominates it at least weakly.

- See section 5.5 of [86] for discussion and proofs.

In what follows, stationary Markov policies are referred to simply as policies.

The aim is to find an optimal policy, in the sense of one that maximizes (1).

Let's now step through these ideas more carefully.

40.3.2 Formal definition

Formally, a discrete dynamic program consists of the following components:

1. A finite set of *states* $S = \{0, \ldots, n-1\}$
2. A finite set of *feasible actions* $A(s)$ for each state $s \in S$, and a corresponding set of *feasible state-action pairs*

$$SA := \{(s, a) \mid s \in S,\ a \in A(s)\}$$

1. A *reward function* $r \colon SA \to \mathbb{R}$
2. A *transition probability function* $Q \colon SA \to \Delta(S)$, where $\Delta(S)$ is the set of probability distributions over S
3. A *discount factor* $\beta \in [0, 1)$

We also use the notation $A := \bigcup_{s \in S} A(s) = \{0, \ldots, m-1\}$ and call this set the *action space*.

A *policy* is a function $\sigma \colon S \to A$.

A policy is called *feasible* if it satisfies $\sigma(s) \in A(s)$ for all $s \in S$.

Denote the set of all feasible policies by Σ.

If a decision maker uses a policy $\sigma \in \Sigma$, then

- the current reward at time t is $r(s_t, \sigma(s_t))$
- the probability that $s_{t+1} = s'$ is $Q(s_t, \sigma(s_t), s')$

For each $\sigma \in \Sigma$, define

- r_σ by $r_\sigma(s) := r(s, \sigma(s))$
- Q_σ by $Q_\sigma(s, s') := Q(s, \sigma(s), s')$

Notice that Q_σ is a stochastic matrix on S.

It gives transition probabilities of the *controlled chain* when we follow policy σ.

If we think of r_σ as a column vector, then so is $Q_\sigma^t r_\sigma$, and the s-th row of the latter has the interpretation

$$(Q_\sigma^t r_\sigma)(s) = \mathbb{E}[r(s_t, \sigma(s_t)) \mid s_0 = s] \quad \text{when } \{s_t\} \sim Q_\sigma \tag{2}$$

Comments

- $\{s_t\} \sim Q_\sigma$ means that the state is generated by stochastic matrix Q_σ
- See this discussion on computing expectations of Markov chains for an explanation of the expression in (2)

Notice that we're not really distinguishing between functions from S to $\mathbb{R}$ and vectors in $\mathbb{R}^n$.

This is natural because they are in one to one correspondence.

40.3.3 Value and Optimality

Let $v_\sigma(s)$ denote the discounted sum of expected reward flows from policy σ when the initial state is s.

To calculate this quantity we pass the expectation through the sum in (1) and use (2) to get

$$v_\sigma(s) = \sum_{t=0}^{\infty} \beta^t (Q_\sigma^t r_\sigma)(s) \qquad (s \in S)$$

This function is called the *policy value function* for the policy σ.

The *optimal value function*, or simply *value function*, is the function $v^* \colon S \to \mathbb{R}$ defined by

$$v^*(s) = \max_{\sigma \in \Sigma} v_\sigma(s) \qquad (s \in S)$$

(We can use max rather than sup here because the domain is a finite set)

A policy $\sigma \in \Sigma$ is called *optimal* if $v_\sigma(s) = v^*(s)$ for all $s \in S$.

Given any $w \colon S \to \mathbb{R}$, a policy $\sigma \in \Sigma$ is called w-greedy if

$$\sigma(s) \in \operatorname*{arg\,max}_{a \in A(s)} \left\{ r(s, a) + \beta \sum_{s' \in S} w(s') Q(s, a, s') \right\} \qquad (s \in S)$$

As discussed in detail below, optimal policies are precisely those that are v^*-greedy.

40.3.4 Two Operators

It is useful to define the following operators:

- The *Bellman operator* $T\colon \mathbb{R}^S \to \mathbb{R}^S$ is defined by

$$(Tv)(s) = \max_{a \in A(s)} \left\{ r(s,a) + \beta \sum_{s' \in S} v(s') Q(s,a,s') \right\} \qquad (s \in S)$$

- For any policy function $\sigma \in \Sigma$, the operator $T_\sigma\colon \mathbb{R}^S \to \mathbb{R}^S$ is defined by

$$(T_\sigma v)(s) = r(s,\sigma(s)) + \beta \sum_{s' \in S} v(s') Q(s,\sigma(s),s') \qquad (s \in S)$$

This can be written more succinctly in operator notation as

$$T_\sigma v = r_\sigma + \beta Q_\sigma v$$

The two operators are both monotone

- $v \leq w$ implies $Tv \leq Tw$ pointwise on S, and similarly for T_σ

They are also contraction mappings with modulus β

- $\|Tv - Tw\| \leq \beta \|v - w\|$ and similarly for T_σ, where $\|\cdot\|$ is the max norm

For any policy σ, its value v_σ is the unique fixed point of T_σ.

For proofs of these results and those in the next section, see, for example, EDTC, chapter 10.

40.3.5 The Bellman Equation and the Principle of Optimality

The main principle of the theory of dynamic programming is that

- the optimal value function v^* is a unique solution to the *Bellman equation*,

$$v(s) = \max_{a \in A(s)} \left\{ r(s,a) + \beta \sum_{s' \in S} v(s') Q(s,a,s') \right\} \qquad (s \in S),$$

  or in other words, v^* is the unique fixed point of T, and
- σ^* is an optimal policy function if and only if it is v^*-greedy

By the definition of greedy policies given above, this means that

$$\sigma^*(s) \in \operatorname*{arg\,max}_{a \in A(s)} \left\{ r(s,a) + \beta \sum_{s' \in S} v^*(s') Q(s,\sigma(s),s') \right\} \qquad (s \in S)$$

40.4 Solving Discrete DPs

Now that the theory has been set out, let's turn to solution methods.

Code for solving discrete DPs is available in ddp.jl from the QuantEcon.jl code library.

It implements the three most important solution methods for discrete dynamic programs, namely

- value function iteration
- policy function iteration
- modified policy function iteration

Let's briefly review these algorithms and their implementation.

40.4.1 Value Function Iteration

Perhaps the most familiar method for solving all manner of dynamic programs is value function iteration.

This algorithm uses the fact that the Bellman operator T is a contraction mapping with fixed point v^*.

Hence, iterative application of T to any initial function $v^0 \colon S \to \mathbb{R}$ converges to v^*.

The details of the algorithm can be found in the appendix.

40.4.2 Policy Function Iteration

This routine, also known as Howard's policy improvement algorithm, exploits more closely the particular structure of a discrete DP problem.

Each iteration consists of

1. A policy evaluation step that computes the value v_σ of a policy σ by solving the linear equation $v = T_\sigma v$.
2. A policy improvement step that computes a v_σ-greedy policy.

In the current setting policy iteration computes an exact optimal policy in finitely many iterations.

- See theorem 10.2.6 of EDTC for a proof

The details of the algorithm can be found in the appendix.

40.4.3 Modified Policy Function Iteration

Modified policy iteration replaces the policy evaluation step in policy iteration with "partial policy evaluation".

The latter computes an approximation to the value of a policy σ by iterating T_σ for a specified number of times.

This approach can be useful when the state space is very large and the linear system in the policy evaluation step of policy iteration is correspondingly difficult to solve.

The details of the algorithm can be found in the appendix.

40.5 Example: A Growth Model

Let's consider a simple consumption-saving model.

A single household either consumes or stores its own output of a single consumption good.

The household starts each period with current stock s.

Next, the household chooses a quantity a to store and consumes $c = s - a$

- Storage is limited by a global upper bound M
- Flow utility is $u(c) = c^\alpha$

Output is drawn from a discrete uniform distribution on $\{0, \dots, B\}$.

The next period stock is therefore

$$s' = a + U \quad \text{where} \quad U \sim U[0, \dots, B]$$

The discount factor is $\beta \in [0, 1)$.

40.5.1 Discrete DP Representation

We want to represent this model in the format of a discrete dynamic program.

To this end, we take

- the state variable to be the stock s
- the state space to be $S = \{0, \dots, M + B\}$
  - hence $n = M + B + 1$
- the action to be the storage quantity a
- the set of feasible actions at s to be $A(s) = \{0, \dots, \min\{s, M\}\}$
  - hence $A = \{0, \dots, M\}$ and $m = M + 1$
- the reward function to be $r(s, a) = u(s - a)$
- the transition probabilities to be

$$Q(s, a, s') := \begin{cases} \frac{1}{B+1} & \text{if } a \leq s' \leq a + B \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

40.5.2 Defining a DiscreteDP Instance

This information will be used to create an instance of DiscreteDP by passing the following information

1. An $n \times m$ reward array R
2. An $n \times m \times n$ transition probability array Q
3. A discount factor β

For R we set $R[s, a] = u(s - a)$ if $a \leq s$ and $-\infty$ otherwise.

For Q we follow the rule in (3).

Note:

- The feasibility constraint is embedded into R by setting $R[s, a] = -\infty$ for $a \notin A(s)$.
- Probability distributions for (s, a) with $a \notin A(s)$ can be arbitrary.

The following code sets up these objects for us.

40.5.3 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, BenchmarkTools, Plots, QuantEcon
        using SparseArrays
```

```
In [3]: using BenchmarkTools, Plots, QuantEcon, Parameters
        gr(fmt = :png);
```

```
In [4]: SimpleOG = @with_kw (B = 10, M = 5, α = 0.5, β = 0.9)

        function transition_matrices(g)
            @unpack B, M, α, β = g
            u(c) = c^α
            n = B + M + 1
            m = M + 1

            R = zeros(n, m)
            Q = zeros(n, m, n)

            for a in 0:M
                Q[:, a + 1, (a:(a + B)) .+ 1] .= 1 / (B + 1)
                for s in 0:(B + M)
                    R[s + 1, a + 1] = (a≤s ? u(s - a) : -Inf)
                end
            end

            return (Q = Q, R = R)
        end
```

```
Out[4]: transition_matrices (generic function with 1 method)
```

Let's run this code and create an instance of `SimpleOG`

```
In [5]: g = SimpleOG();
        Q, R = transition_matrices(g);
```

In case the preceding code was too concise, we can see a more verbose form

```
In [6]: function verbose_matrices(g)
            @unpack B, M, α, β = g
            u(c) = c^α

            #Matrix dimensions. The +1 is due to the 0 state.
```

```
            n = B + M + 1
            m = M + 1

            R = fill(-Inf, n, m) #Start assuming nothing is feasible
            Q = zeros(n,m,n) #Assume 0 by default

            #Create the R matrix
            #Note: indexing into matrix complicated since Julia starts indexing at
↪1 instead of
        0
            #but the state s and choice a can be 0
            for a in 0:M
                 for s in 0:(B + M)
                    if a <= s #i.e. if feasible
                        R[s + 1, a + 1] = u(s - a)
                    end
                end
            end

            #Create the Q multi-array
            for s in 0:(B+M) #For each state
                for a in 0:M #For each action
                    for sp in 0:(B+M) #For each state next period
                       if( sp >= a && sp <= a + B) # The support of all realizations
                            Q[s + 1, a + 1, sp + 1] = 1 / (B + 1) # Same prob of all
                         end
                    end
                 @assert sum(Q[s + 1, a + 1, :]) ≈ 1 #Optional check that matrix is
        stochastic
                end
            end
            return (Q = Q, R = R)
        end
```

```
Out[6]: verbose_matrices (generic function with 1 method)
```

Instances of `DiscreteDP` are created using the signature `DiscreteDP(R, Q, β)`.

Let's create an instance using the objects stored in `g`

```
In [7]: ddp = DiscreteDP(R, Q, g.β);
```

Now that we have an instance `ddp` of `DiscreteDP` we can solve it as follows

```
In [8]: results = solve(ddp, PFI)
```

```
Out[8]: QuantEcon.DPSolveResult{PFI,Float64}([19.01740221695992, 20.
↪017402216959916,
        20.431615779333015, 20.749453024528794, 21.040780991093488, 21.
↪30873018352461,
        21.544798161024403, 21.76928181079986, 21.982703576083246, 22.
↪1882432282385,
        22.384504796519916, 22.578077363861723, 22.761091269771118, 22.
↪943767083452716,
        23.115339958706524, 23.277617618874903], [19.01740221695992, 20.
↪01740221695992,
```

```
       20.431615779333015, 20.749453024528798, 21.040780991093488, 21.
↪30873018352461,
       21.5447981610244, 21.769281810799864, 21.982703576083253, 22.1882432282385,
       22.38450479651991, 22.578077363861723, 22.761091269771114, 22.
↪943767083452716,
       23.115339958706524, 23.277617618874903], 3, [1, 1, 1, 1, 2, 2, 2, 3, 3, 4,
↪4, 5, 6, 6,
       6, 6], Discrete Markov Chain
       stochastic matrix of type Adjoint{Float64,Array{Float64,2}}:
       [0.09090909090909091 0.09090909090909091 … 0.0 0.0; 0.09090909090909091
       0.09090909090909091 … 0.0 0.0; … ; 0.0 0.0 … 0.09090909090909091 0.
↪09090909090909091;
       0.0 0.0 … 0.09090909090909091 0.09090909090909091])
```

Let's see what we've got here

```
In [9]: fieldnames(typeof(results))
```

```
Out[9]: (:v, :Tv, :num_iter, :sigma, :mc)
```

The most important attributes are `v`, the value function, and σ, the optimal policy

```
In [10]: results.v
```

```
Out[10]: 16-element Array{Float64,1}:
          19.01740221695992
          20.017402216959916
          20.431615779333015
          20.749453024528794
          21.040780991093488
          21.30873018352461
          21.544798161024403
          21.76928181079986
          21.982703576083246
          22.1882432282385
          22.384504796519916
          22.578077363861723
          22.761091269771118
          22.943767083452716
          23.115339958706524
          23.277617618874903
```

```
In [11]: results.sigma .- 1
```

```
Out[11]: 16-element Array{Int64,1}:
          0
          0
          0
          0
          1
          1
          1
          2
          2
```

```
3
3
4
5
5
5
5
```

Here 1 is subtracted from results.sigma because we added 1 to each state and action to create valid indices.

Since we've used policy iteration, these results will be exact unless we hit the iteration bound `max_iter`.

Let's make sure this didn't happen

```
In [12]: results.num_iter
```

```
Out[12]: 3
```

In this case we converged in only 3 iterations.

Another interesting object is `results.mc`, which is the controlled chain defined by Q_{σ^*}, where σ^* is the optimal policy.

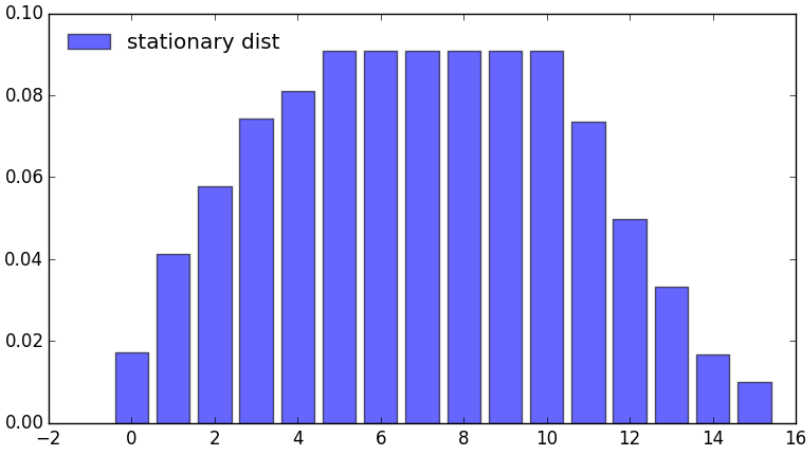
In other words, it gives the dynamics of the state when the agent follows the optimal policy.

Since this object is an instance of MarkovChain from QuantEcon.jl (see this lecture for more discussion), we can easily simulate it, compute its stationary distribution and so on

```
In [13]: stationary_distributions(results.mc)[1]
```

```
Out[13]: 16-element Array{Float64,1}:
          0.01732186732186732
          0.041210632119723034
          0.05773955773955773
          0.07426848335939244
          0.08095823095823096
          0.09090909090909091
          0.0909090909090909
          0.0909090909090909
          0.09090909090909093
          0.09090909090909091
          0.09090909090909091
          0.0735872235872236
          0.049698458789367884
          0.033169533169533166
          0.016640607549698462
          0.009950859950859951
```

Here's the same information in a bar graph



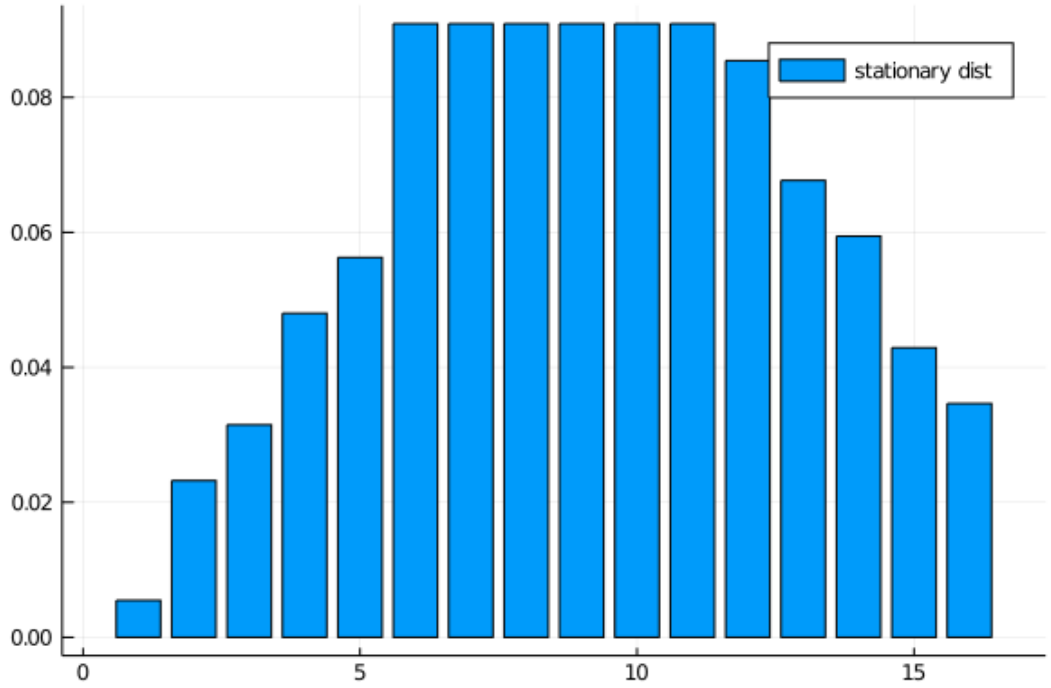
What happens if the agent is more patient?

```
In [14]: g_2 = SimpleOG(β=0.99);
         Q_2, R_2 = transition_matrices(g_2);

         ddp_2 = DiscreteDP(R_2, Q_2, g_2.β)

         results_2 = solve(ddp_2, PFI)

         std_2 = stationary_distributions(results_2.mc)[1]
```

```
Out[14]: 16-element Array{Float64,1}:
          0.005469129800680602
          0.023213417598444343
          0.03147788040836169
          0.04800680602819641
          0.056271268838113765
          0.09090909090909091
          0.09090909090909093
          0.09090909090909093
          0.09090909090909094
          0.09090909090909093
          0.09090909090909094
          0.0854399611084103
          0.06769567331064659
          0.059431210500729234
          0.042902284880894495
          0.03463782207097716
```

```
In [15]: bar(std_2, label = "stationary dist")
```

```
Out[15]:
```



We can see the rightward shift in probability mass.

40.5.4 State-Action Pair Formulation

The `DiscreteDP` type in fact provides a second interface to setting up an instance.

One of the advantages of this alternative set up is that it permits use of a sparse matrix for `Q`.

(An example of using sparse matrices is given in the exercises below)

The call signature of the second formulation is `DiscreteDP(R, Q, β, s_indices, a_indices)` where

- `s_indices` and `a_indices` are arrays of equal length `L` enumerating all feasible state-action pairs
- `R` is an array of length `L` giving corresponding rewards
- `Q` is an `L x n` transition probability array

Here's how we could set up these objects for the preceding example

```
In [16]: B = 10
         M = 5
         α = 0.5
         β = 0.9
         u(c) = c^α
         n = B + M + 1
         m = M + 1

         s_indices = Int64[]
         a_indices = Int64[]
         Q = zeros(0, n)
         R = zeros(0)
```

```
b = 1 / (B + 1)

for s in 0:(M + B)
    for a in 0:min(M, s)
        s_indices = [s_indices; s + 1]
        a_indices = [a_indices; a + 1]
        q = zeros(1, n)
        q[(a + 1):((a + B) + 1)] .= b
        Q = [Q; q]
        R = [R; u(s-a)]
    end
end

ddp = DiscreteDP(R, Q, β, s_indices, a_indices);
results = solve(ddp, PFI)
```

```
Out[16]: QuantEcon.DPSolveResult{PFI,Float64}([19.01740221695992, 20.
↪017402216959916,
        20.431615779333015, 20.749453024528794, 21.040780991093488, 21.
↪30873018352461,
        21.544798161024403, 21.76928181079986, 21.982703576083246, 22.
↪1882432282385,
        22.384504796519916, 22.578077363861723, 22.761091269771118, 22.
↪943767083452716,
        23.115339958706524, 23.277617618874903], [19.01740221695992, 20.
↪01740221695992,
        20.431615779333015, 20.749453024528798, 21.040780991093488, 21.
↪30873018352461,
       21.5447981610244, 21.769281810799864, 21.982703576083253, 22.1882432282385,
        22.38450479651991, 22.578077363861723, 22.761091269771114, 22.
↪943767083452716,
        23.115339958706524, 23.277617618874903], 3, [1, 1, 1, 1, 2, 2, 2, 3, 3,
↪4, 4, 5, 6, 6,
        6, 6], Discrete Markov Chain
        stochastic matrix of type Array{Float64,2}:
        [0.09090909090909091 0.09090909090909091 … 0.0 0.0; 0.09090909090909091
        0.09090909090909091 … 0.0 0.0; … ; 0.0 0.0 … 0.09090909090909091 0.
↪09090909090909091;
        0.0 0.0 … 0.09090909090909091 0.09090909090909091])
```

40.6 Exercises

In the stochastic optimal growth lecture dynamic programming lecture, we solve a benchmark model that has an analytical solution to check we could replicate it numerically.

The exercise is to replicate this solution using `DiscreteDP`.

40.7 Solutions

These were written jointly by Max Huber and Daisuke Oyama.

40.7.1 Setup

Details of the model can be found in the lecture. As in the lecture, we let $f(k) = k^\alpha$ with $\alpha = 0.65$, $u(c) = \log c$, and $\beta = 0.95$.

```
In [17]: α = 0.65
         f(k) = k.^α
         u_log(x) = log(x)
         β = 0.95
```

```
Out[17]: 0.95
```

Here we want to solve a finite state version of the continuous state model above. We discretize the state space into a grid of size `grid_size = 500`, from 10^{-6} to `grid_max=2`.

```
In [18]: grid_max = 2
         grid_size = 500
         grid = range(1e-6, grid_max, length = grid_size)
```

```
Out[18]: 1.0e-6:0.004008014028056112:2.0
```

We choose the action to be the amount of capital to save for the next period (the state is the capital stock at the beginning of the period). Thus the state indices and the action indices are both `1`, …, `grid_size`. Action (indexed by) `a` is feasible at state (indexed by) `s` if and only if `grid[a] < f([grid[s])` (zero consumption is not allowed because of the log utility).

Thus the Bellman equation is:

$$v(k) = \max_{0<k'<f(k)} u(f(k) - k') + \beta v(k'),$$

where k' is the capital stock in the next period.

The transition probability array `Q` will be highly sparse (in fact it is degenerate as the model is deterministic), so we formulate the problem with state-action pairs, to represent `Q` in sparse matrix format.

We first construct indices for state-action pairs:

```
In [19]: C = f.(grid) .- grid'
         coord = repeat(collect(1:grid_size), 1, grid_size) #coordinate matrix
         s_indices = coord[C .> 0]
         a_indices = transpose(coord)[C .> 0]
         L = length(a_indices)
```

```
Out[19]: 118841
```

Now let's set up R and Q

```
In [20]: R = u_log.(C[C.>0]);
```

```
In [21]: using SparseArrays

         Q = spzeros(L, grid_size) # Formerly spzeros

         for i in 1:L
             Q[i, a_indices[i]] = 1
         end
```

We're now in a position to create an instance of `DiscreteDP` corresponding to the growth model.

```
In [22]: ddp = DiscreteDP(R, Q, β, s_indices, a_indices);
```

40.7.2 Solving the Model

```
In [23]: results = solve(ddp, PFI)
         v, σ, num_iter = results.v, results.sigma, results.num_iter
         num_iter
```

```
Out[23]: 10
```

Let us compare the solution of the discrete model with the exact solution of the original continuous model. Here's the exact solution:

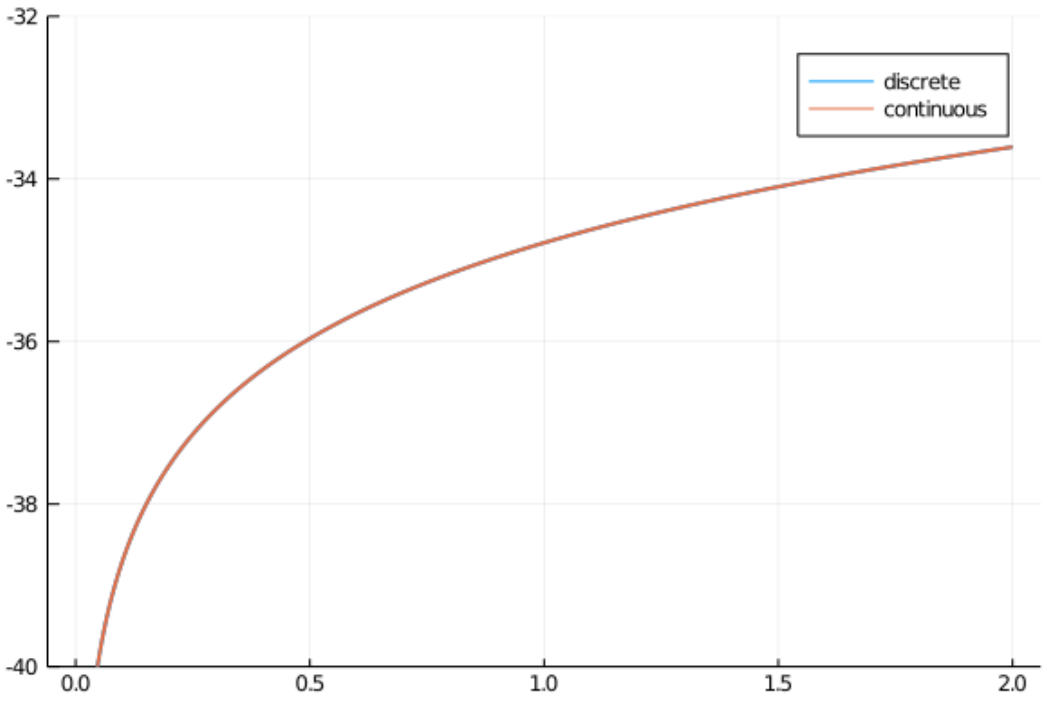
```
In [24]: c = f(grid) - grid[σ]

         ab = α * β
         c1 = (log(1 - α * β) + log(α * β) * α * β / (1 - α * β)) / (1 - β)
         c2 = α / (1 - α * β)

         v_star(k) = c1 + c2 * log(k)
         c_star(k) = (1 - α * β) * k.^α
```

```
Out[24]: c_star (generic function with 1 method)
```

Let's plot the value functions.

```
In [25]: plot(grid, [v v_star.(grid)], ylim = (-40, -32), lw = 2, label =
         ↪["discrete"
                "continuous"])
```

```
Out[25]:
```

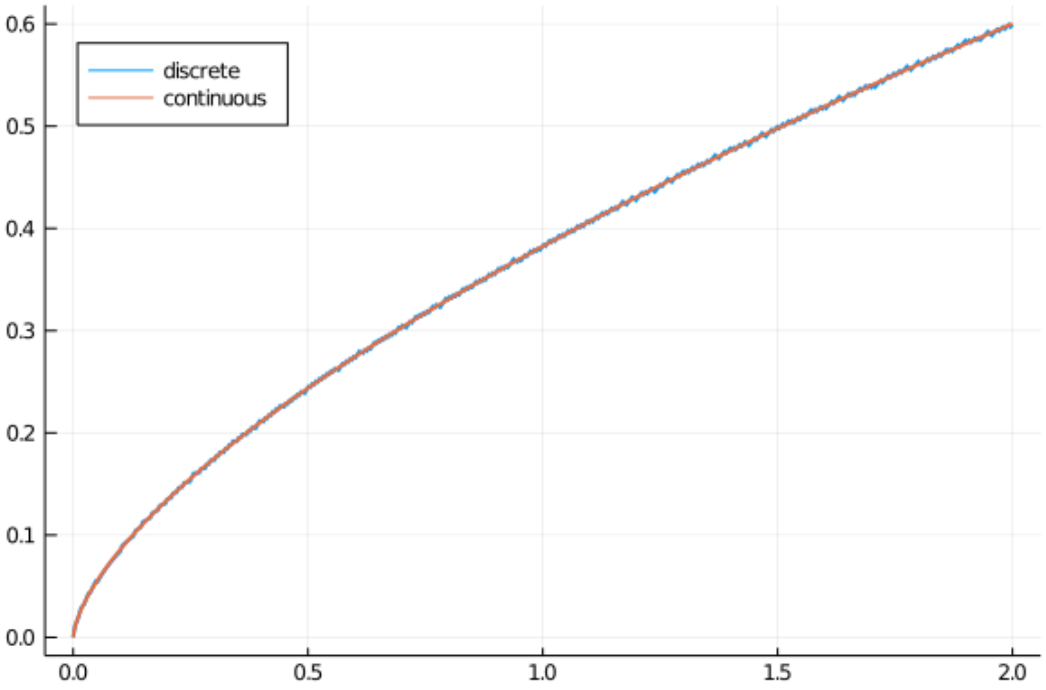


They are barely distinguishable (although you can see the difference if you zoom).

Now let's look at the discrete and exact policy functions for consumption.

```
In [26]: plot(grid, [c c_star.(grid)], lw = 2, label = ["discrete" "continuous"],
  ↪legend =
         :topleft)
```

Out[26]:



These functions are again close, although some difference is visible and becomes more obvious as you zoom. Here are some statistics:

```
In [27]: maximum(abs(x - v_star(y)) for (x, y) in zip(v, grid))
```

```
Out[27]: 121.49819147053378
```

This is a big error, but most of the error occurs at the lowest gridpoint. Otherwise the fit is reasonable:

```
In [28]: maximum(abs(v[idx] - v_star(grid[idx])) for idx in 2:lastindex(v))
```

```
Out[28]: 0.012681735127500815
```

The value function is monotone, as expected:

```
In [29]: all(x -> x ≥ 0, diff(v))
```

```
Out[29]: true
```

40.7.3 Comparison of the solution methods

Let's try different solution methods. The results below show that policy function iteration and modified policy function iteration are much faster that value function iteration.

```
In [30]: @benchmark results = solve(ddp, PFI)
         results = solve(ddp, PFI);
```

```
In [31]: @benchmark res1 = solve(ddp, VFI, max_iter = 500, epsilon = 1e-4)
         res1 = solve(ddp, VFI, max_iter = 500, epsilon = 1e-4);
```

```
In [32]: res1.num_iter
```

```
Out[32]: 294
```

```
In [33]: σ == res1.sigma
```

```
Out[33]: true
```

```
In [34]: @benchmark res2 = solve(ddp, MPFI, max_iter = 500, epsilon = 1e-4)
         res2 = solve(ddp, MPFI, max_iter = 500, epsilon = 1e-4);
```

```
In [35]: res2.num_iter
```

```
Out[35]: 16
```

```
In [36]: σ == res2.sigma
```

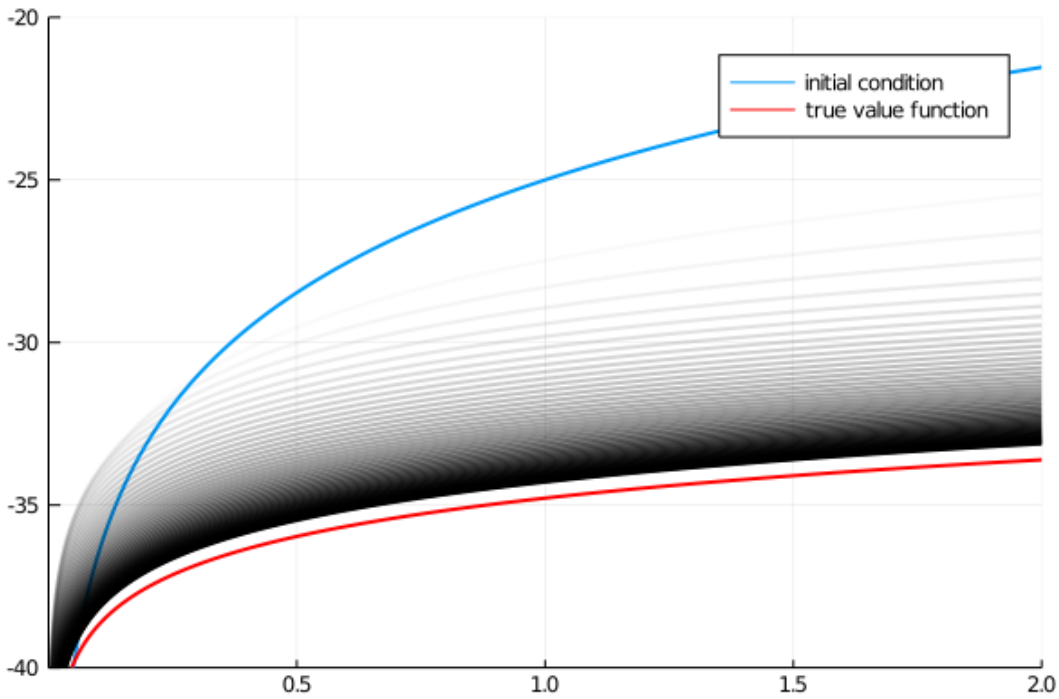
```
Out[36]: true
```

40.7.4 Replication of the figures

Let's visualize convergence of value function iteration, as in the lecture.

In [37]:
```
w_init = 5log.(grid) .- 25  # Initial condition
n = 50

ws = []
colors = []
w = w_init
for i in 0:n-1
    w = bellman_operator(ddp, w)
    push!(ws, w)
    push!(colors, RGBA(0, 0, 0, i/n))
end

plot(grid,
     w_init,
     ylims = (-40, -20),
     lw = 2,
     xlims = extrema(grid),
     label = "initial condition")

plot!(grid, ws,  label = "", color = reshape(colors, 1, length(colors)),
↪lw = 2)
plot!(grid, v_star.(grid), label = "true value function", color = :red,
↪lw = 2)
```

Out[37]:



We next plot the consumption policies along the value iteration. First we write a function to generate the and record the policies at given stages of iteration.

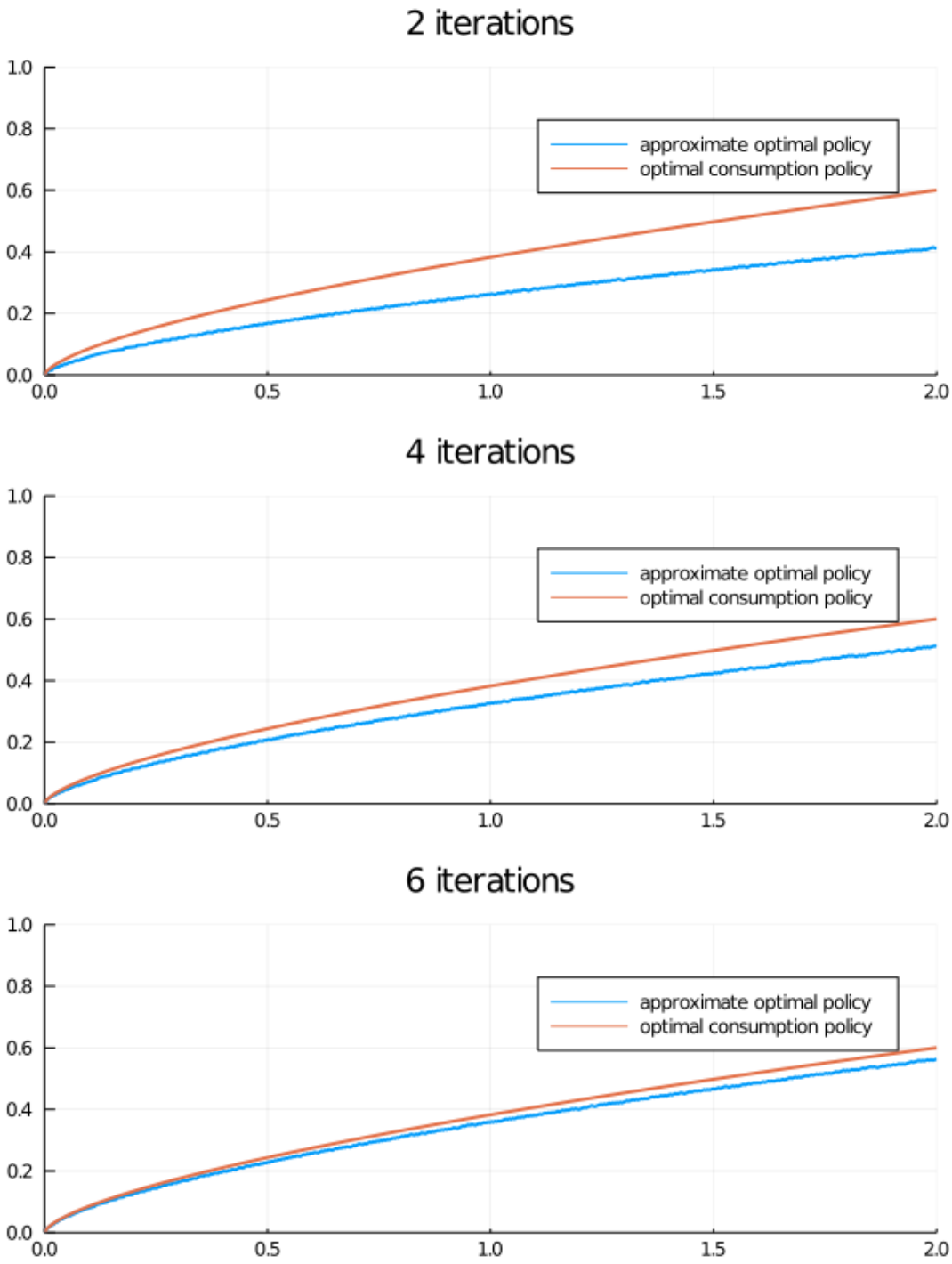
In [38]:
```
function compute_policies(n_vals...)
    c_policies = []
    w = w_init
    for n in 1:maximum(n_vals)
        w = bellman_operator(ddp, w)
        if n in n_vals
            σ = compute_greedy(ddp, w)
            c_policy = f(grid) - grid[σ]
            push!(c_policies, c_policy)
        end
    end
    return c_policies
end
```

Out[38]:
```
compute_policies (generic function with 1 method)
```

Now let's generate the plots.

In [39]:
```
true_c = c_star.(grid)
c_policies = compute_policies(2, 4, 6)
plot_vecs = [c_policies[1] c_policies[2] c_policies[3] true_c true_c
↪true_c]
l1 = "approximate optimal policy"
l2 = "optimal consumption policy"
labels = [l1 l1 l1 l2 l2 l2]
plot(grid,
     plot_vecs,
     xlim = (0, 2),
     ylim = (0, 1),
     layout = (3, 1),
     lw = 2,
     label = labels,
     size = (600, 800),
     title = ["2 iterations" "4 iterations" "6 iterations"])
```

Out[39]:



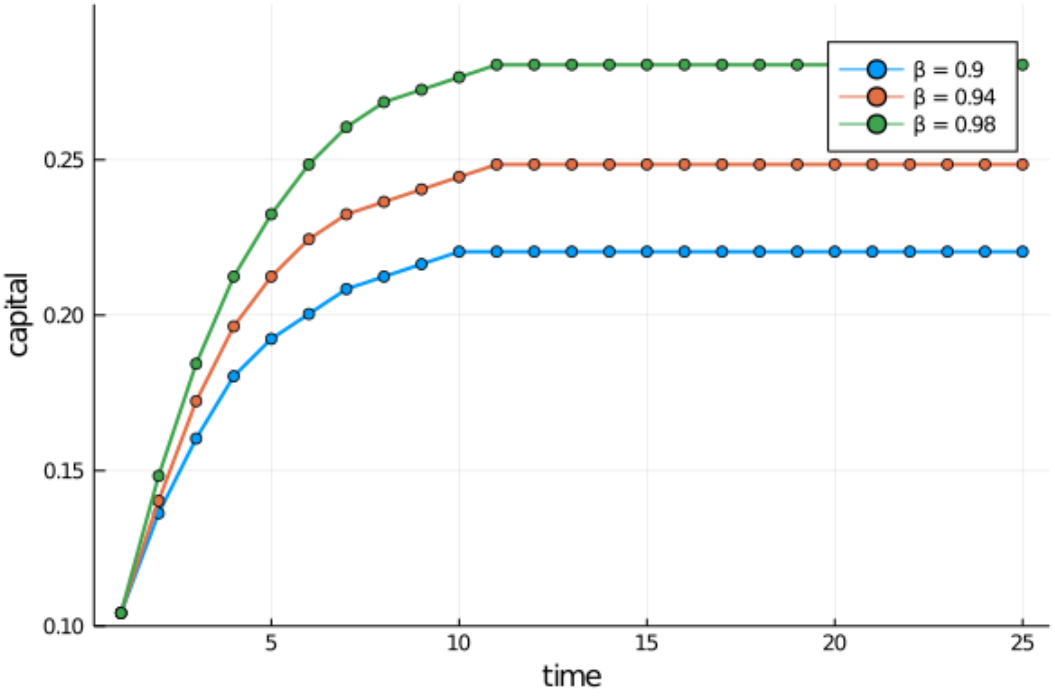
40.7.5 Dynamics of the capital stock

Finally, let us work on Exercise 2, where we plot the trajectories of the capital stock for three different discount factors, 0.9, 0.94, and 0.98, with initial condition $k_0 = 0.1$.

```
In [40]: discount_factors = (0.9, 0.94, 0.98)
         k_init = 0.1

         k_init_ind = findfirst(collect(grid) .≥ k_init)
```

```
sample_size = 25

ddp0 = DiscreteDP(R, Q, β, s_indices, a_indices)
k_paths = []
labels = []

for β in discount_factors
    ddp0.beta = β
    res0 = solve(ddp0, PFI)
    k_path_ind = simulate(res0.mc, sample_size, init=k_init_ind)
    k_path = grid[k_path_ind.+1]
    push!(k_paths, k_path)
    push!(labels, "β = $β")
end

plot(k_paths,
     xlabel = "time",
     ylabel = "capital",
     ylim = (0.1, 0.3),
     lw = 2,
     markershape = :circle,
     label = reshape(labels, 1, length(labels)))
```

Out[40]:



40.8 Appendix: Algorithms

This appendix covers the details of the solution algorithms implemented for `DiscreteDP`.

We will make use of the following notions of approximate optimality:

- For $\varepsilon > 0$, v is called an ε-approximation of v^* if $\|v - v^*\| < \varepsilon$

- A policy $\sigma \in \Sigma$ is called ε-optimal if v_σ is an ε-approximation of v^*

40.8.1 Value Iteration

The `DiscreteDP` value iteration method implements value function iteration as follows

1. Choose any $v^0 \in \mathbb{R}^n$, and specify $\varepsilon > 0$; set $i = 0$.
2. Compute $v^{i+1} = Tv^i$.
3. If $\|v^{i+1} - v^i\| < [(1-\beta)/(2\beta)]\varepsilon$, then go to step 4; otherwise, set $i = i + 1$ and go to step 2.
4. Compute a v^{i+1}-greedy policy σ, and return v^{i+1} and σ.

Given $\varepsilon > 0$, the value iteration algorithm

- terminates in a finite number of iterations
- returns an $\varepsilon/2$-approximation of the optimal value function and an ε-optimal policy function (unless `iter_max` is reached)

(While not explicit, in the actual implementation each algorithm is terminated if the number of iterations reaches `iter_max`)

40.8.2 Policy Iteration

The `DiscreteDP` policy iteration method runs as follows

1. Choose any $v^0 \in \mathbb{R}^n$ and compute a v^0-greedy policy σ^0; set $i = 0$.
2. Compute the value v_{σ^i} by solving the equation $v = T_{\sigma^i} v$.
3. Compute a v_{σ^i}-greedy policy σ^{i+1}; let $\sigma^{i+1} = \sigma^i$ if possible.
4. If $\sigma^{i+1} = \sigma^i$, then return v_{σ^i} and σ^{i+1}; otherwise, set $i = i + 1$ and go to step 2.

The policy iteration algorithm terminates in a finite number of iterations.

It returns an optimal value function and an optimal policy function (unless `iter_max` is reached).

40.8.3 Modified Policy Iteration

The `DiscreteDP` modified policy iteration method runs as follows:

1. Choose any $v^0 \in \mathbb{R}^n$, and specify $\varepsilon > 0$ and $k \geq 0$; set $i = 0$.
2. Compute a v^i-greedy policy σ^{i+1}; let $\sigma^{i+1} = \sigma^i$ if possible (for $i \geq 1$).
3. Compute $u = Tv^i$ $(= T_{\sigma^{i+1}} v^i)$. If $\text{span}(u - v^i) < [(1-\beta)/\beta]\varepsilon$, then go to step 5; otherwise go to step 4.

- Span is defined by $\text{span}(z) = \max(z) - \min(z)$

1. Compute $v^{i+1} = (T_{\sigma^{i+1}})^k u$ $(= (T_{\sigma^{i+1}})^{k+1} v^i)$; set $i = i + 1$ and go to step 2.
2. Return $v = u + [\beta/(1-\beta)][(\min(u - v^i) + \max(u - v^i))/2]\mathbf{1}$ and σ_{i+1}.

Given $\varepsilon > 0$, provided that v^0 is such that $Tv^0 \geq v^0$, the modified policy iteration algorithm terminates in a finite number of iterations.

It returns an $\varepsilon/2$-approximation of the optimal value function and an ε-optimal policy function (unless `iter_max` is reached).

See also the documentation for `DiscreteDP`.

Part V

Modeling in Continuous Time

Chapter 41

Modeling COVID 19 with Differential Equations

41.1 Contents

41.2 Overview

Coauthored with Chris Rackauckas

This is a Julia version of code for analyzing the COVID-19 pandemic.

The purpose of these notes is to introduce economists to quantitative modeling of infectious disease dynamics, and to modeling with ordinary differential equations.

In this lecture, dynamics are modeled using a standard SEIR (Susceptible-Exposed-Infected-Removed) model of disease spread, represented as a system of ordinary differential equations where the number of agents is large and there are no exogenous stochastic shocks.

The first part of the model is inspired by * Notes from Andrew Atkeson and NBER Working Paper No. 26867 * Estimating and Forecasting Disease Scenarios for COVID-19 with an SIR Model by Andrew Atkeson, Karen Kopecky and Tao Zha * Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities by Jesús Fernández-Villaverde and Charles I. Jones * Further variations on the classic SIR model in Julia here.

We then extend this deterministic model in this lecture which build on this model, adding in aggregate shocks and policy tradeoffs.

The interest is primarily in

- studying the impact of suppression through social distancing on the spread of the infection
- the number of infections at a given time (which determines whether or not the health care system is overwhelmed); and

- how long the caseload can be deferred (hopefully until a vaccine arrives)

41.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, Random, SparseArrays
```

In addition, we will be exploring the Ordinary Differential Equations package within the SciML ecosystem.

```
In [3]: using OrdinaryDiffEq
        using Parameters, Plots
        gr(fmt=:png);
```

41.3 The SEIR Model

In the version of the SEIR model, all individuals in the population are assumed to be in a finite number of states.

The states are: susceptible (S), exposed (E), infected (I) and removed (R).

This type of compartmentalized model has many extensions (e.g. SEIRS relaxes lifetime immunity and allow transitions from $R \to S$).

Comments:

- Those in state R have been infected and either recovered or died. Note that in some variations, R may refer only to recovered agents.
- Those who have recovered, and live, are assumed to have acquired immunity.
- Those in the exposed group are not yet infectious.

41.3.1 Changes in the Infected State

Within the SEIR model, the flow across states follows the path $S \to E \to I \to R$.

We will ignore birth and non-covid death during our time horizon, and assume a large, constant, number of individuals of size N throughout.

With this, the symbols S, E, I, R are used for the total number of individuals in each state at each point in time, and $S(t) + E(t) + I(t) + R(t) = N$ for all t.

Since we have assumed that N is large, we can use a continuum approximation for the number of individuals in each state.

The transitions between those states are governed by the following rates

- $\beta(t)$ is called the *transmission rate* or *effective contact rate* (the rate at which individuals bump into others and expose them to the virus).
- σ is called the *infection rate* (the rate at which those who are exposed become infected)
- γ is called the *recovery rate* (the rate at which infected people recover or die)

The rate $\beta(t)$ is influenced by both the characteristics of the disease (e.g. the type and length of prolonged contact required for a transmission) and behavior of the individuals (e.g. social distancing, hygiene).

The SEIR model can then be written as

$$\begin{aligned} \frac{dS}{dt} &= -\beta\, S\, \frac{I}{N} \\ \frac{dE}{dt} &= \beta\, S\, \frac{I}{N} - \sigma E \\ \frac{dI}{dt} &= \sigma E - \gamma I \\ \frac{dR}{dt} &= \gamma I \end{aligned} \tag{1}$$

Here, dy/dt represents the time derivative for the particular variable.

The first term of (1), $-\beta\, S\, \frac{I}{N}$, is the flow of individuals moving from $S \to E$, and highlights the underlying dynamics of the epidemic

- Individuals in the susceptible state (S) have a rate $\beta(t)$ of prolonged contacts with other individuals where transmission would occur if either was infected
- Of these contacts, a fraction $\frac{I(t)}{N}$ will be with infected agents (since we assumed that exposed individuals are not yet infectious)
- Finally, there are $S(t)$ susceptible individuals.
- The sign indicates that the product of those terms is the outflow from the S state, and an inflow to the E state.

41.3.2 Basic Reproduction Number

If β was constant, then we could define $R_0 := \beta/\gamma$. This is the famous *basic reproduction number* for the SEIR model. See [51] for more details.

When the transmission rate is time-varying, we will follow notation in [31] and refer to $R_0(t)$ as a time-varying version of the basic reproduction number.

Analyzing the system in (1) provides some intuition on the $R_0(t) := \beta(t)/\gamma$ expression:

- Individual transitions from the infected to removed state occur at a Poisson rate γ, the expected time in the infected state is $1/\gamma$
- Prolonged interactions occur at rate β, so a new individual entering the infected state will potentially transmit the virus to an average of $R_0 = \beta \times 1/\gamma$ others
- In more complicated models, see [51] for a formal definition for arbitrary models, and an analysis on the role of $R_0 < 1$.

Note that the notation R_0 is standard in the epidemiology literature - though confusing, since R_0 is unrelated to R, the symbol that represents the removed state. For the remainder of the lecture, we will avoid using R for removed state.

Prior to solving the model directly, we make a few changes to (1)

- Re-parameterize using $\beta(t) = \gamma R_0(t)$
- Define the proportion of individuals in each state as $s := S/N$ etc.
- Divide each equation in (1) by N, and write the system of ODEs in terms of the proportions

$$\begin{aligned}
\frac{ds}{dt} &= -\gamma R_0 \, s \, i \\
\frac{de}{dt} &= \gamma R_0 \, s \, i - \sigma e \\
\frac{di}{dt} &= \sigma e - \gamma i \\
\frac{dr}{dt} &= \gamma i
\end{aligned} \tag{2}$$

Since the states form a partition, we could reconstruct the "removed" fraction of the population as $r = 1 - s - e - i$. However, keeping it in the system will make plotting more convenient.

41.3.3 Implementation

We begin by implementing a simple version of this model with a constant R_0 and some baseline parameter values (which we discuss later).

First, define the system of equations

```
In [4]: function F_simple(x, p, t; γ = 1/18, R₀ = 3.0, σ = 1/5.2)
            s, e, i, r = x

            return [-γ*R₀*s*i;        # ds/dt = -γR₀si
                    γ*R₀*s*i -  σ*e;# de/dt =  γR₀si -σe
                    σ*e - γ*i;       # di/dt =         σe -γi
                          γ*i;       # dr/dt =             γi
                   ]
        end
```

```
Out[4]: F_simple (generic function with 1 method)
```

Given this system, we choose an initial condition and a timespan, and create a `ODEProblem` encapsulating the system.

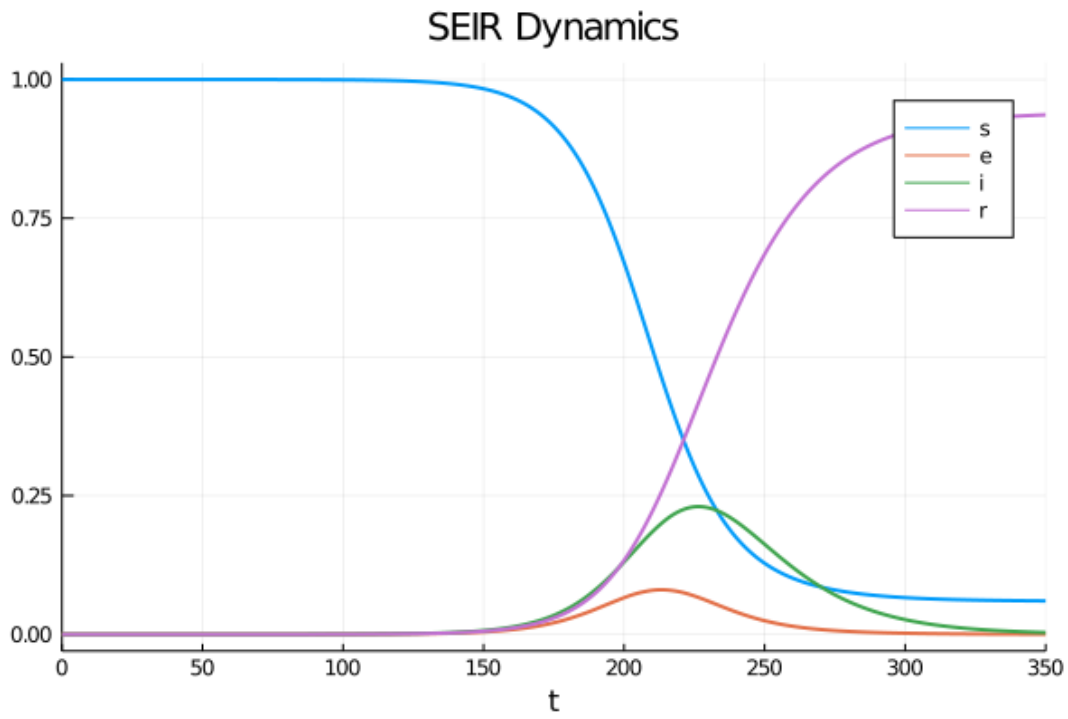
```
In [5]: i_0 = 1E-7                  # 33 = 1E-7 * 330 million population =
        ↪initially infected
        e_0 = 4.0 * i_0             # 132 = 1E-7 *330 million = initially exposed
        s_0 = 1.0 - i_0 - e_0
        r_0 = 0.0
        x_0 = [s_0, e_0, i_0, r_0]  # initial condition

        tspan = (0.0, 350.0)  # ≈ 350 days
        prob = ODEProblem(F_simple, x_0, tspan)
```

```
Out[5]: ODEProblem with uType Array{Float64,1} and tType Float64. In-
        place: false
        timespan: (0.0, 350.0)
        u0: [0.9999995, 4.0e-7, 1.0e-7, 0.0]
```

With this, choose an ODE algorithm and solve the initial value problem. A good default algorithm for non-stiff ODEs of this sort might be `Tsit5()`, which is the Tsitouras 5/4 Runge-Kutta method).

```
In [6]: sol = solve(prob, Tsit5())
        plot(sol, labels = ["s" "e" "i" "r"], title = "SEIR Dynamics", lw = 2)
```

Out[6]:

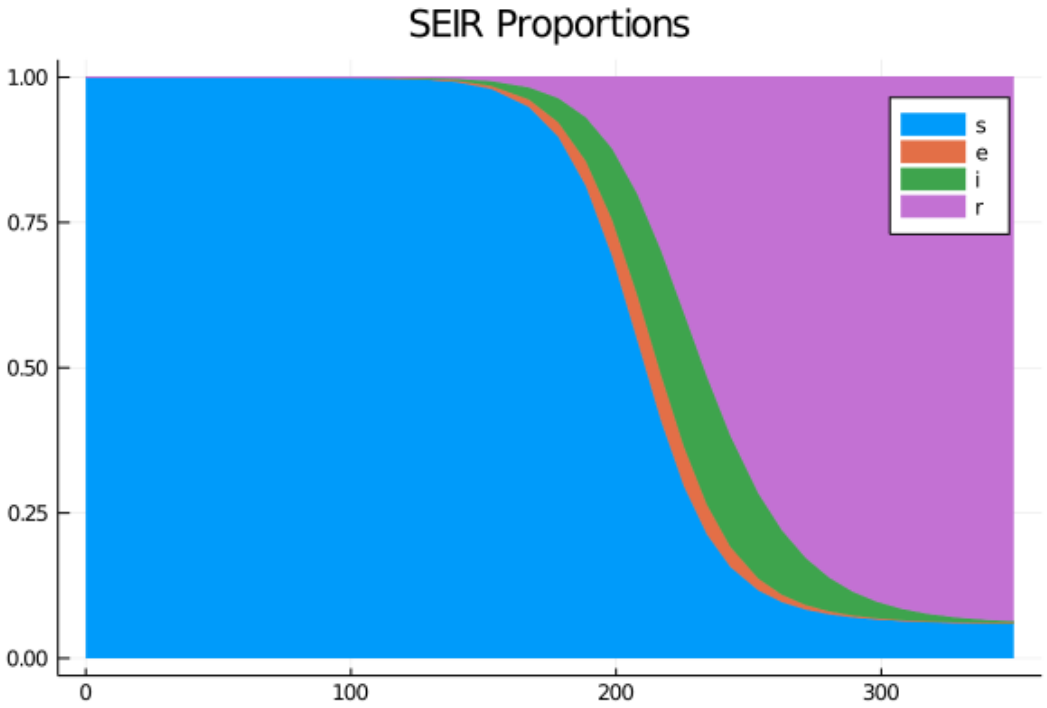


We did not provide either a set of time steps or a `dt` time step size to the `solve`. Most accurate and high-performance ODE solvers appropriate for this problem use adaptive time-stepping, changing the step size based the degree of curvature in the derivatives.

Or, as an alternative visualization, the proportions in each state over time

```
In [7]: areaplot(sol.t, sol', labels = ["s" "e" "i" "r"], title = "SEIR
  ↪Proportions")
```

Out[7]:



While maintaining the core system of ODEs in (s, e, i, r), we will extend the basic model to enable some policy experiments and calculations of aggregate values.

41.3.4 Extending the Model

First, we can consider some additional calculations such as the cumulative caseload (i.e., all those who have or have had the infection) as $c = i + r$. Differentiating that expression and substituting from the time-derivatives of $i(t)$ and $r(t)$ yields $\frac{dc}{dt} = \sigma e$.

We will assume that the transmission rate follows a process with a reversion to a value $\bar{R}_0(t)$ which could conceivably be influenced by policy. The intuition is that even if the targeted $\bar{R}_0(t)$ was changed through social distancing/etc., lags in behavior and implementation would smooth out the transition, where η governs the speed of $R_0(t)$ moves towards $\bar{R}_0(t)$.

$$\frac{dR_0}{dt} = \eta(\bar{R}_0 - R_0) \tag{3}$$

Finally, let δ be the mortality rate, which we will leave constant. The cumulative deaths can be integrated through the flow γi entering the "Removed" state.

Define the cumulative number of deaths as $D(t)$ with the proportion $d(t) := D(t)/N$.

$$\frac{d}{dt}d(t) = \delta\gamma i \tag{4}$$

While we could integrate the deaths given the solution to the model ex-post, it is more convenient to use the integrator built into the ODE solver. That is, we add $\frac{d}{dt}d(t)$ rather than calculating $d(t) = \int_0^t \delta\gamma\, i(\tau)d\tau$ ex-post.

This is a common trick when solving systems of ODEs. While equivalent in principle to using the appropriate quadrature scheme, this becomes especially convenient when adaptive time-stepping algorithms are used to solve the ODEs (i.e. there is not a regular time grid). Note that when doing so, $d(0) = \int_0^0 \delta\gamma i(\tau)d\tau = 0$ is the initial condition.

The system (2) and the supplemental equations can be written in vector form $x := [s, e, i, r, R_0, c, d]$ with parameter tuple $p := (\sigma, \gamma, \eta, \delta, \bar{R}_0(\cdot))$

Note that in those parameters, the targeted reproduction number, $\bar{R}_0(t)$, is an exogenous function.

The model is then $\frac{dx}{dt} = F(x, t)$ where,

$$F(x,t) := \begin{bmatrix} -\gamma\, R_0\, s\, i \\ \gamma\, R_0\, s\, i - \sigma e \\ \sigma\, e - \gamma i \\ \gamma i \\ \eta(\bar{R}_0(t) - R_0) \\ \sigma e \\ \delta\, \gamma\, i \end{bmatrix} \tag{5}$$

Note that if $\bar{R}_0(t)$ is time-invariant, then $F(x, t)$ is time-invariant as well.

41.3.5 Parameters

The parameters, σ, δ, and γ should be thought of as parameters determined from biology and medical technology, and independent of social interactions.

As in Atkeson's note, we set

- $\sigma = 1/5.2$ to reflect an average incubation period of 5.2 days.
- $\gamma = 1/18$ to match an average illness duration of 18 days.
- $\bar{R}_0(t) = R_0(0) = 1.6$ to match a **basic reproduction number** of 1.6, and initially time-invariant
- $\delta = 0.01$ for a one-percent mortality rate

As we will initially consider the case where $R_0(0) = \bar{R}_0(0)$, the parameter η will not influence the first experiment.

41.4 Implementation

First, construct our F from (5)

```
In [8]: function F(x, p, t)
            s, e, i, r, R□, c, d = x
            @unpack σ, γ, R□, η, δ = p

            return [-γ*R□*s*i;          # ds/dt
                    γ*R□*s*i - σ*e;     # de/dt
                    σ*e - γ*i;          # di/dt
                    γ*i;                # dr/dt
                    η*(R□(t, p) - R□);# dR□/dt
```

```
            σ*e;                # dc/dt
            δ*γ*i;              # dd/dt
            ]
end;
```

This function takes the vector `x` of states in the system and extracts the fixed parameters passed into the `p` object.

The only confusing part of the notation is the `R̄(t, p)` which evaluates the `p.R̄` at this time (and also allows it to depend on the `p` parameter).

41.4.1 Parameters

The baseline parameters are put into a named tuple generator (see previous lectures using Parameters.jl) with default values discussed above.

```
In [9]: p_gen = @with_kw ( T = 550.0, γ = 1.0 / 18, σ = 1 / 5.2, η = 1.0 / 20,
                           R̄_n = 1.6, δ = 0.01, N = 3.3E8,
                           R̄ = (t, p) -> p.R̄_n);
```

Note that the default $\bar{R}_0(t)$ function always equals R_{0n} – a parameterizable natural level of R_0 used only by the `R̄` function

Setting initial conditions, we choose a fixed s, i, e, r, as well as $R_0(0) = R_{0n}$ and $m(0) = 0.01$

```
In [10]: p = p_gen()  # use all default parameters

         i_0 = 1E-7
         e_0 = 4.0 * i_0
         s_0 = 1.0 - i_0 - e_0

         x_0 = [s_0, e_0, i_0, 0.0, p.R̄_n, 0.0, 0.0]
         tspan = (0.0, p.T)
         prob = ODEProblem(F, x_0, tspan, p)
```

```
Out[10]: ODEProblem with uType Array{Float64,1} and tType Float64. In-
         place: false
         timespan: (0.0, 550.0)
         u0: [0.9999995, 4.0e-7, 1.0e-7, 0.0, 1.6, 0.0, 0.0]
```

The `tspan` of `(0.0, p.T)` determines the t used by the solver. The time scale needs to be consistent with the arrival rate of the transition probabilities (i.e. the γ, σ were chosen based on daily data, so the unit of t is a day).

The time period we investigate will be 550 days, or around 18 months:

41.5 Experiments

Let's run some experiments using this code.

```
In [11]: sol = solve(prob, Tsit5())
         @show length(sol.t);
```

```
length(sol.t) = 45
```

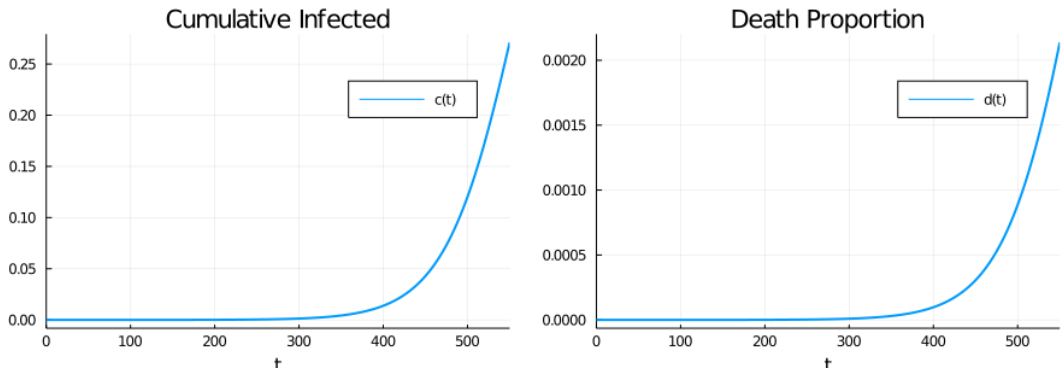
We see that the adaptive time-stepping used approximately 45 time-steps to solve this problem to the desired accuracy. Evaluating the solver at points outside of those time-steps uses an interpolator consistent with the solution to the ODE.

While it may seem that 45 time intervals is extremely small for that range, for much of the t, the functions are very flat - and hence adaptive time-stepping algorithms can move quickly and interpolate accurately.

The solution object has built in plotting support.

```
In [12]: plot(sol, vars = [6, 7], label = ["c(t)" "d(t)"], lw = 2,
              title = ["Cumulative Infected" "Death Proportion"],
              layout = (1,2), size = (900, 300))
```

Out[12]:



A few more comments:

- If you want to ensure that there are specific points that the adaptive-time stepping must include (e.g. at known discontinuities) use tstops.
- The built-in plots for the solutions provide all of the attributes in Plots.jl.
- See here for details on analyzing the solution and extracting the output.

41.5.1 Experiment 1: Constant Reproduction Case

Let's start with the case where $\bar{R}_0(t) = R_{0n}$ is constant.

We calculate the time path of infected people under different assumptions of R_{0n}:

```
In [13]: R₀_n_vals = range(1.6, 3.0, length = 6)
         sols = [solve(ODEProblem(F, x_0, tspan, p_gen(R₀_n = R₀_n)),
                       Tsit5(), saveat=0.5) for R₀_n in R₀_n_vals];
```

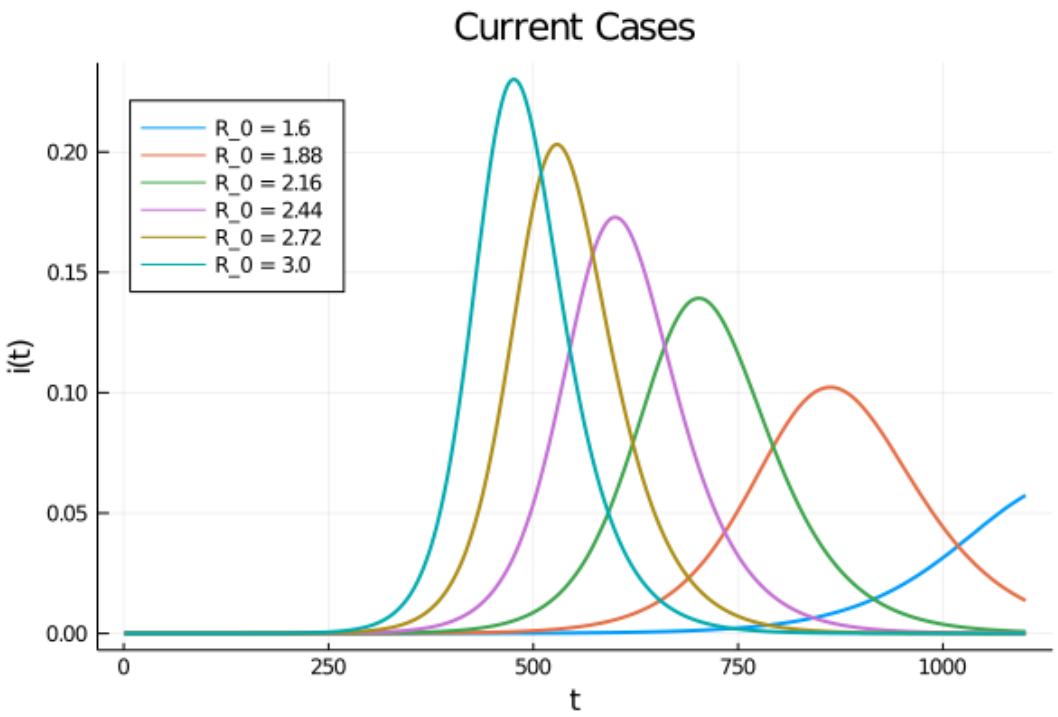
Here we chose `saveat=0.5` to get solutions that were evenly spaced every `0.5`.

Changing the saved points is just a question of storage/interpolation, and does not change the adaptive time-stepping of the solvers.

Let's plot current cases as a fraction of the population.

In [14]:
```
labels = permutedims(["R_0 = $r" for r in R_n_vals])
infecteds = [sol[3,:] for sol in sols]
plot(infecteds, label=labels, legend=:topleft, lw = 2, xlabel = "t",
     ylabel = "i(t)", title = "Current Cases")
```

Out[14]:



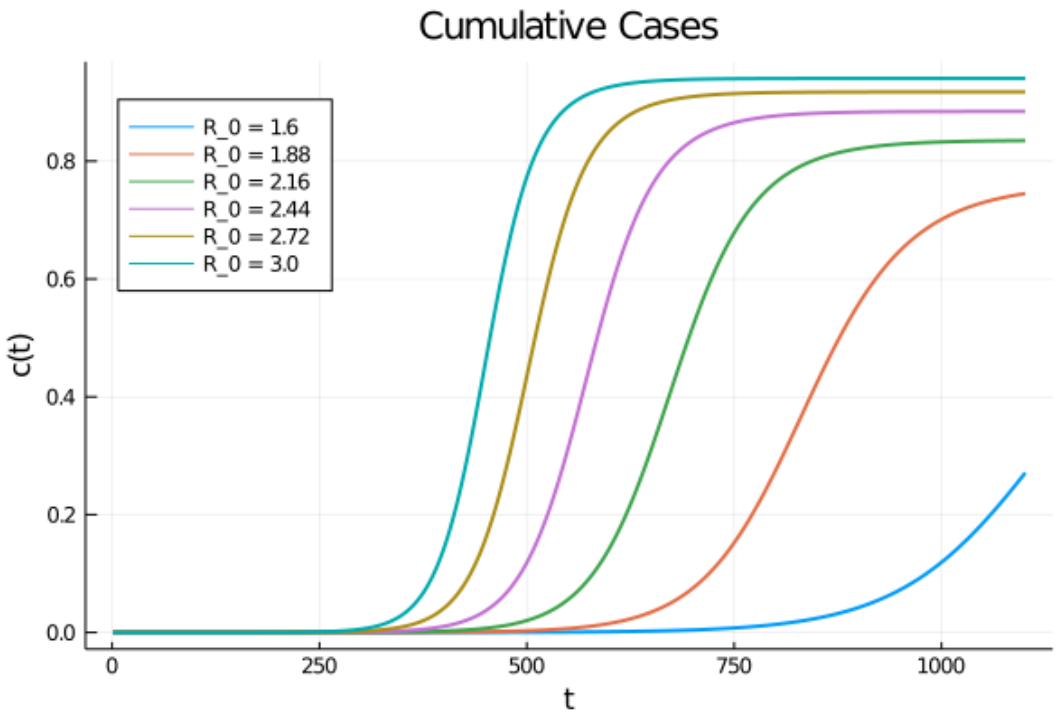
As expected, lower effective transmission rates defer the peak of infections.

They also lead to a lower peak in current cases.

Here is cumulative cases, as a fraction of population:

In [15]:
```
cumulative_infected = [sol[6,:] for sol in sols]
plot(cumulative_infected, label=labels ,legend=:topleft, lw = 2, xlabel =
↪"t",
     ylabel = "c(t)", title = "Cumulative Cases")
```

Out[15]:



41.5.2 Experiment 2: Changing Mitigation

Let's look at a scenario where mitigation (e.g., social distancing) is successively imposed, but the target (maintaining R_{0n}) is fixed.

To do this, we start with $R_0(0) \neq R_{0n}$ and examine the dynamics using the $\frac{dR_0}{dt} = \eta(R_{0n} - R_0)$ ODE.

In the simple case, where $\bar{R}_0(t) = R_{0n}$ is independent of the state, the solution to the ODE given an initial condition is $R_0(t) = R_0(0)e^{-\eta t} + R_{0n}(1 - e^{-\eta t})$

We will examine the case where $R_0(0) = 3$ and then it falls to $R_{0n} = 1.6$ due to the progressive adoption of stricter mitigation measures.

The parameter η controls the rate, or the speed at which restrictions are imposed.

We consider several different rates:

```
In [16]: η_vals = [1/5, 1/10, 1/20, 1/50, 1/100]
         labels = permutedims(["eta = $η" for η in η_vals]);
```

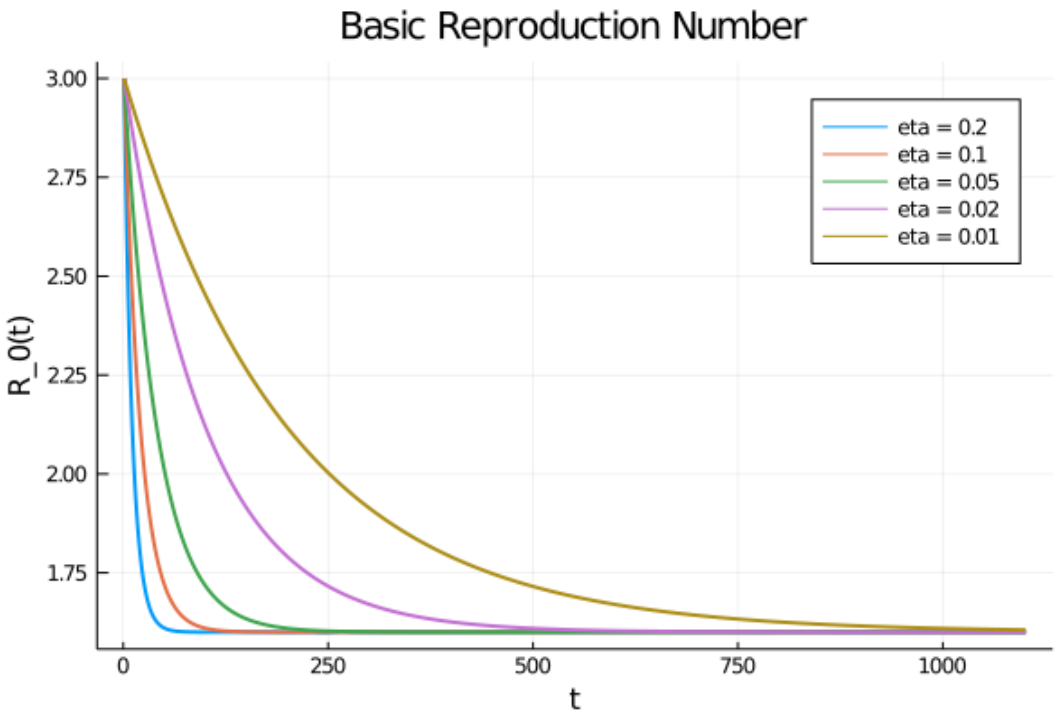
Let's calculate the time path of infected people, current cases, and mortality

```
In [17]: x_0 = [s_0, e_0, i_0, 0.0, 3.0, 0.0, 0.0]
         sols = [solve(ODEProblem(F, x_0, tspan, p_gen(η=η)), Tsit5(), saveat=0.5)
  ↪for η in
         η_vals];
```

Next, plot the R_0 over time:

```
In [18]: Rs = [sol[5,:] for sol in sols]
         plot(Rs, label=labels, legend=:topright, lw = 2, xlabel = "t",
              ylabel = "R_0(t)", title = "Basic Reproduction Number")
```

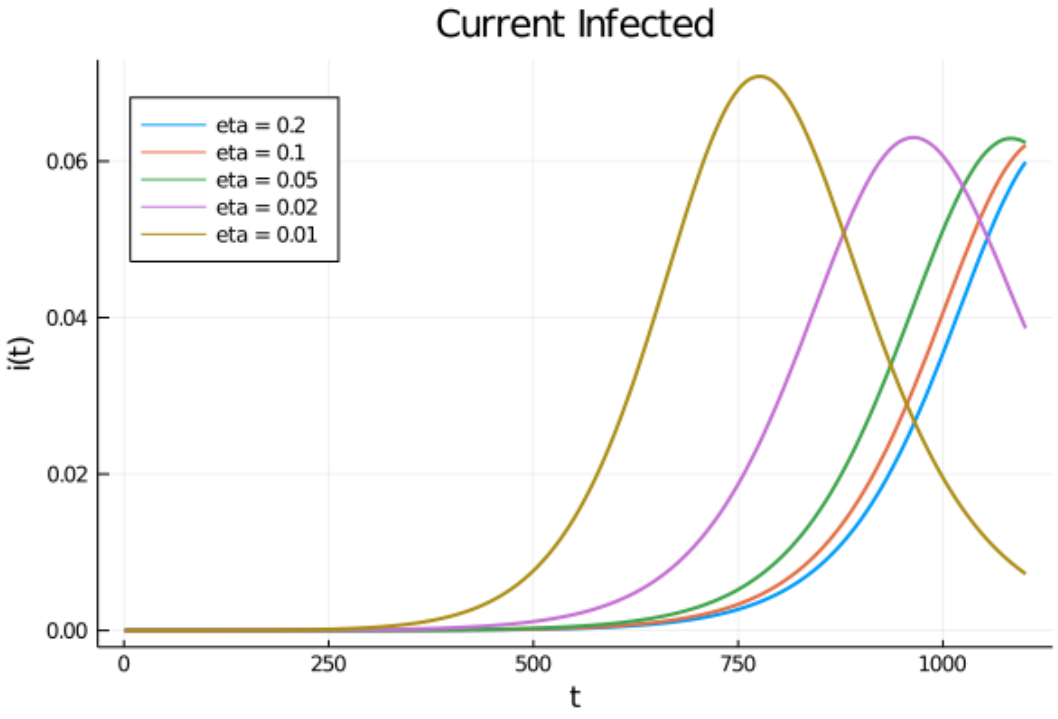
Out[18]:



Now let's plot the number of infected persons and the cumulative number of infected persons:

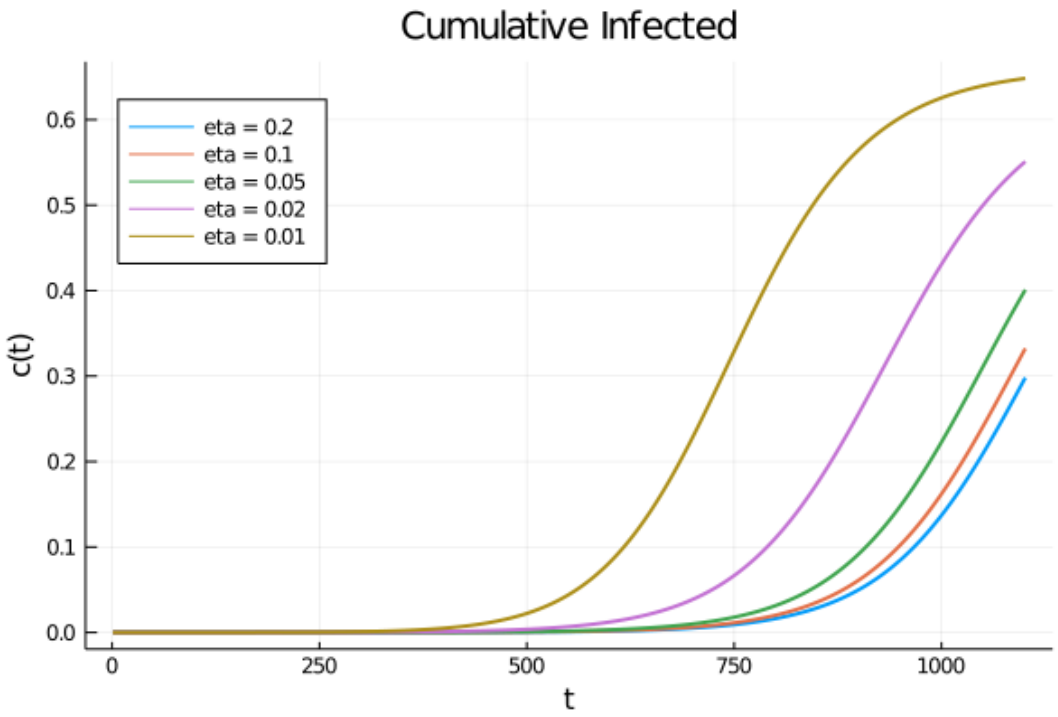
```
In [19]: infecteds = [sol[3,:] for sol in sols]
         plot(infecteds, label=labels, legend=:topleft, lw = 2, xlabel = "t",
              ylabel = "i(t)", title = "Current Infected")
```

Out[19]:



```
In [20]: cumulative_infected = [sol[6,:] for sol in sols]
         plot(cumulative_infected, label=labels ,legend=:topleft, lw = 2, xlabel =
        ↪"t",
              ylabel = "c(t)", title = "Cumulative Infected")
```

Out[20]:



41.6 Ending Lockdown

The following is inspired by additional results by Andrew Atkeson on the timing of lifting lockdown.

Consider these two mitigation scenarios:

1. choose $\bar{R}_0(t)$ to target $R_0(t) = 0.5$ for 30 days and then $R_0(t) = 2$ for the remaining 17 months. This corresponds to lifting lockdown in 30 days.
2. $R_0(t) = 0.5$ for 120 days and then $R_0(t) = 2$ for the remaining 14 months. This corresponds to lifting lockdown in 4 months.

For both of these, we will choose a large η to focus on the case where rapid changes in the lockdown policy remain feasible.

The parameters considered here start the model with 25,000 active infections and 75,000 agents already exposed to the virus and thus soon to be contagious.

```
In [21]: R□_L = 0.5  # lockdown

         R□_lift_early(t, p) = t < 30.0 ? R□_L : 2.0

         R□_lift_late(t, p) = t < 120.0 ? R□_L : 2.0
```

```
p_early = p_gen(R₀ = R₀_lift_early, η = 10.0)
p_late = p_gen(R₀ = R₀_lift_late, η = 10.0)


# initial conditions
i_0 = 25000 / p_early.N
e_0 = 75000 / p_early.N
s_0 = 1.0 - i_0 - e_0

x_0 = [s_0, e_0, i_0, 0.0, R₀_L, 0.0, 0.0] # start in lockdown


# create two problems, with rapid movement of R₀(t) towards R₀(t)
prob_early = ODEProblem(F, x_0, tspan, p_early)
prob_late = ODEProblem(F, x_0, tspan, p_late)
```

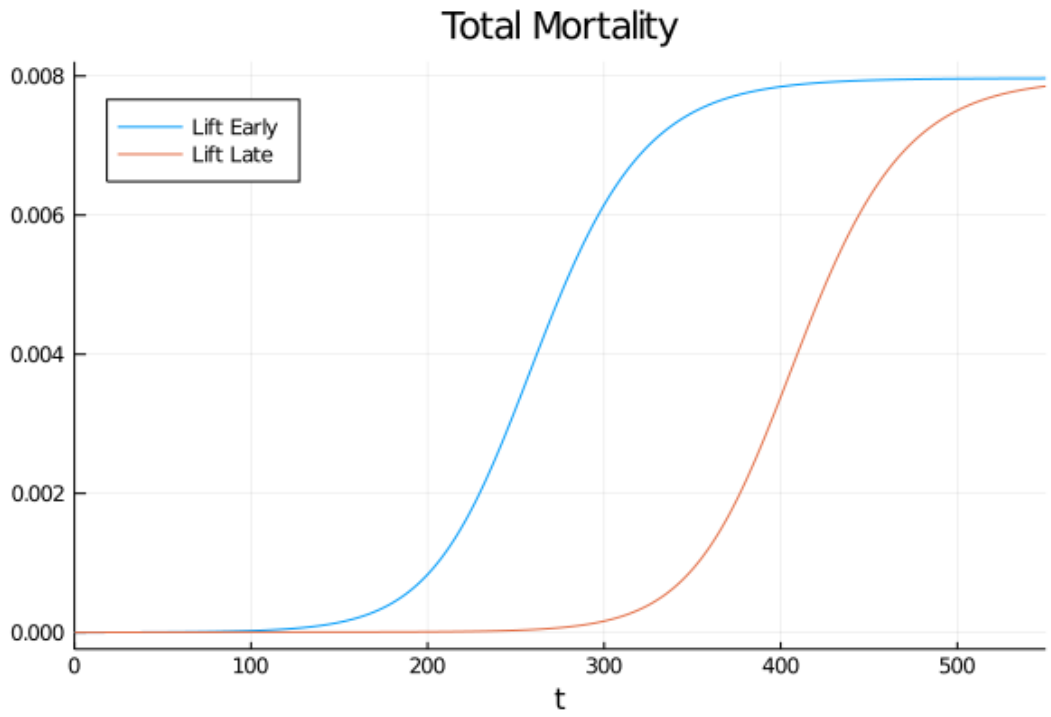
```
Out[21]: ODEProblem with uType Array{Float64,1} and tType Float64. In-
         place: false
         timespan: (0.0, 550.0)
         u0: [0.9996969696969696, 0.00022727272727272727, 7.575757575757576e-5, 0.
↪0, 0.5, 0.0,
         0.0]
```

Unlike the previous examples, the $\bar{R}_0(t)$ functions have discontinuities which might occur. We can improve the efficiency of the adaptive time-stepping methods by telling them to include a step exactly at those points by using `tstops`

Let's calculate the paths:

```
In [22]: sol_early = solve(prob_early, Tsit5(), tstops = [30.0, 120.0])
         sol_late = solve(prob_late, Tsit5(), tstops = [30.0, 120.0])
         plot(sol_early, vars = [7], title = "Total Mortality", label = "Lift
↪Early", legend =
         :topleft)
         plot!(sol_late, vars = [7], label = "Lift Late")
```

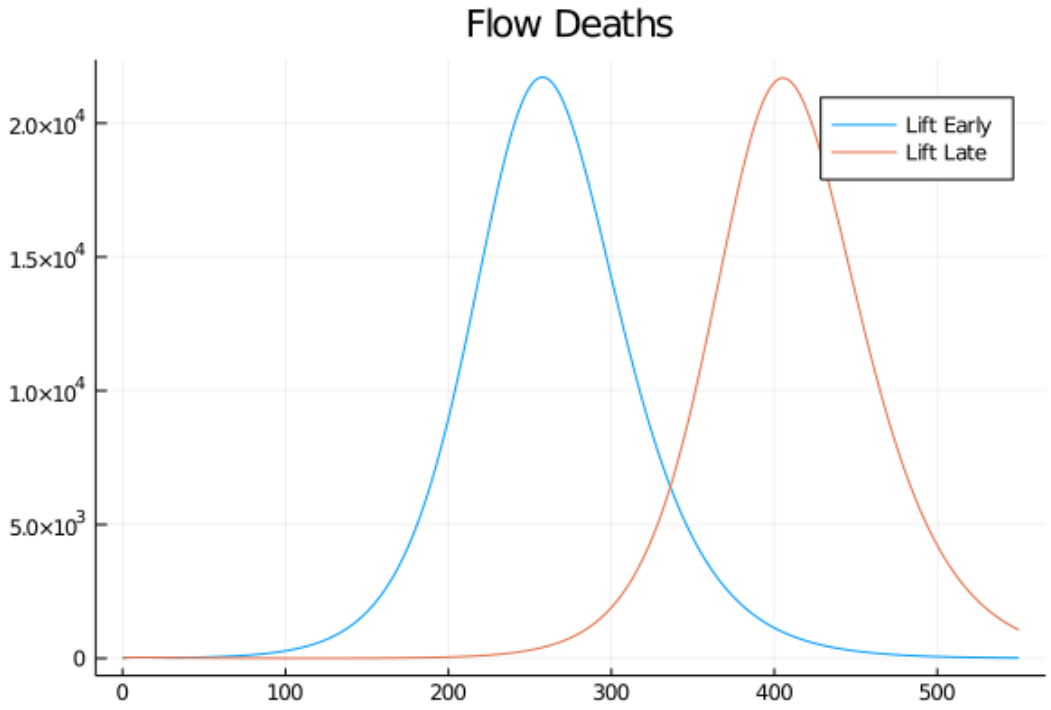
```
Out[22]:
```



Next we examine the daily deaths, $\frac{dD(t)}{dt} = N\delta\gamma i(t)$.

```
In [23]: flow_deaths(sol, p) = p.N * p.δ * p.γ * sol[3,:]

         plot(sol_early.t, flow_deaths(sol_early, p_early), title = "Flow Deaths",
        ↪label = "Lift
         Early")
         plot!(sol_late.t, flow_deaths(sol_late, p_late), label = "Lift Late")
```

Out[23]:



Pushing the peak of curve further into the future may reduce cumulative deaths if a vaccine is found, or allow health authorities to better smooth the caseload.

41.6.1 Randomness

Despite its richness, the model above is fully deterministic. The policy $\bar{R}_0(t)$ could change over time, but only in predictable ways.

One way that randomness can lead to aggregate fluctuations is the granularity that comes through the discreteness of individuals. This topic, the connection between SDEs and the Langevin equations typically used in the approximation of chemical reactions in well-mixed media is explored in further lectures on continuous time Markov chains.

Instead, in the next lecture, we will concentrate on randomness that comes from aggregate changes in behavior or policy.

Chapter 42

Modeling Shocks in COVID 19 with Stochastic Differential Equations

42.1 Contents

42.2 Overview

Coauthored with Chris Rackauckas

This lecture continues the analyzing of the COVID-19 pandemic established in this lecture.

As before, the model is inspired by * Notes from Andrew Atkeson and NBER Working Paper No. 26867 * Estimating and Forecasting Disease Scenarios for COVID-19 with an SIR Model by Andrew Atkeson, Karen Kopecky and Tao Zha * Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities by Jesús Fernández-Villaverde and Charles I. Jones * Further variations on the classic SIR model in Julia here.

Here we extend the model to include policy-relevant aggregate shocks.

42.2.1 Continuous-Time Stochastic Processes

In continuous-time, there is an important distinction between randomness that leads to continuous paths vs. those which have (almost surely right-continuous) jumps in their paths. The most tractable of these includes the theory of Levy Processes.

Among the appealing features of Levy Processes is that they fit well into the sorts of Markov modeling techniques that economists tend to use in discrete time, and usually fulfill the measurability required for calculating expected present discounted values.

Unlike in discrete-time, where a modeller has license to be creative, the rules of continuous-time stochastic processes are much stricter. One can show that a Levy process's noise can be decomposed into two portions:

1. Weiner Processes (as known as Brownian Motion) which leads to a diffusion equations, and is the only continuous-time Levy process with continuous paths
2. Poisson Processes with an arrival rate of jumps in the variable.

Every other Levy Process can be represented by these building blocks (e.g. a Diffusion Process such as Geometric Brownian Motion is a transformation of a Weiner process, a jump diffusion is a diffusion process with a Poisson arrival of jumps, and a continuous-time markov chain (CMTC) is a Poisson process jumping between a finite number of states).

In this lecture, we will examine shocks driven by transformations of Brownian motion, as the prototypical Stochastic Differential Equation (SDE).

42.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, Random, SparseArrays
```

In addition, we will be exploring packages within the SciML ecosystem and others covered in previous lectures

```
In [3]: using OrdinaryDiffEq, StochasticDiffEq
        using Parameters, Plots
        gr(fmt=:png);
```

42.3 The Basic SIR/SIRD Model

To demonstrate another common compartmentalized model we will change the previous SEIR model to remove the exposed state, and more carefully manage the death state, D.

The states are are now: susceptible (S), infected (I), resistant (R), or dead (D).

Comments:

- Unlike the previous SEIR model, the R state is only for those recovered, alive, and currently resistant.
- As before, we start by assuming those have recovered have acquired immunity.
- Later, we could consider transitions from R to S if resistance is not permanent due to virus mutation, etc.

42.3.1 Transition Rates

See the previous lecture, for a more detailed development of the model.

- $\beta(t)$ is called the *transmission rate* or *effective contact rate* (the rate at which individuals bump into others and expose them to the virus)
- γ is called the *resolution rate* (the rate at which infected people recover or die)
- $\delta(t) \in [0, 1]$ is the *death probability*

- As before, we re-parameterize as $R_0(t) := \beta(t)/\gamma$, where R_0 has previous interpretation

Jumping directly to the equations in s, i, r, d already normalized by N,

$$\begin{aligned} ds &= -\gamma\, R_0\, s\, i\, dt \\ di &= (\gamma\, R_0\, s\, i - \gamma\, i)\, dt \\ dr &= (1-\delta)\gamma\, i\, dt \\ dd &= \delta\, \gamma\, i\, dt \end{aligned} \tag{1}$$

Note that the notation has changed to heuristically put the dt on the right hand side, which will be used when adding the stochastic shocks.

42.4 Introduction to SDEs

We start by extending our model to include randomness in $R_0(t)$ and then the mortality rate $\delta(t)$.

The result is a system of Stochastic Differential Equations (SDEs).

42.4.1 Shocks to Transmission Rates

As before, we assume that the basic reproduction number, $R_0(t)$, follows a process with a reversion to a value $\bar{R}_0(t)$ which could conceivably be influenced by policy. The intuition is that even if the targeted $\bar{R}_0(t)$ was changed through social distancing/etc., lags in behavior and implementation would smooth out the transition, where η governs the speed of $R_0(t)$ moves towards $\bar{R}_0(t)$.

Beyond changes in policy, randomness in $R_0(t)$ may come from shocks to the $\beta(t)$ process. For example,

- Misinformation on Facebook spreading non-uniformly.
- Large political rallies, elections, or protests.
- Deviations in the implementation and timing of lockdown policy between demographics, locations, or businesses within the system.
- Aggregate shocks in opening/closing industries.

To implement these sorts of randomness, we will add on a diffusion term with an instantaneous volatility of $\sigma\sqrt{R_0}$.

- This equation is used in the Cox-Ingersoll-Ross and Heston models of interest rates and stochastic volatility.
- The scaling by the $\sqrt{R_0}$ ensure that the process stays weakly positive. The heuristic explanation is that the variance of the shocks converges to zero as R goes to zero, enabling the upwards drift to dominate.
- See here for a heuristic description of when the process is weakly and strictly positive.

The notation for this SDE is then

$$dR_{0t} = \eta(\bar{R}_{0t} - R_{0t})dt + \sigma\sqrt{R_{0t}}dW_t \tag{2}$$

where W is standard Brownian motion (i.e a Weiner Process.

Heuristically, if $\sigma = 0$, divide this equation by dt and it nests the original ODE used in the previous lecture.

While we do not consider any calibration for the σ parameter, empirical studies such as Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities (Figure 6) show highly volatile $R_0(t)$ estimates over time.

Even after lockdowns are first implemented, we see variation between 0.5 and 1.5. Since countries are made of interconnecting cities with such variable contact rates, a high σ seems reasonable both intuitively and empirically.

42.4.2 Mortality Rates

Unlike the previous lecture, we will build up towards mortality rates which change over time.

Imperfect mixing of different demographic groups could lead to aggregate shocks in mortality (e.g. if a retirement home is afflicted vs. an elementary school). These sorts of relatively small changes might be best modeled as a continuous path process.

Let $\delta(t)$ be the mortality rate and in addition,

- Assume that the base mortality rate is $\bar{\delta}$, which acts as the mean of the process, reverting at rate θ. In more elaborate models, this could be time-varying.
- The diffusion term has a volatility $\xi\sqrt{\delta(1-\delta)}$.
- As the process gets closer to either $\delta = 1$ or $\delta = 0$, the volatility goes to 0, which acts as a force to allow the mean reversion to keep the process within the bounds
- Unlike the well-studied Cox-Ingersoll-Ross model, we make no claims on the long-run behavior of this process, but will be examining the behavior on a small timescale so this is not an issue.

Given this, the stochastic process for the mortality rate is,

$$d\delta_t = \theta(\bar{\delta} - \delta_t)dt + \xi\sqrt{(\delta_t(1-\delta_t)}dW_t \tag{3}$$

Where the W_t Brownian motion is independent from the previous process.

42.4.3 System of SDEs

The system (1) can be written in vector form $x := [s, i, r, d, R_0, \delta]$ with parameter tuple parameter tuple $p := (\gamma, \eta, \sigma, \theta, \xi, \bar{R}_0(\cdot), \bar{\delta})$

The general form of the SDE is.

$$dx_t = F(x_t, t; p)dt + G(x_t, t; p)dW$$

With the drift,

$$F(x, t; p) := \begin{bmatrix} -\gamma\, R_0\, s\, i \\ \gamma\, R_0\, s\, i - \gamma i \\ (1-\delta)\gamma i \\ \delta\gamma i \\ \eta(\bar{R}_0(t) - R_0) \\ \theta(\bar{\delta} - \delta) \end{bmatrix} \tag{4}$$

Here, it is convenient but not necessary for dW to have the same dimension as x. If so, then we can use a square matrix $G(x, t; p)$ to associate the shocks with the appropriate x (e.g. diagonal noise, or using a covariance matrix).

As the two independent sources of Brownian motion only affect the dR_0 and $d\delta$ terms (i.e. the 5th and 6th equations), define the covariance matrix as

$$G(x,t) := diag\left(\begin{bmatrix}0 & 0 & 0 & 0 & \sigma\sqrt{R_0} & \xi\sqrt{\delta(1-\delta)}\end{bmatrix}\right) \tag{5}$$

42.4.4 Implementation

First, construct our F from (4) and G from (5)

```
In [4]: function F(x, p, t)
            s, i, r, d, R□, δ = x
            @unpack γ, R□, η, σ, ξ, θ, δ_bar = p

            return [-γ*R□*s*i          # ds/dt
                    γ*R□*s*i - γ*i;    # di/dt
                    (1-δ)*γ*i;         # dr/dt
                    δ*γ*i;             # dd/dt
                    η*(R□(t, p) - R□);# dR□/dt
                    θ*(δ_bar - δ);     # dδ/dt
                    ]
        end

        function G(x, p, t)
            s, i, r, d, R□, δ = x
            @unpack γ, R□, η, σ, ξ, θ, δ_bar = p

            return [0; 0; 0; 0; σ*sqrt(R□); ξ*sqrt(δ * (1-δ))]
        end
```

```
Out[4]: G (generic function with 1 method)
```

Next create a settings generator, and then define a SDEProblem with Diagonal Noise.

```
In [5]: p_gen = @with_kw (T = 550.0, γ = 1.0 / 18, η = 1.0 / 20,
                          R□_n = 1.6, R□ = (t, p) -> p.R□_n, δ_bar = 0.01,
                          σ = 0.03, ξ = 0.004, θ = 0.2, N = 3.3E8)
        p =  p_gen()  # use all defaults
        i_0 = 25000 / p.N
        r_0 = 0.0
        d_0 = 0.0
        s_0 = 1.0 - i_0 - r_0 - d_0
        R□_0 = 0.5  # starting in lockdown
        δ_0 = p.δ_bar
        x_0 = [s_0, i_0, r_0, d_0, R□_0, δ_0]

        prob = SDEProblem(F, G, x_0, (0, p.T), p)
```

```
Out[5]: SDEProblem with uType Array{Float64,1} and tType Float64. In-
        place: false
        timespan: (0.0, 550.0)
        u0: [0.9999242424242424, 7.575757575757576e-5, 0.0, 0.0, 0.5, 0.01]
```

We solve the problem with the SOSRI algorithm (Adaptive strong order 1.5 methods for diagonal noise Ito and Stratonovich SDEs).

```
In [6]: sol_1 = solve(prob, SOSRI());
        @show length(sol_1.t);
```

```
length(sol_1.t) = 628
```

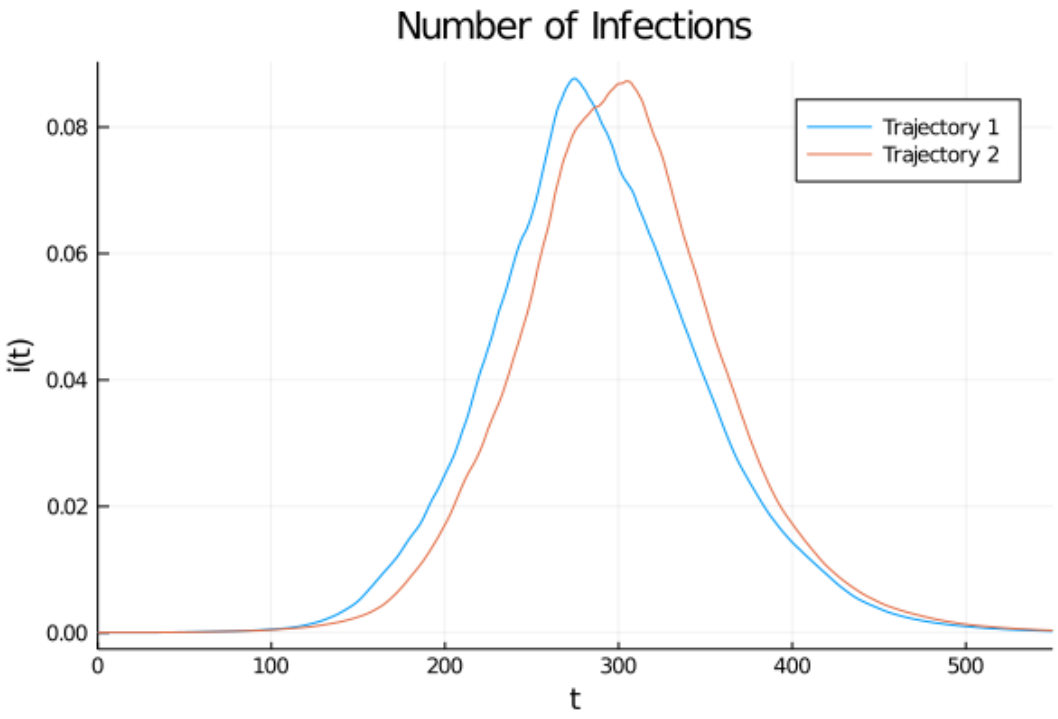
As in the deterministic case of the previous lecture, we are using an adaptive time-stepping method. However, since this is an SDE, (1) you will tend to see more timesteps required due to the greater curvature; and (2) the number of timesteps will change with different shock realizations.

With stochastic differential equations, a "solution" is akin to a simulation for a particular realization of the noise process.

If we take two solutions and plot the number of infections, we will see differences over time:

```
In [7]: sol_2 = solve(prob, SOSRI())
        plot(sol_1, vars=[2], title = "Number of Infections", label = "Trajectory
      ↪1",
             lm = 2, xlabel = "t", ylabel = "i(t)")
        plot!(sol_2, vars=[2], label = "Trajectory 2", lm = 2, ylabel = "i(t)")
```

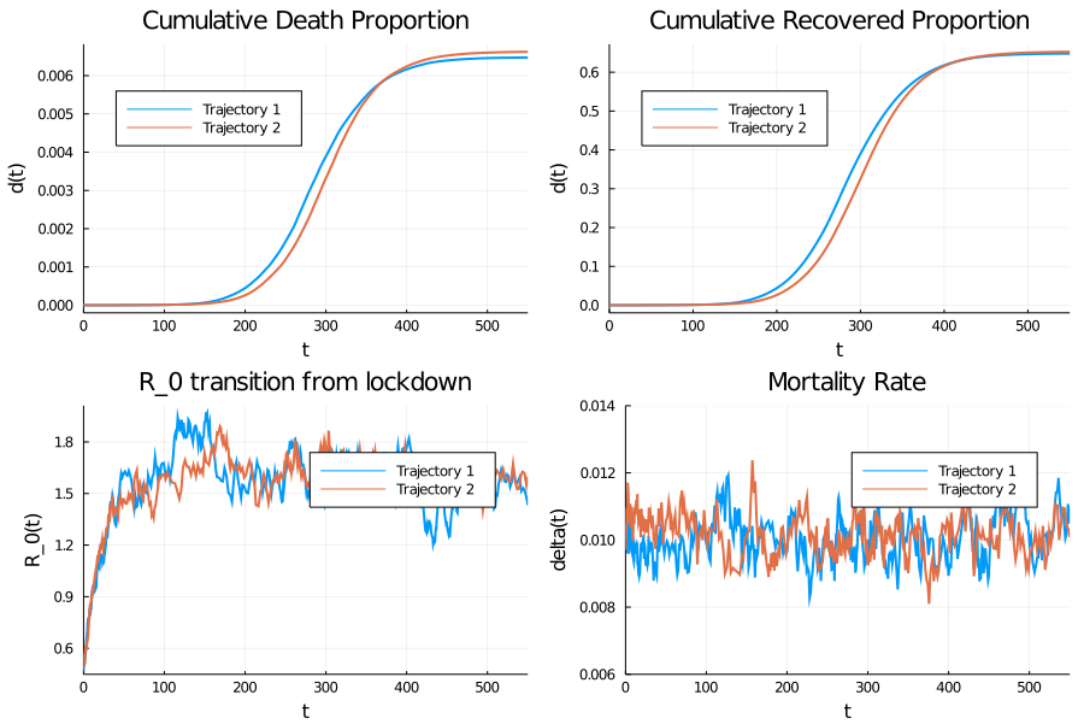
```
Out[7]:
```



The same holds for other variables such as the cumulative deaths, mortality, and R_0:

```
In [8]: plot_1 = plot(sol_1, vars=[4], title = "Cumulative Death Proportion",
  ↪label =
        "Trajectory 1",
                      lw = 2, xlabel = "t", ylabel = "d(t)", legend = :topleft)
        plot!(plot_1, sol_2, vars=[4], label = "Trajectory 2", lw = 2)
        plot_2 = plot(sol_1, vars=[3], title = "Cumulative Recovered Proportion",
  ↪label =
        "Trajectory 1",
                      lw = 2, xlabel = "t", ylabel = "d(t)", legend = :topleft)
        plot!(plot_2, sol_2, vars=[3], label = "Trajectory 2", lw = 2)
        plot_3 = plot(sol_1, vars=[5], title = "R_0 transition from lockdown",
  ↪label =
        "Trajectory 1",
                      lw = 2, xlabel = "t", ylabel = "R_0(t)")
        plot!(plot_3, sol_2, vars=[5], label = "Trajectory 2", lw = 2)
        plot_4 = plot(sol_1, vars=[6], title = "Mortality Rate", label =
  ↪"Trajectory 1",
                      lw = 2, xlabel = "t", ylabel = "delta(t)", ylim = (0.006, 0.
  ↪014))
        plot!(plot_4, sol_2, vars=[6], label = "Trajectory 2", lw = 2)
        plot(plot_1, plot_2, plot_3, plot_4, size = (900, 600))
```

Out[8]:



See here for comments on finding the appropriate SDE algorithm given the structure of $F(x,t)$ and $G(x,t)$

- If G has diagonal noise (i.e. $G(x,t)$ is a diagonal, and possibly a function of the state), then `SOSRI` is the typical choice.

- If G has additive (i.e. $G(t)$ is a independent from the state), then `SOSRA` is usually the best algorithm for even mildly stiff F.
- If the noise process is more general, `LambaEM` and `RKMilGeneral` are flexible to all noise processes.
- If high accuracy and adaptivity are not required, then `EM` (i.e. Euler-Maruyama method typically used by economists) is flexible in its ability to handle different noise processes.

42.4.5 Ensembles

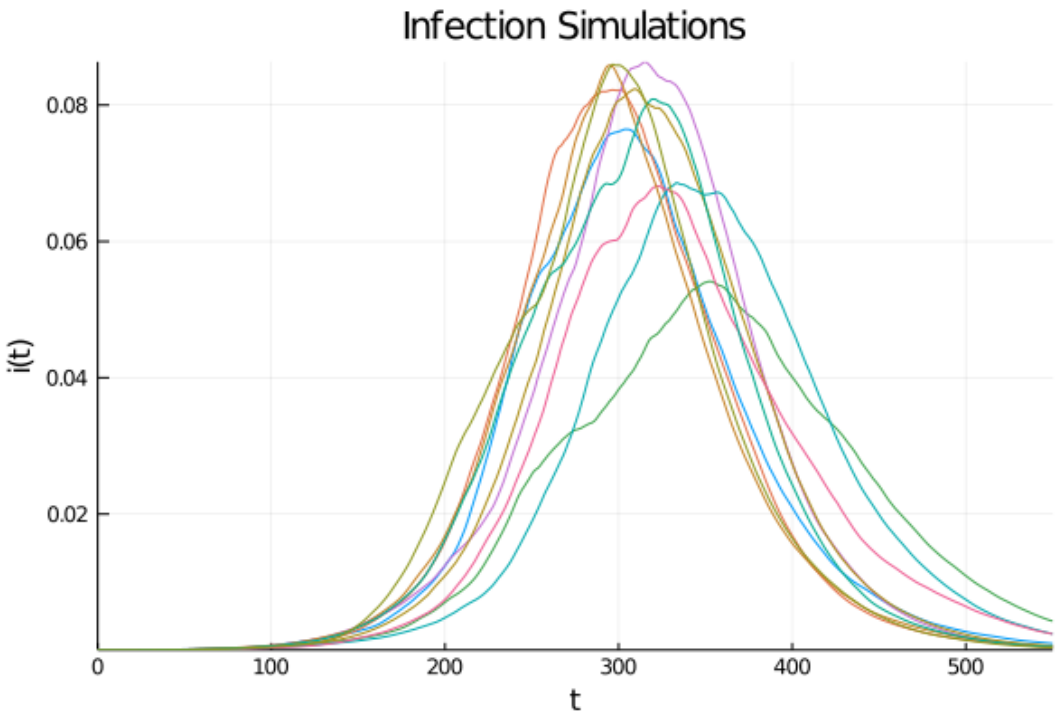
While individual simulations are useful, you often want to look at an ensemble of trajectories of the SDE in order to get an accurate picture of how the system evolves.

To do this, use the `EnsembleProblem` in order to have the solution compute multiple trajectories at once. The returned `EnsembleSolution` acts like an array of solutions but is imbued to plot recipes to showcase aggregate quantities.

For example:

```
In [9]: ensembleprob = EnsembleProblem(prob)
        sol = solve(ensembleprob, SOSRI(), EnsembleSerial(), trajectories = 10)
        plot(sol, vars = [2], title = "Infection Simulations", ylabel = "i(t)",
    ↪xlabel = "t", lm
        = 2)
```

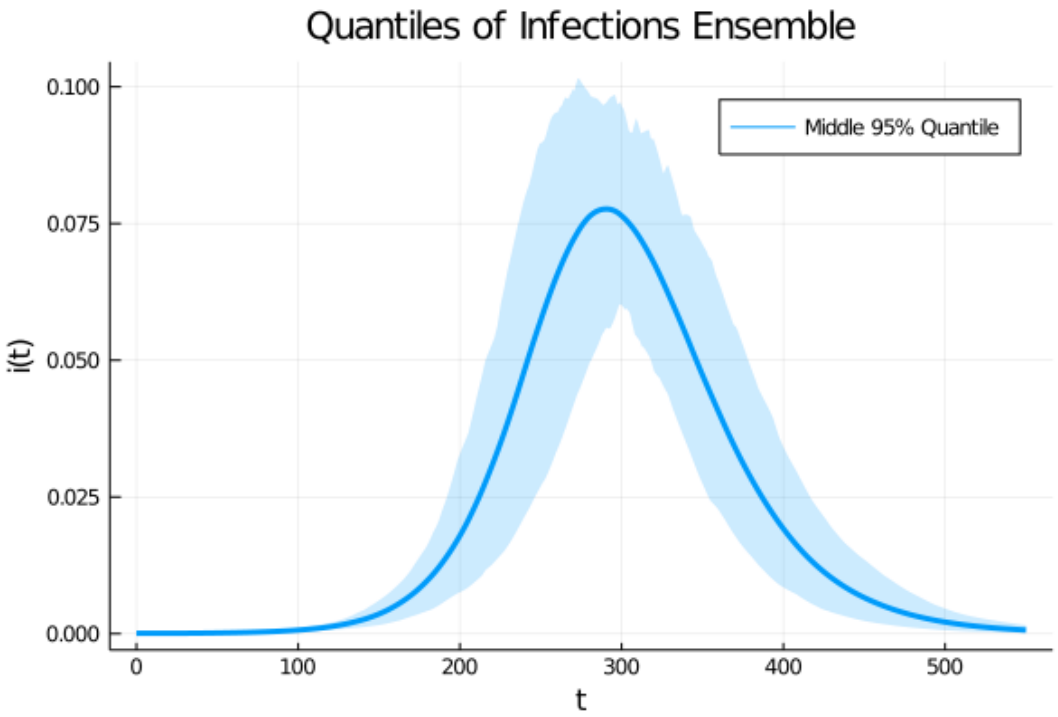
```
Out[9]:
```



Or, more frequently, you may want to run many trajectories and plot quantiles, which can be automatically run in parallel using multiple threads, processes, or GPUs. Here we showcase `EnsembleSummary` which calculates summary information from an ensemble and plots the mean of the solution along with calculated quantiles of the simulation:

```
In [10]: trajectories = 100  # choose larger for smoother quantiles
         sol = solve(ensembleprob, SOSRI(), EnsembleThreads(), trajectories =
 ↪trajectories)
         summ = EnsembleSummary(sol) # defaults to saving 0.05, 0.95 quantiles
         plot(summ, idxs = (2,), title = "Quantiles of Infections Ensemble",
 ↪ylabel = "i(t)",
              xlabel = "t", labels = "Middle 95% Quantile", legend = :topright)
```

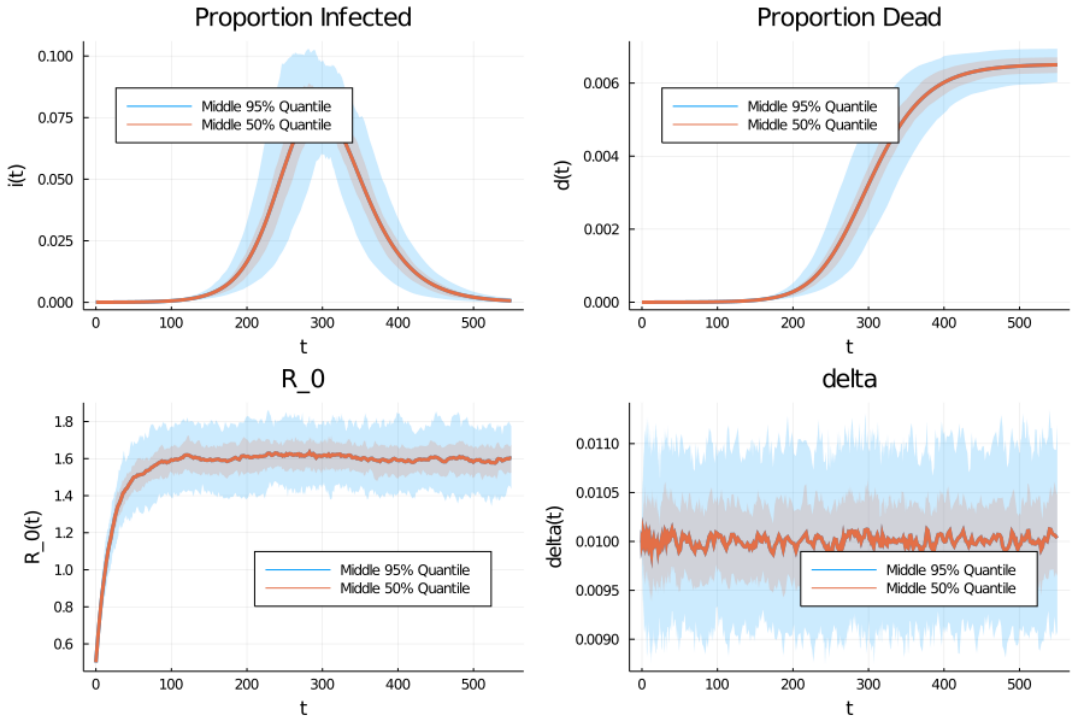
Out[10]:



In addition, you can calculate more quantiles and stack graphs

```
In [11]: sol = solve(ensembleprob, SOSRI(), EnsembleThreads(), trajectories =
 ↪trajectories)
         summ = EnsembleSummary(sol) # defaults to saving 0.05, 0.95 quantiles
         summ2 = EnsembleSummary(sol, quantiles = (0.25, 0.75))

         plot(summ, idxs = (2,4,5,6),
             title = ["Proportion Infected" "Proportion Dead" "R_0" "delta"],
             ylabel = ["i(t)" "d(t)" "R_0(t)" "delta(t)"], xlabel = "t",
             legend = [:topleft :topleft :bottomright :bottomright],
             labels = "Middle 95% Quantile", layout = (2, 2), size = (900, 600))
         plot!(summ2, idxs = (2,4,5,6),
             labels = "Middle 50% Quantile", legend =  [:topleft :topleft :
 ↪bottomright
         :bottomright])
```

Out[11]:



Some additional features of the ensemble and SDE infrastructure are

- Plotting
- Noise Processes, Non-diagonal noise, and Correlated Noise
- Parallel Ensemble features
- Transforming the ensemble calculations with an output_func or reduction
- Auto-GPU accelerated by using `EnsembleGPUArray()` from DiffEqGPU

42.4.6 Changing Mitigation

Consider a policy maker who wants to consider the impact of relaxing lockdown at various speeds.

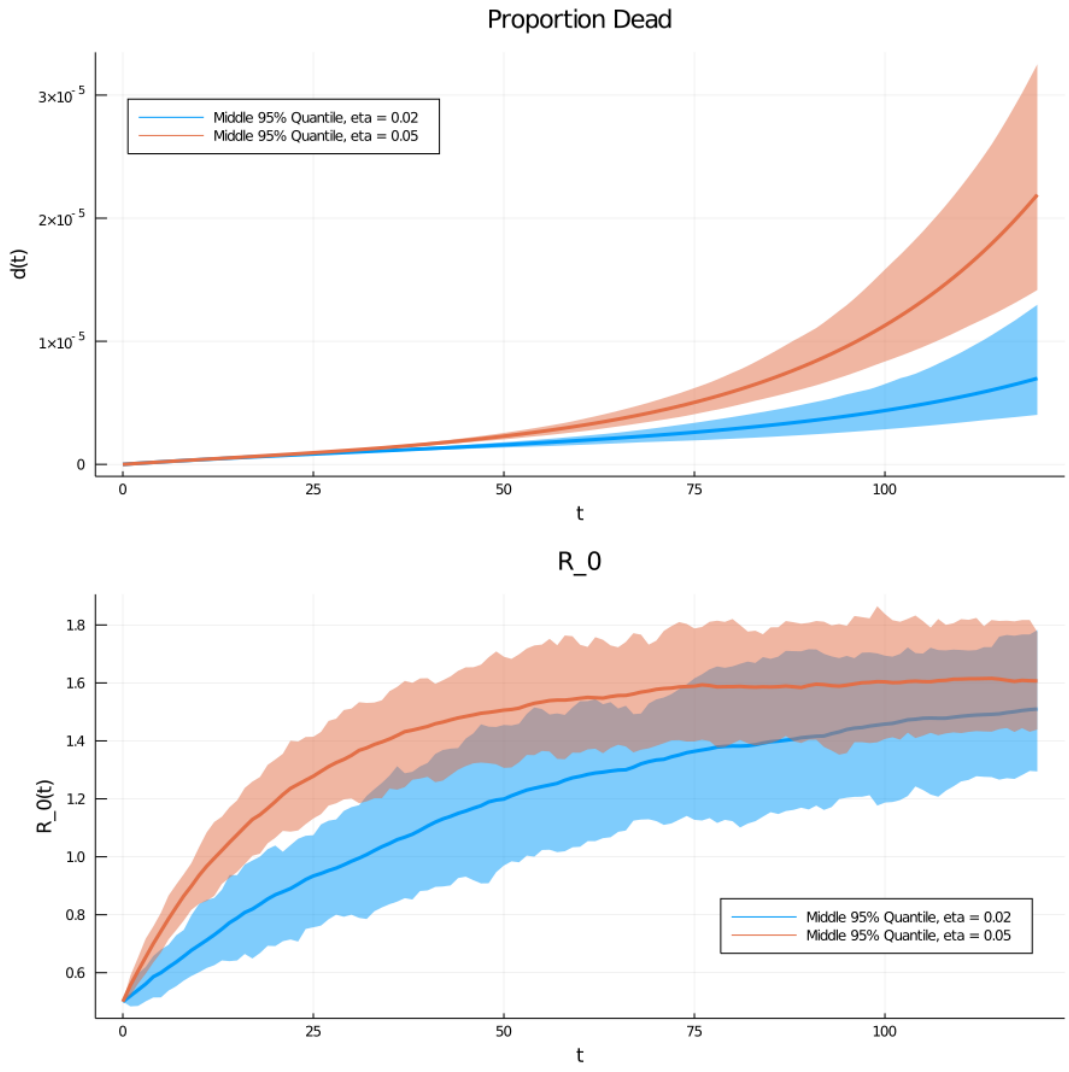
We will shut down the shocks to the mortality rate (i.e. $\xi = 0$) to focus on the variation caused by the volatility in $R_0(t)$.

Consider $\eta = 1/50$ and $\eta = 1/20$, where we start at the same initial condition of $R_0(0) = 0.5$.

```
In [12]: function generate_η_experiment(η; p_gen = p_gen, trajectories = 100,
                                        saveat = 1.0, x_0 = x_0, T = 120.0)
             p = p_gen(η = η, ξ = 0.0)
             ensembleprob = EnsembleProblem(SDEProblem(F, G, x_0, (0, T), p))
             sol = solve(ensembleprob, SOSRI(), EnsembleThreads(),
                         trajectories = trajectories, saveat = saveat)
             return EnsembleSummary(sol)
         end

         # Evaluate two different lockdown scenarios
         η_1 = 1/50
         η_2 = 1/20
         summ_1 = generate_η_experiment(η_1)
         summ_2 = generate_η_experiment(η_2)
```

```
    plot(summ_1, idxs = (4,5),
        title = ["Proportion Dead" "R_0"],
        ylabel = ["d(t)" "R_0(t)"], xlabel = "t",
        legend = [:topleft :bottomright],
        labels = "Middle 95% Quantile, eta = $η_1",
        layout = (2, 1), size = (900, 900), fillalpha = 0.5)
    plot!(summ_2, idxs = (4,5),
        legend = [:topleft :bottomright],
        labels = "Middle 95% Quantile, eta = $η_2", size = (900, 900),
↪fillalpha = 0.5)
```

Out[12]:



While the the mean of the $d(t)$ increases, unsurprisingly, we see that the 95% quantile for later time periods is also much larger - even after the R_0 has converged.

That is, volatile contact rates (and hence R_0) can interact to make catastrophic worst-case scenarios due to the nonlinear dynamics of the system.

42.5 Ending Lockdown

As in the deterministic lecture, we can consider two mitigation scenarios

1. choose $\bar{R}_0(t)$ to target $R_0 = 0.5$ for 30 days and then $R_0 = 2$ for the remaining 17 months. This corresponds to lifting lockdown in 30 days.
2. target $R_0 = 0.5$ for 120 days and then $R_0 = 2$ for the remaining 14 months. This corresponds to lifting lockdown in 4 months.

Since empirical estimates of $R_0(t)$ discussed in [31] and other papers show it to have wide variation, we will maintain a fairly larger σ.

We start the model with 100,000 active infections.

In [13]:
```
R_L = 0.5  # lockdown
η_experiment = 1.0/10
σ_experiment = 0.04

R_lift_early(t, p) = t < 30.0 ? R_L : 2.0

R_lift_late(t, p) = t < 120.0 ? R_L : 2.0

p_early = p_gen(R = R_lift_early, η = η_experiment, σ = σ_experiment)
p_late = p_gen(R = R_lift_late, η = η_experiment, σ = σ_experiment)


# initial conditions
i_0 = 100000 / p_early.N
r_0 = 0.0
d_0 = 0.0
s_0 = 1.0 - i_0 - r_0 - d_0
δ_0 = p_early.δ_bar

x_0 = [s_0, i_0, r_0, d_0, R_L, δ_0]  # start in lockdown
prob_early = SDEProblem(F, G, x_0, (0, p_early.T), p_early)
prob_late = SDEProblem(F, G, x_0, (0, p_late.T), p_late)
```

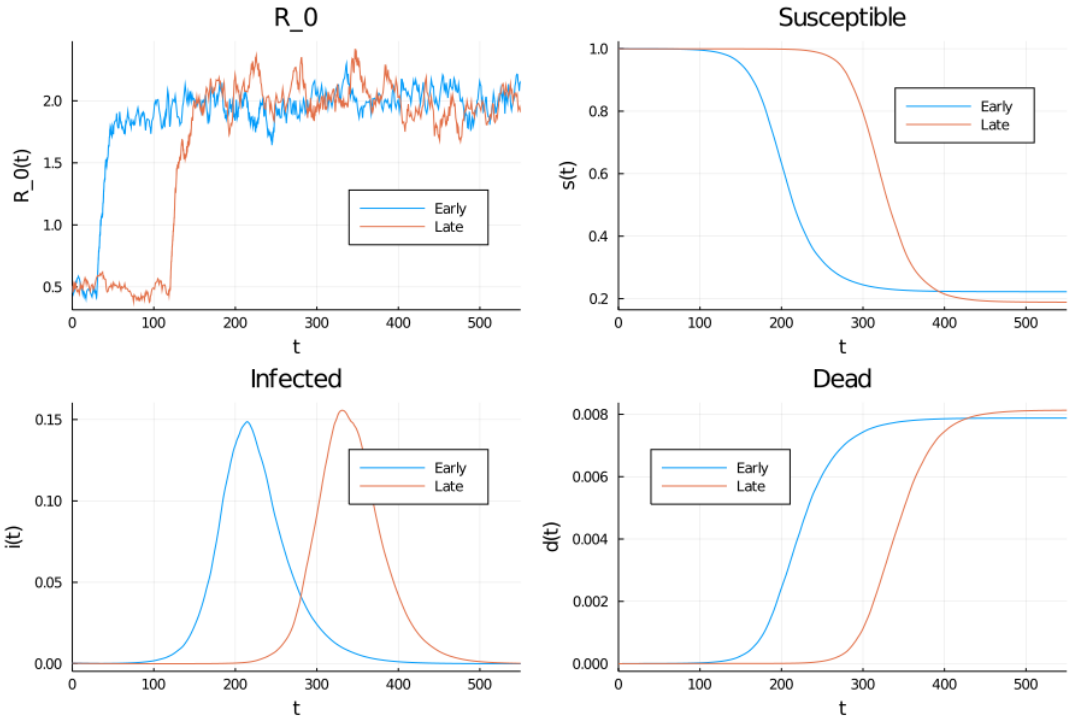
Out[13]:
```
SDEProblem with uType Array{Float64,1} and tType Float64. In-
place: false
timespan: (0.0, 550.0)
u0: [0.9996969696969698, 0.00030303030303030303, 0.0, 0.0, 0.5, 0.01]
```

Simulating for a single realization of the shocks, we see the results are qualitatively similar to what we had before

In [14]:
```
sol_early = solve(prob_early, SOSRI())
sol_late = solve(prob_late, SOSRI())
plot(sol_early, vars = [5, 1,2,4],
    title = ["R_0" "Susceptible" "Infected" "Dead"],
    layout = (2, 2), size = (900, 600),
    ylabel = ["R_0(t)" "s(t)" "i(t)" "d(t)"], xlabel = "t",
        legend = [:bottomright :topright :topright :topleft],
        label = ["Early" "Early" "Early" "Early"])
```

```
        plot!(sol_late, vars = [5, 1,2,4],
                legend = [:bottomright :topright :topright :topleft],
                label = ["Late" "Late" "Late" "Late"])
```

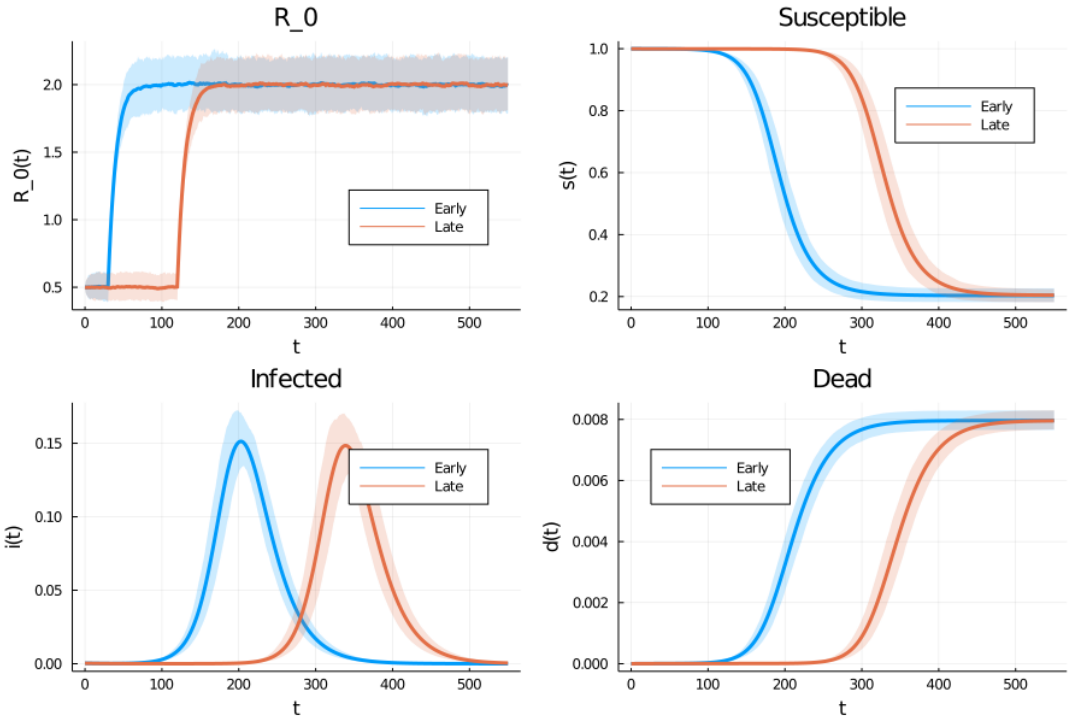
Out[14]:



However, note that this masks highly volatile values induced by the in R_0 variation, as seen in the ensemble

In [15]:
```
trajectories = 400
saveat = 1.0
ensemble_sol_early = solve(EnsembleProblem(prob_early), SOSRI(),
                           EnsembleThreads(), trajectories = trajectories,
↪saveat =
saveat)
ensemble_sol_late = solve(EnsembleProblem(prob_late), SOSRI(),
                           EnsembleThreads(), trajectories = trajectories,
↪saveat =
saveat)
summ_early = EnsembleSummary(ensemble_sol_early)
summ_late = EnsembleSummary(ensemble_sol_late)

plot(summ_early, idxs = (5, 1, 2, 4),
    title = ["R_0" "Susceptible" "Infected" "Dead"], layout = (2, 2),
↪size = (900, 600),
    ylabel = ["R_0(t)" "s(t)" "i(t)" "d(t)"], xlabel = "t",
    legend = [:bottomright :topright :topright :topleft],
    label = ["Early" "Early" "Early" "Early"])
plot!(summ_late, idxs = (5, 1,2,4),
    legend = [:bottomright :topright :topright :topleft],
    label = ["Late" "Late" "Late" "Late"])
```

Out[15]:

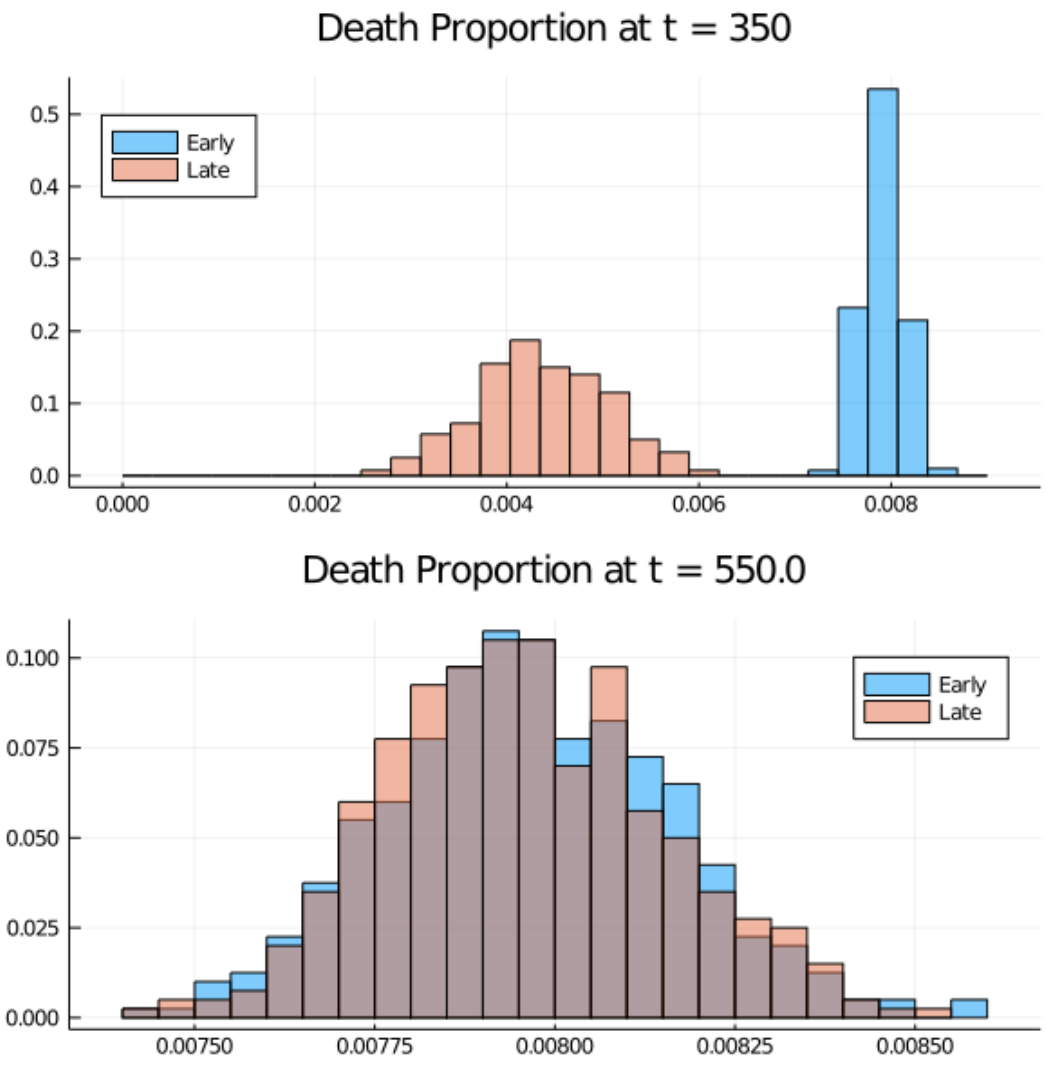


Finally, rather than looking at the ensemble summary, we can use data directly from the ensemble to do our own analysis.

For example, evaluating at an intermediate (`t = 350`) and final time step.

In [16]:
```
N = p_early.N
t_1 = 350
t_2 = p_early.T  # i.e. the last element
bins_1 = range(0.000, 0.009, length = 30)
bins_2 = 30  # number rather than grid.

hist_1 = histogram([ensemble_sol_early.u[i](t_1)[4] for i in 1:
↪trajectories],
                   fillalpha = 0.5, normalize = :probability,
                   legend = :topleft, bins = bins_1,
                  label = "Early", title = "Death Proportion at t = $t_1")
histogram!(hist_1, [ensemble_sol_late.u[i](t_1)[4] for i in 1:
↪trajectories],
           label = "Late", fillalpha = 0.5, normalize = :probability, bins
↪= bins_1)
hist_2 = histogram([ensemble_sol_early.u[i][4, end] for i in 1:
↪trajectories],
                   fillalpha = 0.5, normalize = :probability, bins = bins_2,
                   label = "Early", title = "Death Proportion at t = $t_2")
histogram!(hist_2, [ensemble_sol_late.u[i][4, end] for i in 1:
↪trajectories],
           label = "Late", fillalpha = 0.5, normalize = :probability, bins
↪= bins_2)
plot(hist_1, hist_2, size = (600,600), layout = (2, 1))
```

Out[16]:



This shows that there are significant differences after a year, but by 550 days the graphs largely coincide.

In the above code given the return from `solve` on an `EnsembleProblem` , e.g. `ensemble_sol = solve(...)`

- You can access the i'th simulation as `ensemble_sol[i]`, which then has all of the standard solution handling features
- You can evaluate at a real time period, `t`, with `ensemble_sol[i](t)`. Or access the 4th element with `ensemble_sol[i](t)[4]`
- If the `t` was not exactly one of the `saveat` values (if specified) or the adaptive timesteps (if it was not), then it will use interpolation
- Alternatively, to access the results of the ODE as a grid exactly at the timesteps, where `j` is timestep index, use `ensemble_sol[i][j]` or the 4th element with `ensemble_sol[i][4, j]`
- Warning: unless you have chosen a `saveat` grid, the timesteps will not be aligned between simulations. That is, `ensemble_sol[i_1].t` wouldn't match `ensemble_sol[i_2].t`. In that case, use interpolation with `ensemble_sol[i_1](t)` etc.

42.6 Reinfection

As a final experiment, consider a model where the immunity is only temporary, and individuals become susceptible again.

In particular, assume that at rate ν immunity is lost. For illustration, we will examine the case if the average immunity lasts 12 months (i.e. $1/\nu = 360$)

The transition modifies the differential equation (1) to become

$$\begin{aligned} ds &= (-\gamma\, R_0\, s\, i + \nu\, r)\, dt \\ di &= (\gamma\, R_0\, s\, i - \gamma i)\, dt \\ dr &= ((1-\delta)\gamma i - \nu\, r)\, dt \\ dd &= \delta\gamma i\, dt \end{aligned} \tag{6}$$

This change modifies the underlying F function and adds a parameter, but otherwise the model remains the same.

We will redo the "Ending Lockdown" simulation from above, where the only difference is the new transition.

```
In [17]: function F_reinfect(x, p, t)
             s, i, r, d, R□, δ = x
             @unpack γ, R□, η, σ, ξ, θ, δ_bar, ν = p

             return [-γ*R□*s*i + ν*r;  # ds/dt
                     γ*R□*s*i - γ*i;   # di/dt
                     (1-δ)*γ*i - ν*r   # dr/dt
                     δ*γ*i;            # dd/dt
                     η*(R□(t, p) - R□);# dR□/dt
                     θ*(δ_bar - δ);    # dδ/dt
                     ]
         end

         p_re_gen = @with_kw ( T = 550.0, γ = 1.0 / 18, η = 1.0 / 20,
                               R□_n = 1.6, R□ = (t, p) -> p.R□_n,
                              δ_bar = 0.01, σ = 0.03, ξ = 0.004, θ = 0.2, N = 3.3E8, ν =□
 ↪1/360)

         p_re_early = p_re_gen(R□ = R□_lift_early, η = η_experiment, σ =□
 ↪σ_experiment)
        p_re_late = p_re_gen(R□ = R□_lift_late, η = η_experiment, σ = σ_experiment)

         trajectories = 400
         saveat = 1.0
         prob_re_early = SDEProblem(F_reinfect, G, x_0, (0, p_re_early.T),□
 ↪p_re_early)
        prob_re_late = SDEProblem(F_reinfect, G, x_0, (0, p_re_late.T), p_re_late)
         ensemble_sol_re_early = solve(EnsembleProblem(prob_re_early), SOSRI(),
         EnsembleThreads(),
                                       trajectories = trajectories, saveat = saveat)
         ensemble_sol_re_late = solve(EnsembleProblem(prob_re_late), SOSRI(),□
 ↪EnsembleThreads(),
```

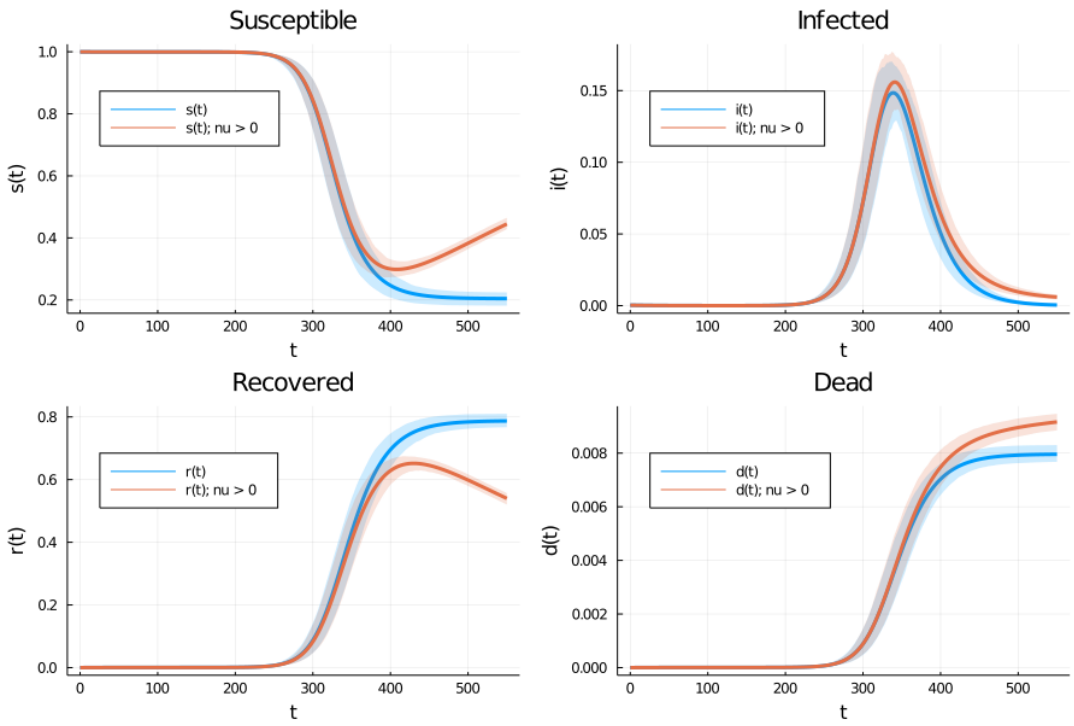
```
                                    trajectories = trajectories, saveat = saveat)
summ_re_early = EnsembleSummary(ensemble_sol_re_early)
summ_re_late = EnsembleSummary(ensemble_sol_re_late)
```

```
Out[17]: EnsembleSolution Solution of length 551 with uType:
         Float64
```

The ensemble simulations for the $\nu = 0$ and $\nu > 0$ can be compared to see the impact in the absence of medical innovations.

```
In [18]: plot(summ_late, idxs = (1, 2, 3, 4),
             title = ["Susceptible" "Infected" "Recovered" "Dead"],
             layout = (2, 2), size = (900, 600),
             ylabel = ["s(t)" "i(t)" "r(t)" "d(t)"], xlabel = "t",
             legend = :topleft,
             label = ["s(t)" "i(t)" "r(t)" "d(t)"])
         plot!(summ_re_late, idxs =  (1, 2, 3, 4),
             legend = :topleft,
             label = ["s(t); nu > 0" "i(t); nu > 0" "r(t); nu > 0" "d(t); nu > 0"])
```

```
Out[18]:
```

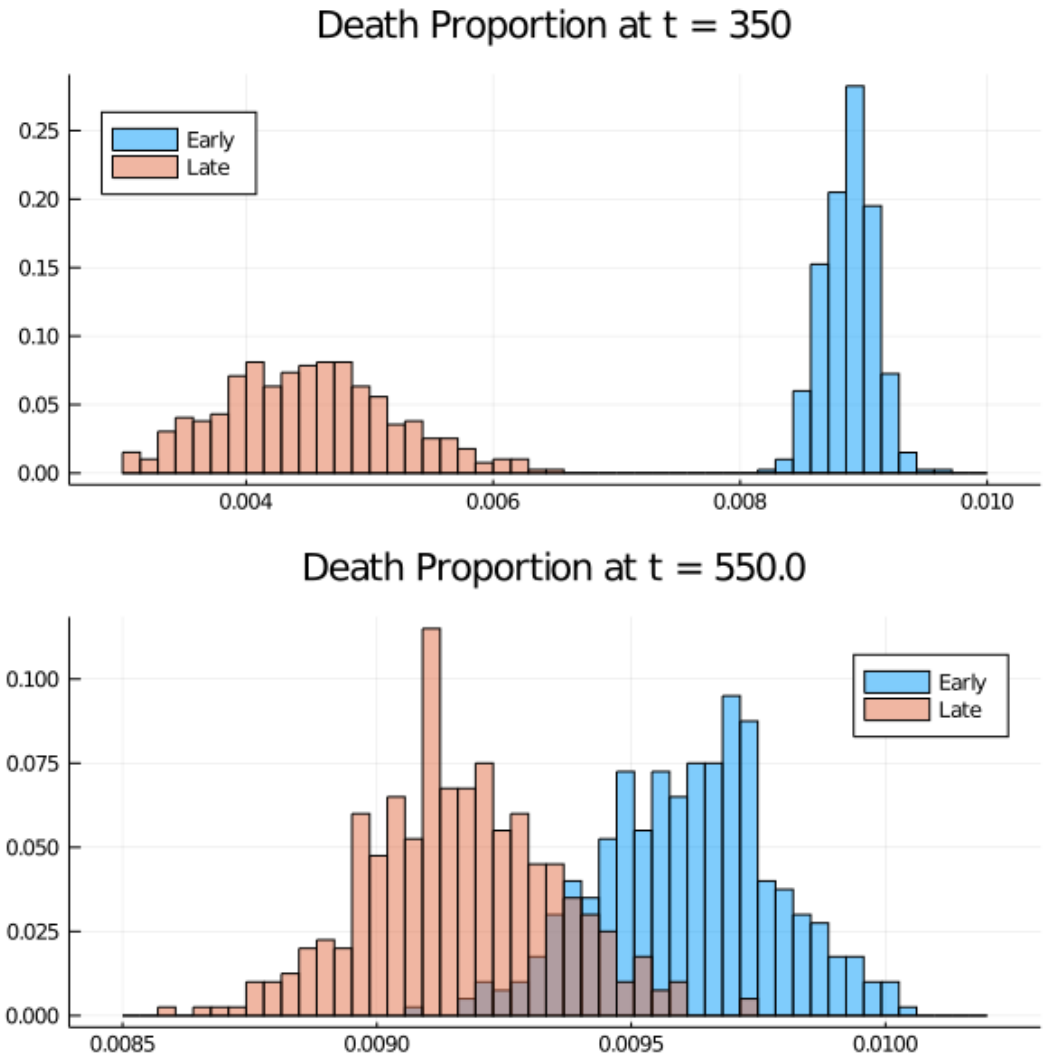


Finally, we can examine the same early vs. late lockdown histogram

```
In [19]: bins_re_1 = range(0.003, 0.010, length = 50)
         bins_re_2 = range(0.0085, 0.0102, length = 50)
         hist_re_1 = histogram([ensemble_sol_re_early.u[i](t_1)[4] for i in 1:
↪trajectories],
                               fillalpha = 0.5, normalize = :probability,
                               legend = :topleft, bins = bins_re_1,
```

```
                            label = "Early", title = "Death Proportion at t = $t_1")
        histogram!(hist_re_1, [ensemble_sol_re_late.u[i](t_1)[4] for i in 1:
↪trajectories],
                   label = "Late", fillalpha = 0.5, normalize = :probability, bins =
↪bins_re_1)
        hist_re_2 = histogram([ensemble_sol_re_early.u[i][4, end] for i in 1:
↪trajectories],
                              fillalpha = 0.5, normalize = :probability, bins =
↪bins_re_2,
                            label = "Early", title = "Death Proportion at t = $t_2")
        histogram!(hist_re_2, [ensemble_sol_re_late.u[i][4, end] for i in 1:
↪trajectories],
                   label = "Late", fillalpha = 0.5, normalize = :probability,
                   bins =  bins = bins_re_2)
        plot(hist_re_1, hist_re_2, size = (600,600), layout = (2, 1))
```

Out[19]:



In this case, there are significant differences between the early and late deaths and high variance.

This bleak simulation has assumed that no individuals has long-term immunity and that there will be no medical advancements on that time horizon - both of which are unlikely to be true.

Nevertheless, it suggest that the timing of lifting lockdown has a more profound impact after 18 months if we allow stochastic shocks imperfect immunity.

Part VI

Multiple Agent Models

Chapter 43

Schelling's Segregation Model

43.1 Contents

43.2 Overview

In 1969, Thomas C. Schelling developed a simple but striking model of racial segregation [97].

His model studies the dynamics of racially mixed neighborhoods.

Like much of Schelling's work, the model shows how local interactions can lead to surprising aggregate structure.

In particular, it shows that relatively mild preference for neighbors of similar race can lead in aggregate to the collapse of mixed neighborhoods, and high levels of segregation.

In recognition of this and other research, Schelling was awarded the 2005 Nobel Prize in Economic Sciences (joint with Robert Aumann).

In this lecture we (in fact you) will build and run a version of Schelling's model.

43.3 The Model

We will cover a variation of Schelling's model that is easy to program and captures the main idea.

Suppose we have two types of people: orange people and green people.

For the purpose of this lecture, we will assume there are 250 of each type.

These agents all live on a single unit square.

The location of an agent is just a point (x, y), where $0 < x, y < 1$.

43.3.1 Preferences

We will say that an agent is *happy* if half or more of her 10 nearest neighbors are of the same type.

Here 'nearest' is in terms of Euclidean distance.

An agent who is not happy is called *unhappy*.

An important point here is that agents are not averse to living in mixed areas.

They are perfectly happy if half their neighbors are of the other color.

43.3.2 Behavior

Initially, agents are mixed together (integrated).

In particular, the initial location of each agent is an independent draw from a bivariate uniform distribution on $S = (0, 1)^2$.

Now, cycling through the set of all agents, each agent is now given the chance to stay or move.

We assume that each agent will stay put if they are happy and move if unhappy.

The algorithm for moving is as follows

1. Draw a random location in S
2. If happy at new location, move there
3. Else, go to step 1

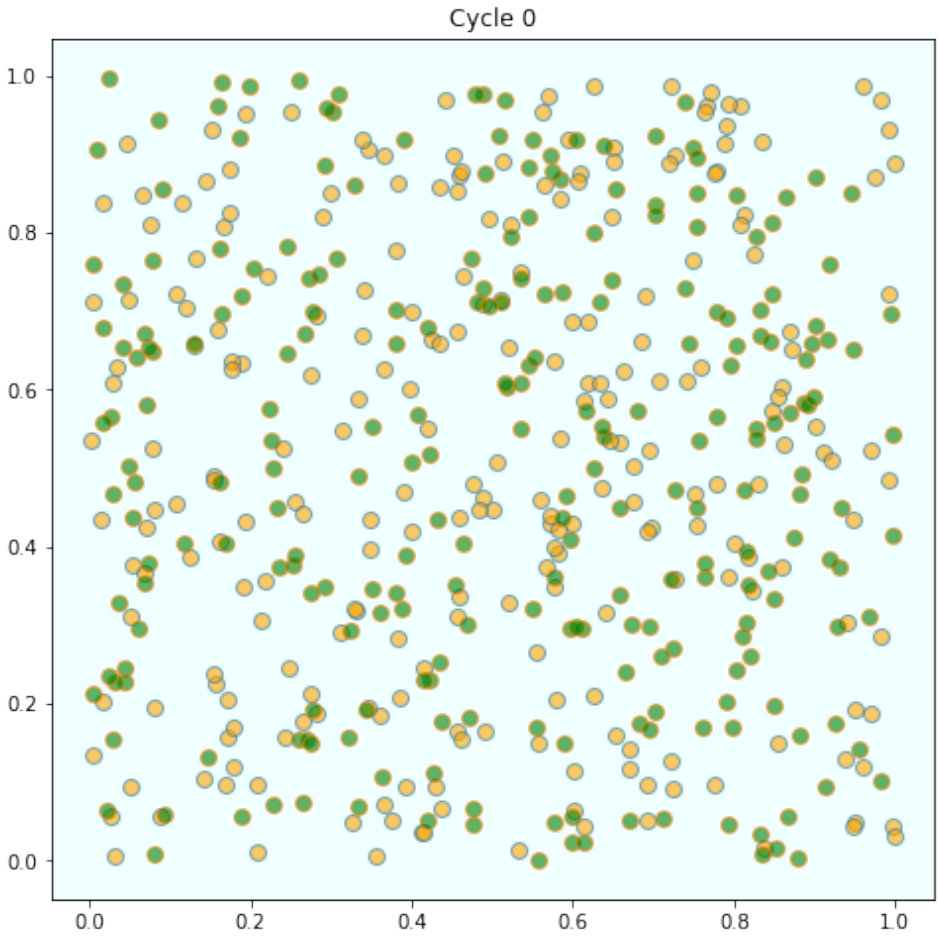
In this way, we cycle continuously through the agents, moving as required.

We continue to cycle until no one wishes to move.

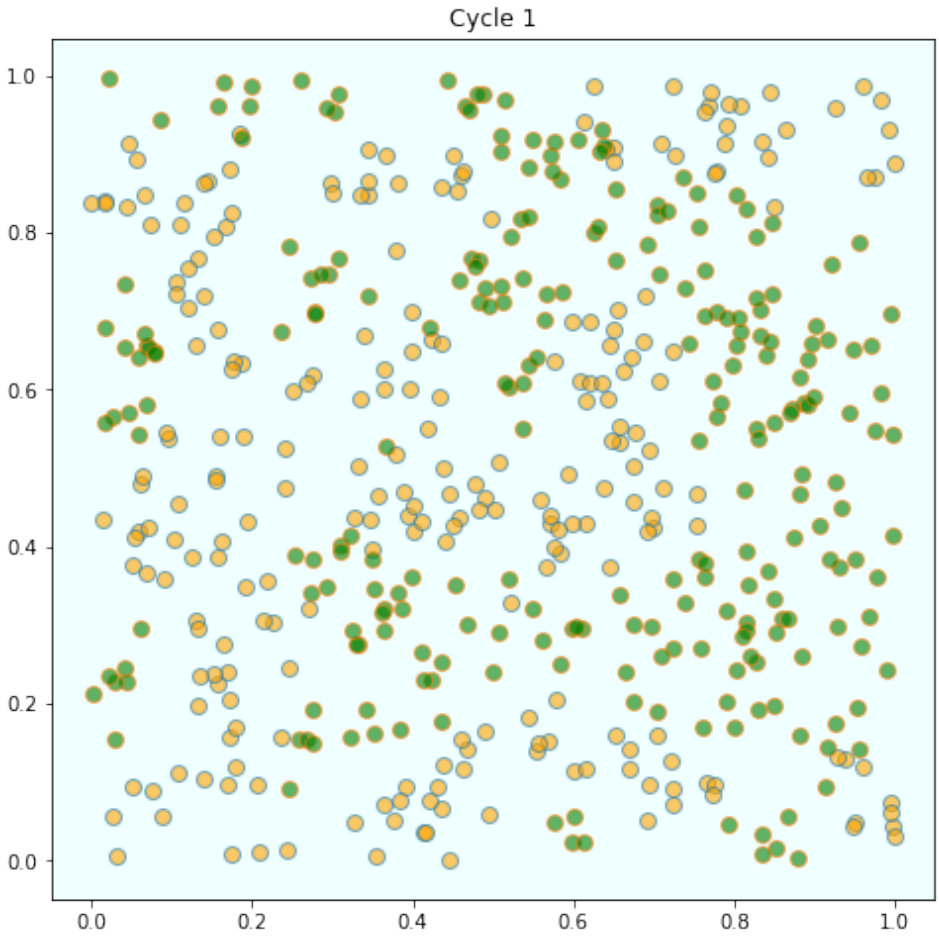
43.4 Results

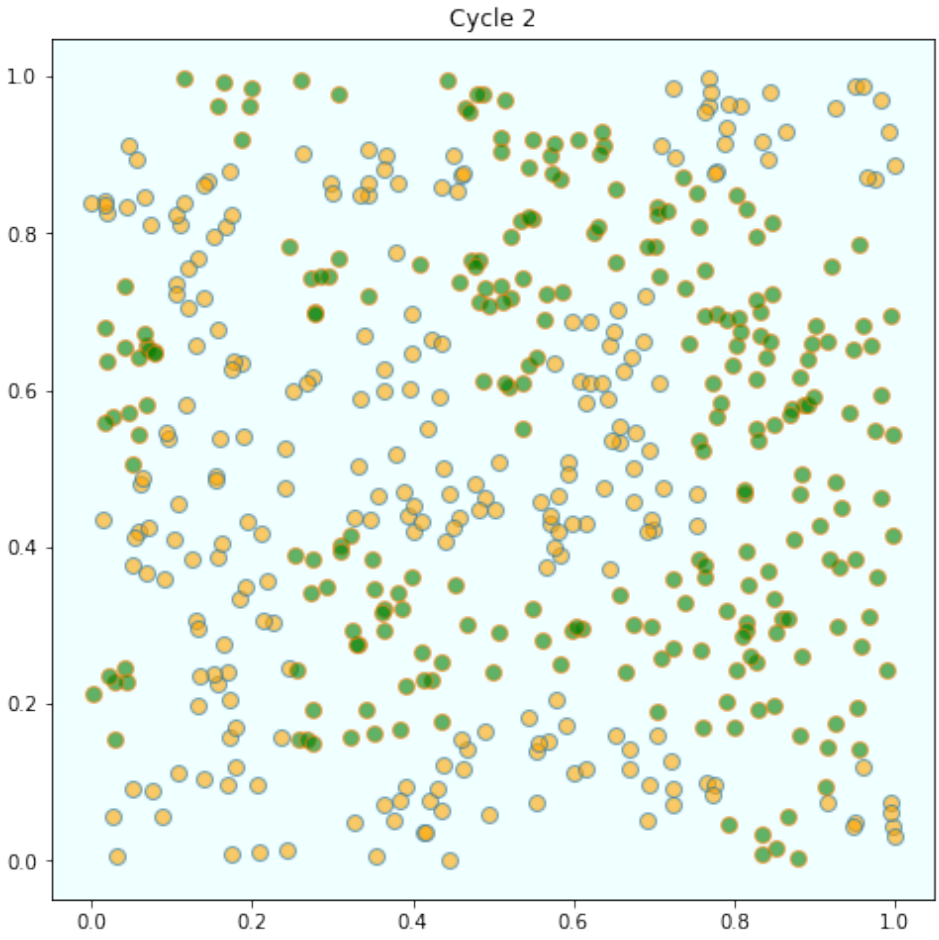
Let's have a look at the results we got when we coded and ran this model.

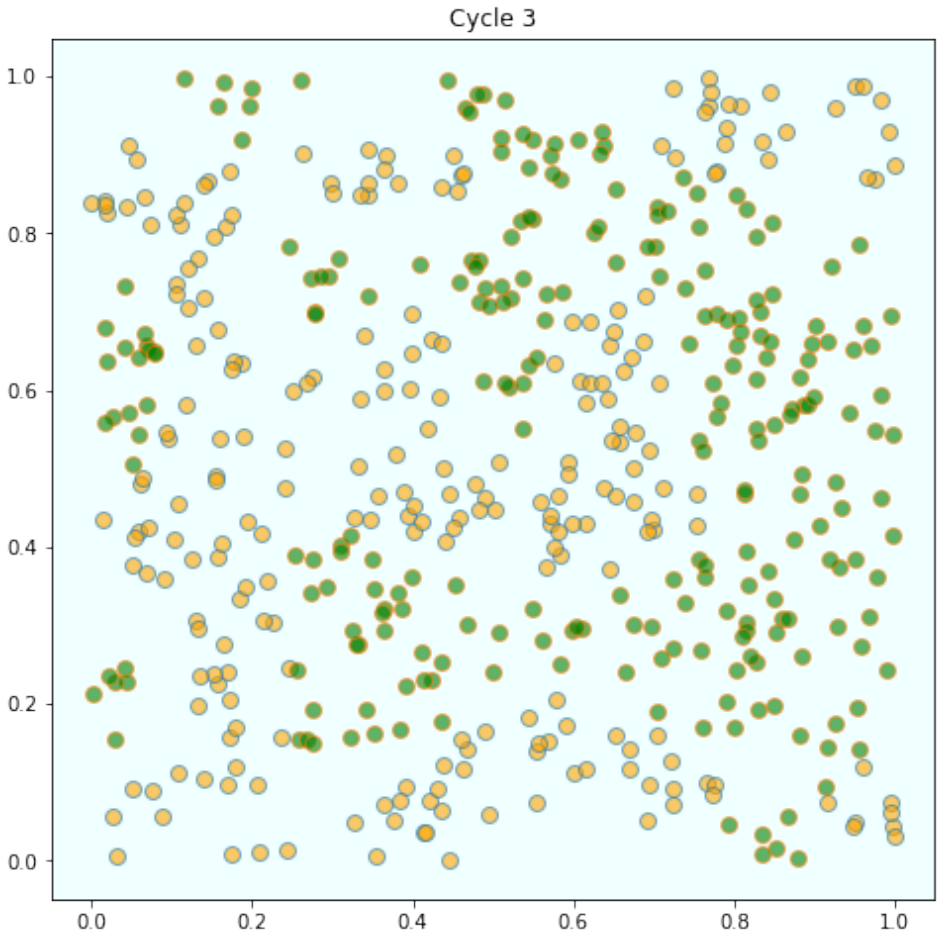
As discussed above, agents are initially mixed randomly together



But after several cycles they become segregated into distinct regions


Cycle 1
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0


Cycle 2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0



In this instance, the program terminated after 4 cycles through the set of agents, indicating that all agents had reached a state of happiness.

What is striking about the pictures is how rapidly racial integration breaks down.

This is despite the fact that people in the model don't actually mind living mixed with the other type.

Even with these preferences, the outcome is a high degree of segregation.

43.5 Exercises

43.5.1 Exercise 1

Implement and run this simulation for yourself.

Use 250 agents of each type.

43.6 Solutions

43.6.1 Exercise 1

Here's one solution that does the job we want. If you feel like a further exercise you can probably speed up some of the computations and then increase the number of agents.

43.6.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using Parameters, Plots, LinearAlgebra, Statistics
        gr(fmt = :png);
```

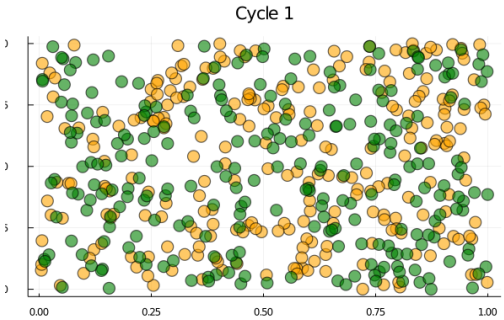
```
In [3]: Agent = @with_kw (kind, location = rand(2))

        draw_location!(a) = a.location .= rand(2)

        # distance is just 2 norm: uses our subtraction function
        get_distance(a, agent) = norm(a.location - agent.location)

        function is_happy(a)
            distances = [(get_distance(a, agent), agent) for agent in agents]
            sort!(distances)
            neighbors = [agent for (d, agent) in distances[1:neighborhood_size]]
            share = mean(isequal(a.kind), other.kind for other in neighbors)

            # can also do
            # share = mean(isequal(a.kind),
            #              first(agents[idx]) for idx in
            #              partialsortperm(get_distance.(Ref(a), agents),
            #                              1:neighborhood_size))

            return share ≥ preference
        end

        function update!(a)
            # If not happy, then randomly choose new locations until happy.
            while !is_happy(a)
                draw_location!(a)
            end
        end

        function plot_distribution(agents)
            x_vals_0, y_vals_0 = zeros(0), zeros(0)
            x_vals_1, y_vals_1 = zeros(0), zeros(0)

            # obtain locations of each type
            for agent in agents
                x, y = agent.location
                if agent.kind == 0
                    push!(x_vals_0, x)
```

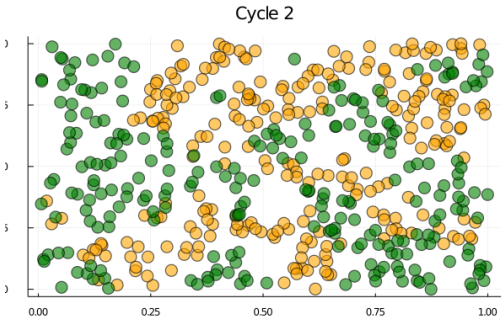
```
                push!(y_vals_0, y)
            else
                push!(x_vals_1, x)
                push!(y_vals_1, y)
            end
        end

        p = scatter(x_vals_0, y_vals_0, color = :orange, markersize = 8, alpha
↪= 0.6)
       scatter!(x_vals_1, y_vals_1, color = :green, markersize = 8, alpha = 0.6)
        return plot!(legend = :none)
    end
```

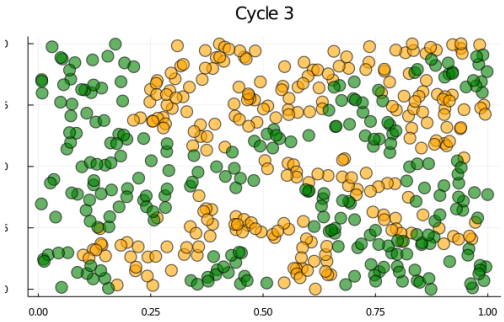
```
Out[3]: plot_distribution (generic function with 1 method)
```

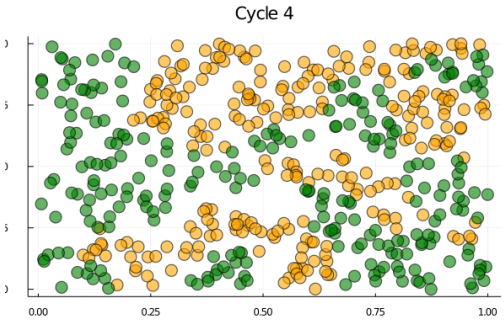
```
In [4]: num_of_type_0 = 250
        num_of_type_1 = 250
        neighborhood_size = 10 # Number of agents regarded as neighbors
        preference = 0.5 # Want their kind to make at least this share of the
↪neighborhood

        # Create a list of agents
        agents = vcat([Agent(kind = 0) for i in 1:num_of_type_0],
                      [Agent(kind = 1) for i in 1:num_of_type_1])

        plot_array = Any[]

        # loop until none wishes to move
        while true
            push!(plot_array, plot_distribution(agents))
            no_one_moved = true
            for agent in agents
                old_location = copy(agent.location)
                update!(agent)
                if norm(old_location - agent.location) ≠ 0
                    no_one_moved = false
                end
            end
            if no_one_moved
                break
            end
        end
        n = length(plot_array)
        plot(plot_array...,
             layout = (n, 1),
             size = (600, 400n),
             title = reshape(["Cycle $i" for i in 1:n], 1, n))
```

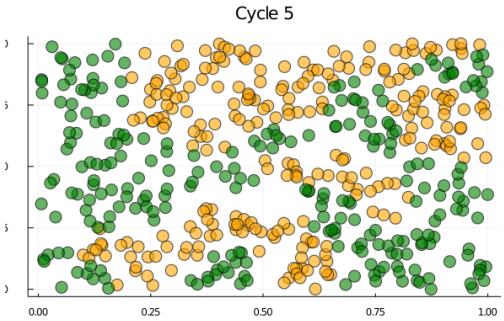
```
Out[4]:
```

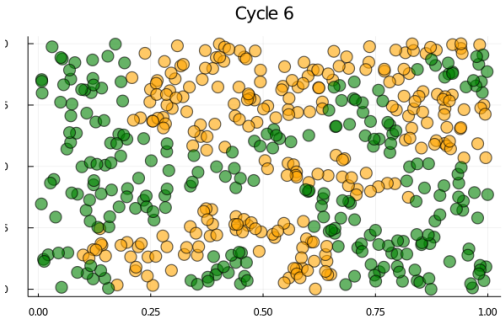

Cycle 1
0.00
0.25
0.50
0.75
1.00


Cycle 2
0.00
0.25
0.50
0.75
1.00


Cycle 3
0.00
0.25
0.50
0.75
1.00


Cycle 4
0.00
0.25
0.50
0.75
1.00


Cycle 5
0.00
0.25
0.50
0.75
1.00


Cycle 6
0.00
0.25
0.50
0.75
1.00

Chapter 44

A Lake Model of Employment and Unemployment

44.1 Contents

44.2 Overview

This lecture describes what has come to be called a *lake model*.

The lake model is a basic tool for modeling unemployment.

It allows us to analyze

- flows between unemployment and employment
- how these flows influence steady state employment and unemployment rates

It is a good model for interpreting monthly labor department reports on gross and net jobs created and jobs destroyed.

The "lakes" in the model are the pools of employed and unemployed.

The "flows" between the lakes are caused by

- firing and hiring
- entry and exit from the labor force

For the first part of this lecture, the parameters governing transitions into and out of unemployment and employment are exogenous.

Later, we'll determine some of these transition rates endogenously using the McCall search model.

We'll also use some nifty concepts like ergodicity, which provides a fundamental link between

cross-sectional and *long run time series* distributions.

These concepts will help us build an equilibrium model of ex ante homogeneous workers whose different luck generates variations in their ex post experiences.

44.2.1 Prerequisites

Before working through what follows, we recommend you read the lecture on finite Markov chains.

You will also need some basic linear algebra and probability.

44.3 The Model

The economy is inhabited by a very large number of ex ante identical workers.

The workers live forever, spending their lives moving between unemployment and employment.

Their rates of transition between employment and unemployment are governed by the following parameters:

- λ, the job finding rate for currently unemployed workers
- α, the dismissal rate for currently employed workers
- b, the entry rate into the labor force
- d, the exit rate from the labor force

The growth rate of the labor force evidently equals $g = b - d$.

44.3.1 Aggregate Variables

We want to derive the dynamics of the following aggregates

- E_t, the total number of employed workers at date t
- U_t, the total number of unemployed workers at t
- N_t, the number of workers in the labor force at t

We also want to know the values of the following objects

- The employment rate $e_t := E_t/N_t$.
- The unemployment rate $u_t := U_t/N_t$.

(Here and below, capital letters represent stocks and lowercase letters represent flows)

44.3.2 Laws of Motion for Stock Variables

We begin by constructing laws of motion for the aggregate variables E_t, U_t, N_t.

Of the mass of workers E_t who are employed at date t,

- $(1 - d)E_t$ will remain in the labor force
- of these, $(1 - \alpha)(1 - d)E_t$ will remain employed

Of the mass of workers U_t workers who are currently unemployed,

- $(1 - d)U_t$ will remain in the labor force

- of these, $(1-d)\lambda U_t$ will become employed

Therefore, the number of workers who will be employed at date $t+1$ will be

$$E_{t+1} = (1-d)(1-\alpha)E_t + (1-d)\lambda U_t$$

A similar analysis implies

$$U_{t+1} = (1-d)\alpha E_t + (1-d)(1-\lambda)U_t + b(E_t + U_t)$$

The value $b(E_t + U_t)$ is the mass of new workers entering the labor force unemployed.

The total stock of workers $N_t = E_t + U_t$ evolves as

$$N_{t+1} = (1+b-d)N_t = (1+g)N_t$$

Letting $X_t := \begin{pmatrix} U_t \\ E_t \end{pmatrix}$, the law of motion for X is

$$X_{t+1} = AX_t \quad \text{where} \quad A := \begin{pmatrix} (1-d)(1-\lambda)+b & (1-d)\alpha + b \\ (1-d)\lambda & (1-d)(1-\alpha) \end{pmatrix}$$

This law tells us how total employment and unemployment evolve over time.

44.3.3 Laws of Motion for Rates

Now let's derive the law of motion for rates.

To get these we can divide both sides of $X_{t+1} = AX_t$ by N_{t+1} to get

$$\begin{pmatrix} U_{t+1}/N_{t+1} \\ E_{t+1}/N_{t+1} \end{pmatrix} = \frac{1}{1+g} A \begin{pmatrix} U_t/N_t \\ E_t/N_t \end{pmatrix}$$

Letting

$$x_t := \begin{pmatrix} u_t \\ e_t \end{pmatrix} = \begin{pmatrix} U_t/N_t \\ E_t/N_t \end{pmatrix}$$

we can also write this as

$$x_{t+1} = \hat{A} x_t \quad \text{where} \quad \hat{A} := \frac{1}{1+g} A$$

You can check that $e_t + u_t = 1$ implies that $e_{t+1} + u_{t+1} = 1$.

This follows from the fact that the columns of $\hat{A}$ sum to 1.

44.4 Implementation

Let's code up these equations.

Here's the code:

44.4.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")

In [2]: using LinearAlgebra, Statistics
        using Distributions, Expectations, NLsolve, Parameters, Plots
        using QuantEcon, Roots, Random

In [3]: gr(fmt = :png);

In [4]: LakeModel = @with_kw (λ = 0.283, α = 0.013, b = 0.0124, d = 0.00822)

        function transition_matrices(lm)
            @unpack λ, α, b, d = lm
            g = b - d
            A = [(1 - λ) * (1 - d) + b      (1 - d) * α + b
                 (1 - d) * λ                (1 - d) * (1 - α)]
            Â = A ./ (1 + g)
            return (A = A, Â = Â)
        end

        function rate_steady_state(lm)
            @unpack Â = transition_matrices(lm)
            sol = fixedpoint(x -> Â * x, fill(0.5, 2))
            converged(sol) || error("Failed to converge in $(result.iterations)
        iterations")
            return sol.zero
        end

        function simulate_stock_path(lm, X0, T)
            @unpack A = transition_matrices(lm)
            X_path = zeros(eltype(X0), 2, T)
            X = copy(X0)
            for t in 1:T
                X_path[:, t] = X
                X = A * X
            end
            return X_path
        end

        function simulate_rate_path(lm, x0, T)
            @unpack Â = transition_matrices(lm)
            x_path = zeros(eltype(x0), 2, T)
            x = copy(x0)
            for t in 1:T
                x_path[:, t] = x
                x = Â * x
            end
            return x_path
        end

Out[4]: simulate_rate_path (generic function with 1 method)
```

Let's observe these matrices for the baseline model

```
In [5]: lm = LakeModel()
        A, Â = transition_matrices(lm)
        A
```

```
Out[5]: 2×2 Array{Float64,2}:
         0.723506  0.0252931
         0.280674  0.978887
```

```
In [6]: Â
```

```
Out[6]: 2×2 Array{Float64,2}:
         0.720495  0.0251879
         0.279505  0.974812
```

And a revised model

```
In [7]: lm = LakeModel(α = 2.0)
        A, Â = transition_matrices(lm)
        A
```

```
Out[7]: 2×2 Array{Float64,2}:
         0.723506   1.99596
         0.280674  -0.99178
```

```
In [8]: Â
```

```
Out[8]: 2×2 Array{Float64,2}:
         0.720495   1.98765
         0.279505  -0.987652
```

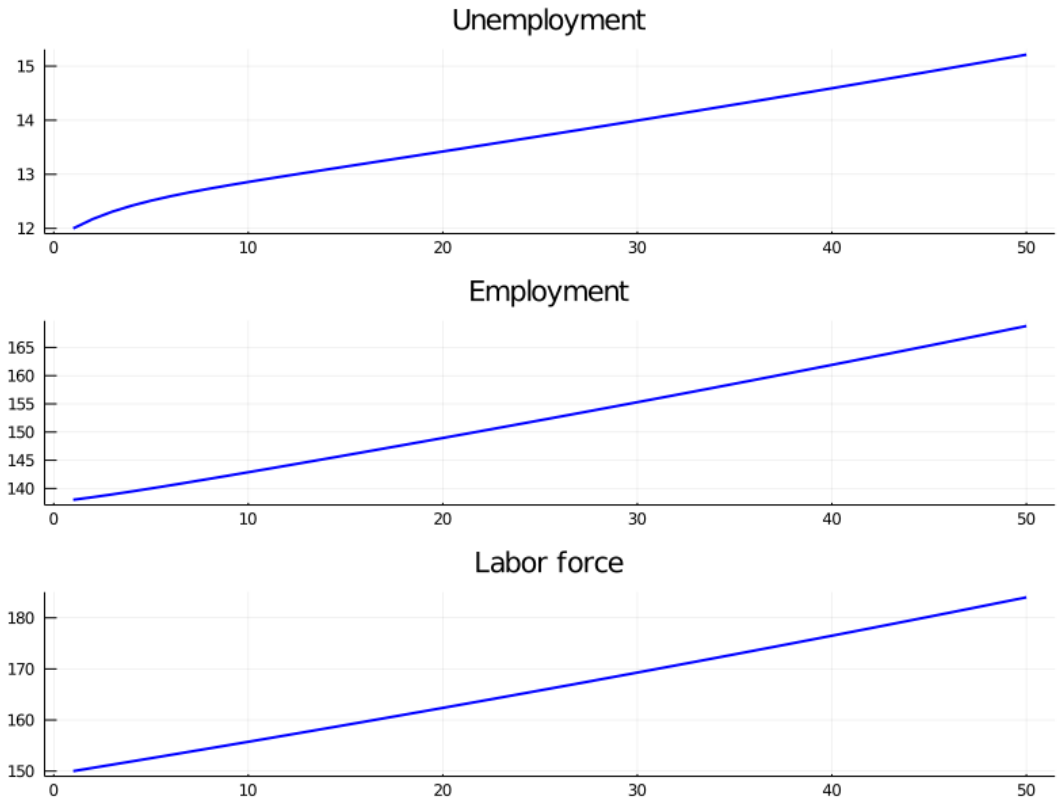
44.4.2 Aggregate Dynamics

Let's run a simulation under the default parameters (see above) starting from $X_0 = (12, 138)$

```
In [9]: lm = LakeModel()
        N_0 = 150      # population
        e_0 = 0.92     # initial employment rate
        u_0 = 1 - e_0  # initial unemployment rate
        T = 50         # simulation length

        U_0 = u_0 * N_0
        E_0 = e_0 * N_0
        X_0 = [U_0; E_0]

        X_path = simulate_stock_path(lm, X_0, T)

        x1 = X_path[1, :]
        x2 = X_path[2, :]
        x3 = dropdims(sum(X_path, dims = 1), dims = 1)

        plt_unemp = plot(title = "Unemployment", 1:T, x1, color = :blue, lw = 2,
↪grid = true,
```

```
        label = "")
        plt_emp = plot(title = "Employment", 1:T, x2, color = :blue, lw = 2, grid
↪= true, label
        = "")
        plt_labor = plot(title = "Labor force", 1:T, x3, color = :blue, lw = 2,
↪grid = true,
        label = "")

        plot(plt_unemp, plt_emp, plt_labor, layout = (3, 1), size = (800, 600))
```

Out[9]:



The aggregates E_t and U_t don't converge because their sum $E_t + U_t$ grows at rate g.

On the other hand, the vector of employment and unemployment rates x_t can be in a steady state $\bar{x}$ if there exists an $\bar{x}$ such that

- $\bar{x} = \hat{A}\bar{x}$
- the components satisfy $\bar{e} + \bar{u} = 1$

This equation tells us that a steady state level $\bar{x}$ is an eigenvector of $\hat{A}$ associated with a unit eigenvalue.

We also have $x_t \to \bar{x}$ as $t \to \infty$ provided that the remaining eigenvalue of $\hat{A}$ has modulus less that 1.

This is the case for our default parameters:

```
In [10]: lm = LakeModel()
         A, Â = transition_matrices(lm)
```

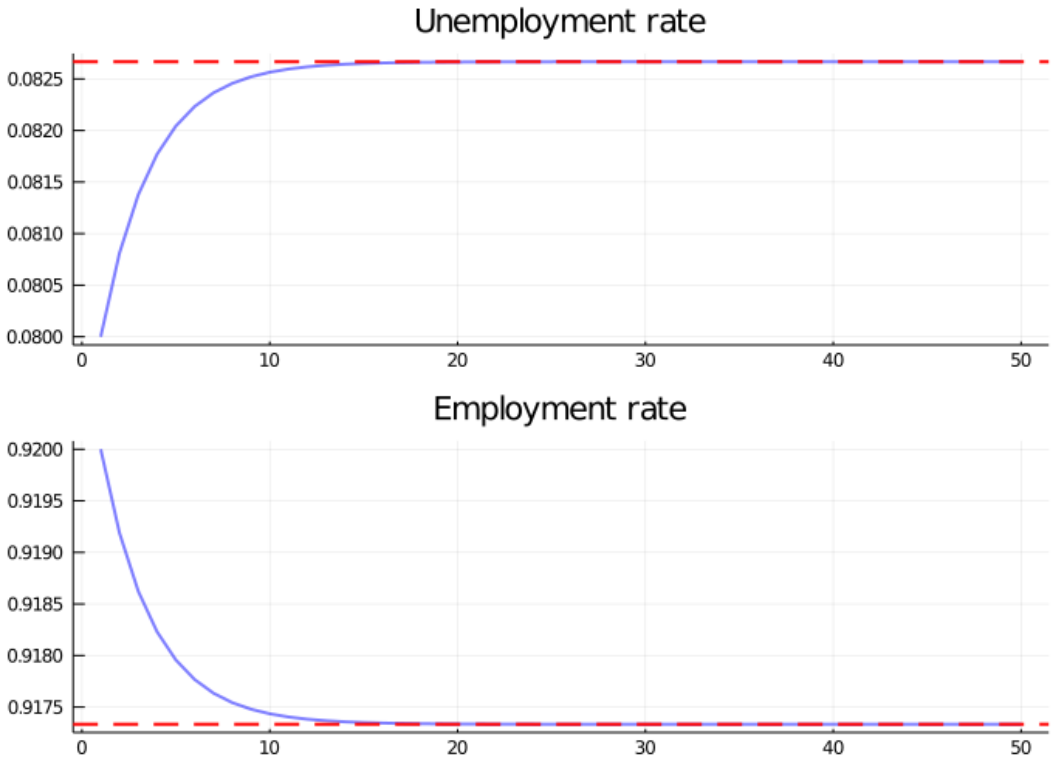
```
e, f = eigvals(Â)
abs(e), abs(f)
```

```
Out[10]: (0.6953067378358462, 1.0)
```

Let's look at the convergence of the unemployment and employment rate to steady state levels (dashed red line)

```
In [11]: lm = LakeModel()
         e_0 = 0.92     # initial employment rate
         u_0 = 1 - e_0  # initial unemployment rate
         T = 50         # simulation length

         xbar = rate_steady_state(lm)
         x_0 = [u_0; e_0]
         x_path = simulate_rate_path(lm, x_0, T)

         plt_unemp = plot(title ="Unemployment rate", 1:T, x_path[1, :],color = :
 ↪blue, lw = 2,
                          alpha = 0.5, grid = true, label = "")
         plot!(plt_unemp, [xbar[1]], color=:red, linetype = :hline, linestyle = :
 ↪dash, lw = 2,
         label = "")
         plt_emp = plot(title = "Employment rate", 1:T, x_path[2, :],color = :
 ↪blue, lw = 2, alpha
         = 0.5,
                        grid = true, label = "")
         plot!(plt_emp, [xbar[2]], color=:red, linetype = :hline, linestyle = :
 ↪dash, lw = 2,
         label = "")
         plot(plt_unemp, plt_emp, layout = (2, 1), size=(700,500))
```

```
Out[11]:
```



44.5 Dynamics of an Individual Worker

An individual worker's employment dynamics are governed by a finite state Markov process.

The worker can be in one of two states:

- $s_t = 0$ means unemployed
- $s_t = 1$ means employed

Let's start off under the assumption that $b = d = 0$.

The associated transition matrix is then

$$P = \begin{pmatrix} 1 - \lambda & \lambda \\ \alpha & 1 - \alpha \end{pmatrix}$$

Let ψ_t denote the marginal distribution over employment / unemployment states for the worker at time t.

As usual, we regard it as a row vector.

We know from an earlier discussion that ψ_t follows the law of motion

$$\psi_{t+1} = \psi_t P$$

We also know from the lecture on finite Markov chains that if $\alpha \in (0, 1)$ and $\lambda \in (0, 1)$, then P has a unique stationary distribution, denoted here by ψ^*.

The unique stationary distribution satisfies

$$\psi^*[0] = \frac{\alpha}{\alpha + \lambda}$$

Not surprisingly, probability mass on the unemployment state increases with the dismissal rate and falls with the job finding rate rate.

44.5.1 Ergodicity

Let's look at a typical lifetime of employment-unemployment spells.

We want to compute the average amounts of time an infinitely lived worker would spend employed and unemployed.

Let

$$\bar{s}_{u,T} := \frac{1}{T} \sum_{t=1}^{T} \mathbb{1}\{s_t = 0\}$$

and

$$\bar{s}_{e,T} := \frac{1}{T} \sum_{t=1}^{T} \mathbb{1}\{s_t = 1\}$$

(As usual, $\mathbb{1}\{Q\} = 1$ if statement Q is true and 0 otherwise)

These are the fraction of time a worker spends unemployed and employed, respectively, up until period T.

If $\alpha \in (0, 1)$ and $\lambda \in (0, 1)$, then P is ergodic, and hence we have

$$\lim_{T \to \infty} \bar{s}_{u,T} = \psi^*[0] \quad \text{and} \quad \lim_{T \to \infty} \bar{s}_{e,T} = \psi^*[1]$$

with probability one.

Inspection tells us that P is exactly the transpose of $\hat{A}$ under the assumption $b = d = 0$.

Thus, the percentages of time that an infinitely lived worker spends employed and unemployed equal the fractions of workers employed and unemployed in the steady state distribution.

44.5.2 Convergence rate

How long does it take for time series sample averages to converge to cross sectional averages?

We can use QuantEcon.jl's MarkovChain type to investigate this.

Let's plot the path of the sample averages over 5,000 periods

```
In [12]: using QuantEcon, Roots, Random
```

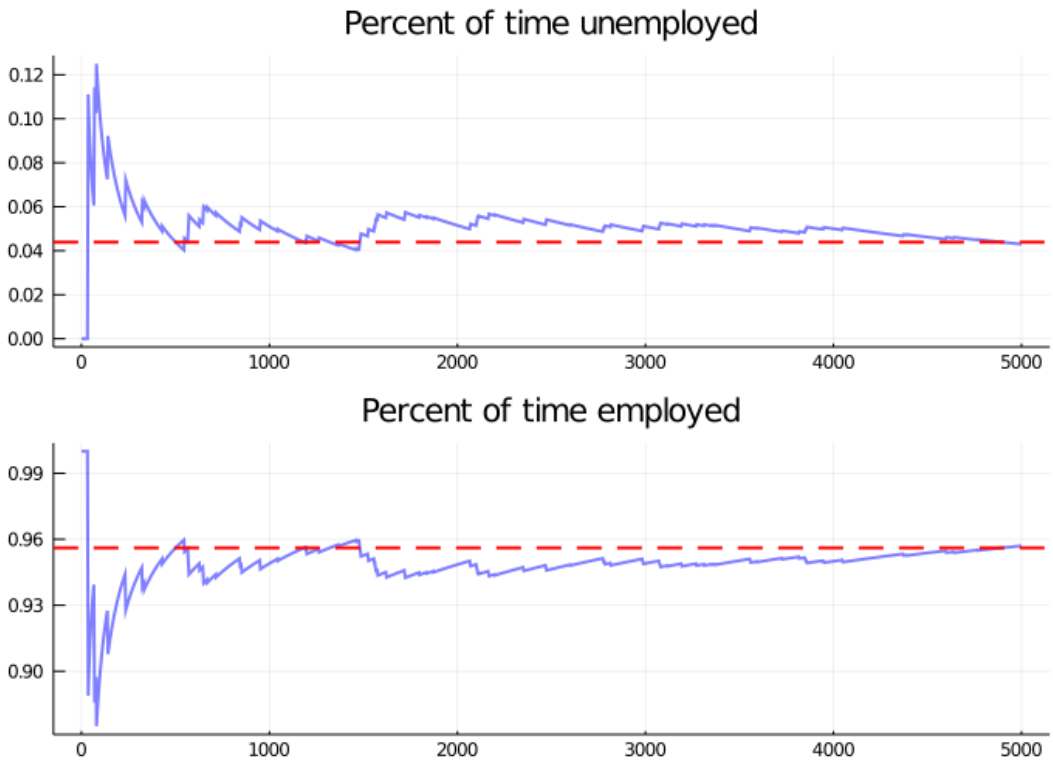
```
In [13]: lm = LakeModel(d = 0, b = 0)
         T = 5000                          # Simulation length
```

```
@unpack α, λ = lm
P = [(1 - λ)     λ
     α       (1 - α)]
```

Out[13]:
```
2×2 Array{Float64,2}:
 0.717  0.283
 0.013  0.987
```

In [14]:
```
Random.seed!(42)
mc = MarkovChain(P, [0; 1])      # 0=unemployed, 1=employed
xbar = rate_steady_state(lm)

s_path = simulate(mc, T; init=2)
s_e = cumsum(s_path) ./ (1:T)
s_u = 1 .- s_e
s_bars = [s_u s_e]

plt_unemp = plot(title = "Percent of time unemployed", 1:T, s_bars[:
↪,1],color = :blue,
lw = 2,
                 alpha = 0.5, label = "", grid = true)
plot!(plt_unemp, [xbar[1]], linetype = :hline, linestyle = :dash, color=:
↪red, lw = 2,
label = "")
plt_emp = plot(title = "Percent of time employed", 1:T, s_bars[:,2],color
↪= :blue, lw =
2,
               alpha = 0.5, label = "", grid = true)
plot!(plt_emp, [xbar[2]], linetype = :hline, linestyle = :dash, color=:
↪red, lw = 2,
label = "")
plot(plt_unemp, plt_emp, layout = (2, 1), size=(700,500))
```

Out[14]:



The stationary probabilities are given by the dashed red line.

In this case it takes much of the sample for these two objects to converge.

This is largely due to the high persistence in the Markov chain.

44.6 Endogenous Job Finding Rate

We now make the hiring rate endogenous.

The transition rate from unemployment to employment will be determined by the McCall search model [76].

All details relevant to the following discussion can be found in our treatment of that model.

44.6.1 Reservation Wage

The most important thing to remember about the model is that optimal decisions are characterized by a reservation wage $\bar{w}$.

- If the wage offer w in hand is greater than or equal to $\bar{w}$, then the worker accepts.
- Otherwise, the worker rejects.

As we saw in our discussion of the model, the reservation wage depends on the wage offer distribution and the parameters

- α, the separation rate
- β, the discount factor
- γ, the offer arrival rate
- c, unemployment compensation

44.6.2 Linking the McCall Search Model to the Lake Model

Suppose that all workers inside a lake model behave according to the McCall search model.

The exogenous probability of leaving employment remains α.

But their optimal decision rules determine the probability λ of leaving unemployment.

This is now

$$\lambda = \gamma \mathbb{P}\{w_t \geq \bar{w}\} = \gamma \sum_{w' \geq \bar{w}} p(w') \tag{1}$$

44.6.3 Fiscal Policy

We can use the McCall search version of the Lake Model to find an optimal level of unemployment insurance.

We assume that the government sets unemployment compensation c.

The government imposes a lump sum tax τ sufficient to finance total unemployment payments.

To attain a balanced budget at a steady state, taxes, the steady state unemployment rate u, and the unemployment compensation rate must satisfy

$$\tau = uc$$

The lump sum tax applies to everyone, including unemployed workers.

Thus, the post-tax income of an employed worker with wage w is $w - \tau$.

The post-tax income of an unemployed worker is $c - \tau$.

For each specification (c, τ) of government policy, we can solve for the worker's optimal reservation wage.

This determines λ via (1) evaluated at post tax wages, which in turn determines a steady state unemployment rate $u(c, \tau)$.

For a given level of unemployment benefit c, we can solve for a tax that balances the budget in the steady state

$$\tau = u(c, \tau)c$$

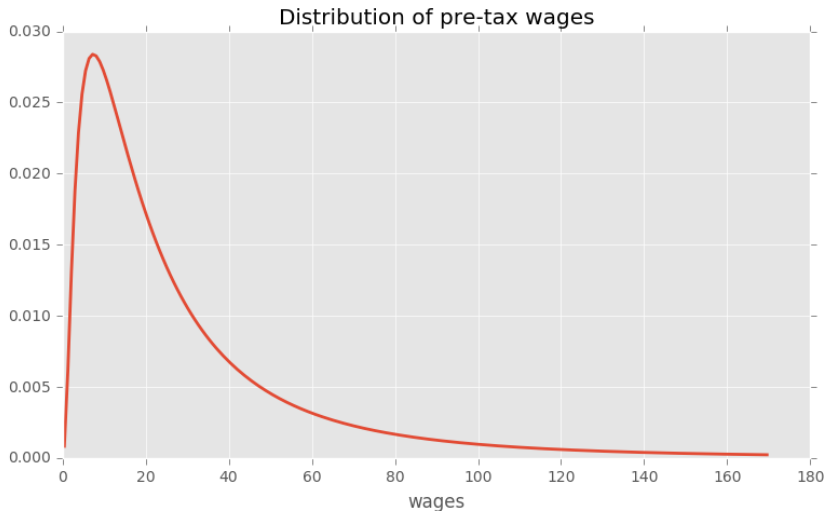
To evaluate alternative government tax-unemployment compensation pairs, we require a welfare criterion.

We use a steady state welfare criterion

$$W := e\,\mathbb{E}[V \,|\, \text{employed}] + u\,U$$

where the notation V and U is as defined in the McCall search model lecture.

The wage offer distribution will be a discretized version of the lognormal distribution $LN(\log(20), 1)$, as shown in the next figure



We take a period to be a month.

We set b and d to match monthly birth and death rates, respectively, in the U.S. population

- $b = 0.0124$
- $d = 0.00822$

Following [19], we set α, the hazard rate of leaving employment, to

- $\alpha = 0.013$

44.6.4 Fiscal Policy Code

We will make use of (with some tweaks) the code we wrote in the McCall model lecture, embedded below for convenience.

```
In [15]: function solve_mccall_model(mcm; U_iv = 1.0, V_iv = ones(length(mcm.w)),
  ↪tol = 1e-5,
                                       iter = 2_000)
             @unpack α, β, σ, c, γ, w, E, u = mcm

             # necessary objects
             u_w = u.(w, σ)
             u_c = u(c, σ)

             # Bellman operator T. Fixed point is x* s.t. T(x*) = x*
             function T(x)
                 V = x[1:end-1]
                 U = x[end]
                 [u_w + β * ((1 - α) * V .+ α * U); u_c + β * (1 - γ) * U + β * γ *
  ↪E * max.(U,
                    V)]
             end

             # value function iteration
             x_iv = [V_iv; U_iv] # initial x val
             xstar = fixedpoint(T, x_iv, iterations = iter, xtol = tol, m = 0).zero
             V = xstar[1:end-1]
```

```
        U = xstar[end]

        # compute the reservation wage
        w_barindex = searchsortedfirst(V .- U, 0.0)
        if w_barindex >= length(w) # if this is true, you never want to accept
            w̄ = Inf
        else
            w̄ = w[w_barindex] # otherwise, return the number
        end

        # return a NamedTuple, so we can select values by name
        return (V = V, U = U, w̄ = w̄)
    end
```

```
Out[15]: solve_mccall_model (generic function with 1 method)
```

And the McCall object

```
In [16]: # a default utility function
         u(c, σ) = c > 0 ? (c^(1 - σ) - 1) / (1 - σ) : -10e-6

         # model constructor
         McCallModel = @with_kw (α = 0.2,
                                 β = 0.98, # discount rate
                                 γ = 0.7,
                                 c = 6.0, # unemployment compensation
                                 σ = 2.0,
                                 u = u, # utility function
                                 w = range(10, 20, length = 60), # wage values
                                 E = Expectation(BetaBinomial(59, 600, 400))) #
       ↪distribution over
         wage values
```

```
Out[16]: ##NamedTuple_kw#267 (generic function with 2 methods)
```

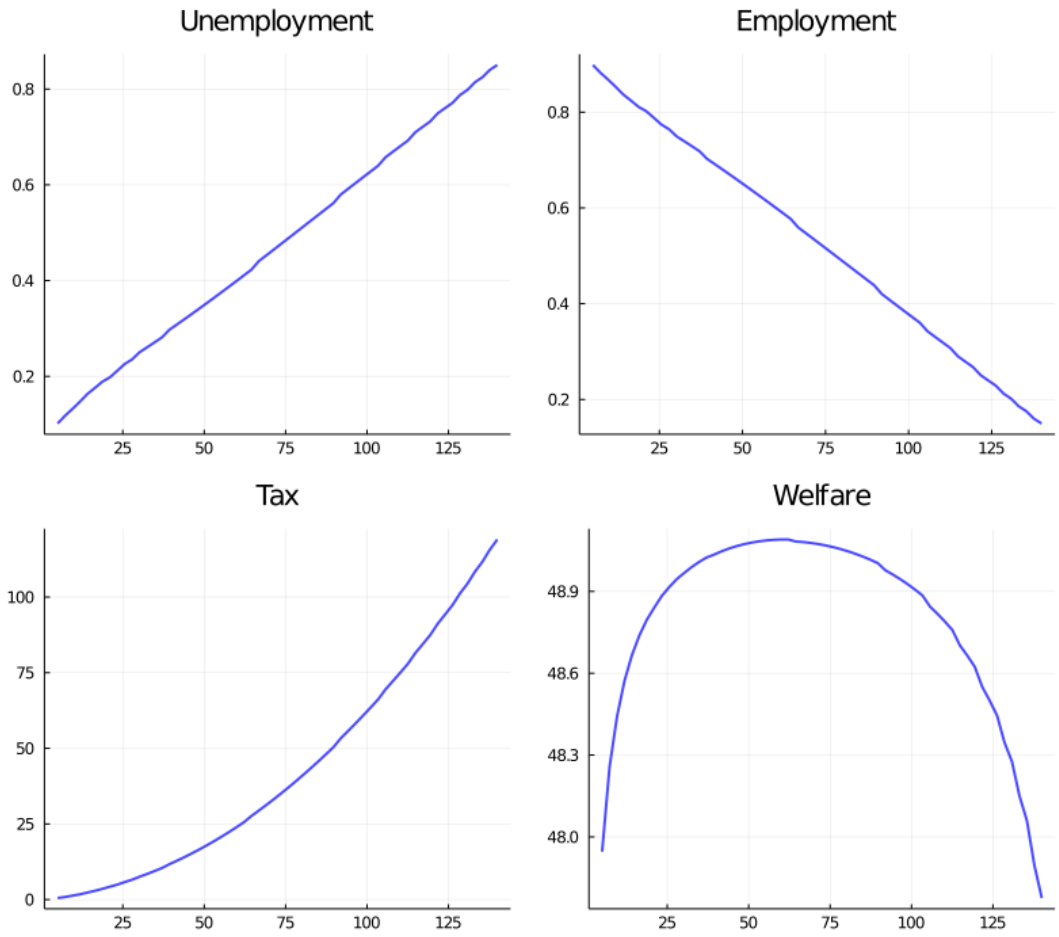
Now let's compute and plot welfare, employment, unemployment, and tax revenue as a function of the unemployment compensation rate

```
In [17]: # some global variables that will stay constant
         α = 0.013
         α_q = (1 - (1 - α)^3)
         b_param = 0.0124
         d_param = 0.00822
         β = 0.98
         γ = 1.0
         σ = 2.0

         # the default wage distribution: a discretized log normal
         log_wage_mean, wage_grid_size, max_wage = 20, 200, 170
         w_vec = range(1e-3, max_wage, length = wage_grid_size + 1)

         logw_dist = Normal(log(log_wage_mean), 1)
         cdf_logw = cdf.(logw_dist, log.(w_vec))
         pdf_logw = cdf_logw[2:end] - cdf_logw[1:end-1]
```

```
p_vec = pdf_logw ./ sum(pdf_logw)
w_vec = (w_vec[1:end-1] + w_vec[2:end]) / 2

E = expectation(Categorical(p_vec)) # expectation object

function compute_optimal_quantities(c, τ)
    mcm = McCallModel(α = α_q,
                      β = β,
                      γ = γ,
                      c = c - τ, # post-tax compensation
                      σ = σ,
                      w = w_vec .- τ, # post-tax wages
                      E = E) # expectation operator

    @unpack V, U, w̄ = solve_mccall_model(mcm)
    indicator = wage -> wage > w̄
    λ = γ * E * indicator.(w_vec .- τ)

    return w̄, λ, V, U
end

function compute_steady_state_quantities(c, τ)
    w̄, λ_param, V, U = compute_optimal_quantities(c, τ)

    # compute steady state employment and unemployment rates
    lm = LakeModel(λ = λ_param, α = α_q, b = b_param, d = d_param)
    x = rate_steady_state(lm)
    u_rate, e_rate = x

    # compute steady state welfare
    indicator(wage) = wage > w̄
    indicator(wage) = wage > w̄
    decisions = indicator.(w_vec .- τ)
    w = (E * (V .* decisions)) / (E * decisions)
    welfare = e_rate .* w + u_rate .* U

    return u_rate, e_rate, welfare
end

function find_balanced_budget_tax(c)
    function steady_state_budget(t)
        u_rate, e_rate, w = compute_steady_state_quantities(c, t)
        return t - u_rate * c
    end

    τ = find_zero(steady_state_budget, (0.0, 0.9c))
    return τ
end

# levels of unemployment insurance we wish to study
Nc = 60
c_vec = range(5, 140, length = Nc)

tax_vec = zeros(Nc)
```

```
    unempl_vec = similar(tax_vec)
    empl_vec = similar(tax_vec)
    welfare_vec = similar(tax_vec)

    for i in 1:Nc
        t = find_balanced_budget_tax(c_vec[i])
        u_rate, e_rate, welfare = compute_steady_state_quantities(c_vec[i], t)
        tax_vec[i] = t
        unempl_vec[i] = u_rate
        empl_vec[i] = e_rate
        welfare_vec[i] = welfare
    end

    plt_unemp = plot(title = "Unemployment", c_vec, unempl_vec, color = :
↪blue, lw = 2,
    alpha=0.7,
                     label = "",grid = true)
    plt_tax = plot(title = "Tax", c_vec, tax_vec, color = :blue, lw = 2,
↪alpha=0.7, label =
    "",
                   grid = true)
    plt_emp = plot(title = "Employment", c_vec, empl_vec, color = :blue, lw =
↪2, alpha=0.7,
    label = "",
                   grid = true)
    plt_welf = plot(title = "Welfare", c_vec, welfare_vec, color = :blue, lw
↪= 2, alpha=0.7,
    label = "",
                    grid = true)

    plot(plt_unemp, plt_emp, plt_tax, plt_welf, layout = (2,2), size = (800,
↪700))
```

Out[17]:



Welfare first increases and then decreases as unemployment benefits rise.

The level that maximizes steady state welfare is approximately 62.

44.7 Exercises

44.7.1 Exercise 1

Consider an economy with initial stock of workers $N_0 = 100$ at the steady state level of employment in the baseline parameterization

- $\alpha = 0.013$
- $\lambda = 0.283$
- $b = 0.0124$
- $d = 0.00822$

(The values for α and λ follow [19])

Suppose that in response to new legislation the hiring rate reduces to $\lambda = 0.2$.

Plot the transition dynamics of the unemployment and employment stocks for 50 periods.

Plot the transition dynamics for the rates.

How long does the economy take to converge to its new steady state?

What is the new steady state level of employment?

44.7.2 Exercise 2

Consider an economy with initial stock of workers $N_0 = 100$ at the steady state level of employment in the baseline parameterization.

Suppose that for 20 periods the birth rate was temporarily high ($b = 0.0025$) and then returned to its original level.

Plot the transition dynamics of the unemployment and employment stocks for 50 periods.

Plot the transition dynamics for the rates.

How long does the economy take to return to its original steady state?

44.8 Solutions

44.8.1 Exercise 1

We begin by constructing an object containing the default parameters and assigning the steady state values to x0

```
In [18]: lm = LakeModel()
         x0 = rate_steady_state(lm)
         println("Initial Steady State: $x0")
```

```
Initial Steady State: [0.08266626766923271, 0.9173337323307673]
```

Initialize the simulation values

```
In [19]: N0 = 100
         T = 50
```

```
Out[19]: 50
```

New legislation changes λ to 0.2

```
In [20]: lm = LakeModel(λ = 0.2)
```

```
Out[20]: (λ = 0.2, α = 0.013, b = 0.0124, d = 0.00822)
```

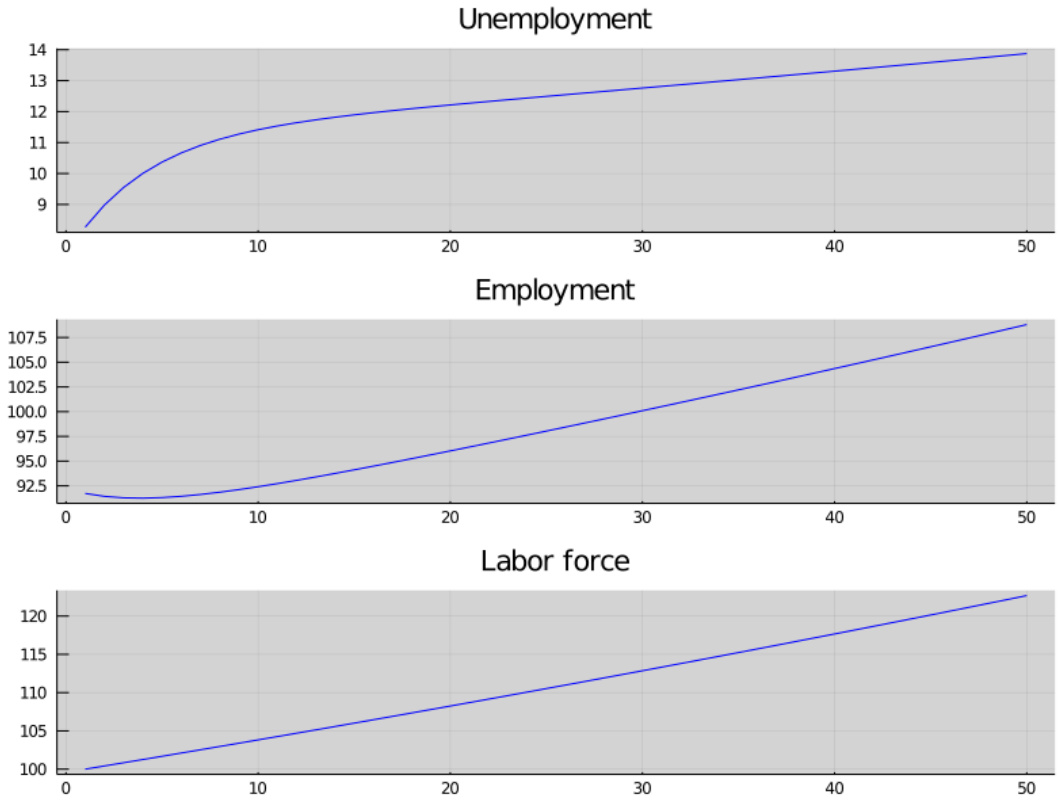
```
In [21]: xbar = rate_steady_state(lm) # new steady state
         X_path = simulate_stock_path(lm, x0 * N0, T)
         x_path = simulate_rate_path(lm, x0, T)
         println("New Steady State: $xbar")
```

```
New Steady State: [0.11309294549489424, 0.8869070545051054]
```

Now plot stocks

```
In [22]: x1 = X_path[1, :]
         x2 = X_path[2, :]
         x3 = dropdims(sum(X_path, dims = 1), dims = 1)

         plt_unemp = plot(title = "Unemployment", 1:T, x1, color = :blue, grid =
 ↪true, label =
         "",
                          bg_inside = :lightgrey)
         plt_emp = plot(title = "Employment", 1:T, x2, color = :blue, grid = true,
 ↪label = "",
                        bg_inside = :lightgrey)
         plt_labor = plot(title = "Labor force", 1:T, x3, color = :blue, grid =
 ↪true, label = "",
                          bg_inside = :lightgrey)

         plot(plt_unemp, plt_emp, plt_labor, layout = (3, 1), size = (800, 600))
```

Out[22]:



And how the rates evolve

```
In [23]: plt_unemp = plot(title = "Unemployment rate", 1:T, x_path[1,:], color = :
 ↪blue, grid =
         true,
                          label = "", bg_inside = :lightgrey)
         plot!(plt_unemp, [xbar[1]], linetype = :hline, linestyle = :dash, color =:
 ↪red, label =
         "")
```

```
        plt_emp = plot(title = "Employment rate", 1:T, x_path[2,:], color = :
↪blue, grid = true,
                       label = "", bg_inside = :lightgrey)
        plot!(plt_emp, [xbar[2]], linetype = :hline, linestyle = :dash, color =:
↪red, label = "")

        plot(plt_unemp, plt_emp, layout = (2, 1), size = (800, 600))
```

Out[23]:

We see that it takes 20 periods for the economy to converge to it's new steady state levels.

44.8.2 Exercise 2

This next exercise has the economy experiencing a boom in entrances to the labor market and then later returning to the original levels.

For 20 periods the economy has a new entry rate into the labor market.

Let's start off at the baseline parameterization and record the steady state

In [24]:
```
lm = LakeModel()
x0 = rate_steady_state(lm)
```

Out[24]:
```
2-element Array{Float64,1}:
 0.08266626766923271
 0.9173337323307673
```

Here are the other parameters:

```
In [25]: b = 0.003
         T = 20
```

```
Out[25]: 20
```

Let's increase b to the new value and simulate for 20 periods

```
In [26]: lm = LakeModel(b=b)
         X_path1 = simulate_stock_path(lm, x0 * N0, T)   # simulate stocks
         x_path1 = simulate_rate_path(lm, x0, T)         # simulate rates
```

```
Out[26]: 2×20 Array{Float64,2}:
          0.0826663  0.0739981  0.0679141  …  0.0536612  0.0536401  0.0536253
          0.917334   0.926002   0.932086      0.946339   0.94636    0.946375
```

Now we reset b to the original value and then, using the state after 20 periods for the new initial conditions, we simulate for the additional 30 periods

```
In [27]: lm = LakeModel(b = 0.0124)
         X_path2 = simulate_stock_path(lm, X_path1[:, end-1], T-T+1)    # simulate
 ↪stocks
         x_path2 = simulate_rate_path(lm, x_path1[:, end-1], T-T+1)     # simulate
 ↪rates
```

```
Out[27]: 2×31 Array{Float64,2}:
          0.0536401  0.0624842  0.0686335  …  0.0826652  0.0826655  0.0826657
          0.94636    0.937516   0.931366      0.917335   0.917335   0.917334
```

Finally we combine these two paths and plot

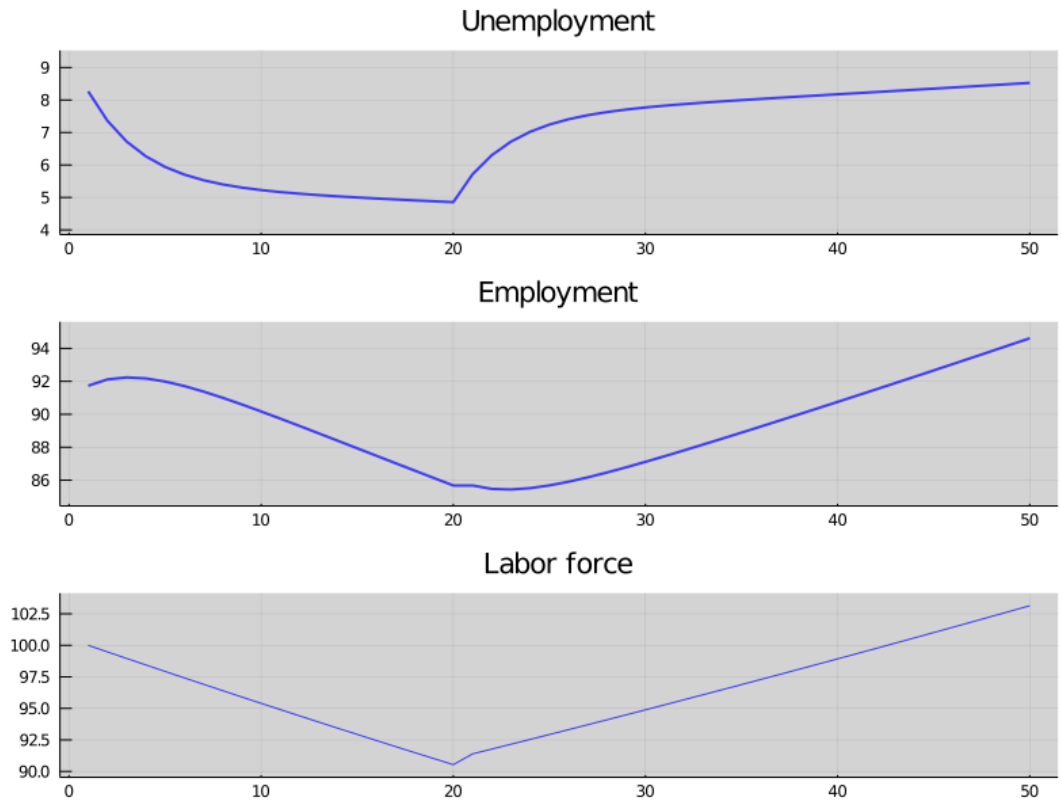
```
In [28]: x_path = hcat(x_path1, x_path2[:, 2:end])  # note [2:] to avoid doubling
 ↪period 20
         X_path = hcat(X_path1, X_path2[:, 2:end])
```

```
Out[28]: 2×50 Array{Float64,2}:
            8.26663   7.36118   6.72069   6.26524  …   8.45538   8.49076   8.52628
           91.7334   92.1168   92.238    92.1769      93.8293   94.2215   94.6153
```

```
In [29]: x1 = X_path[1,:]
         x2 = X_path[2,:]
         x3 = dropdims(sum(X_path, dims = 1), dims = 1)

         plt_unemp = plot(title = "Unemployment", 1:T, x1, color = :blue, lw = 2,
 ↪alpha = 0.7,
                          grid = true, label = "", bg_inside = :lightgrey)
         plot!(plt_unemp, ylims = extrema(x1) .+ (-1, 1))
```

```
        plt_emp = plot(title = "Employment", 1:T, x2, color = :blue, lw = 2,
↪alpha = 0.7, grid =
        true,
                       label = "", bg_inside = :lightgrey)
        plot!(plt_emp, ylims = extrema(x2) .+ (-1, 1))

        plt_labor = plot(title = "Labor force", 1:T, x3, color = :blue, alpha = 0.
↪7, grid =
        true,
                        label = "", bg_inside = :lightgrey)
        plot!(plt_labor, ylims = extrema(x3) .+ (-1, 1))
        plot(plt_unemp, plt_emp, plt_labor, layout = (3, 1), size = (800, 600))
```

Out[29]:

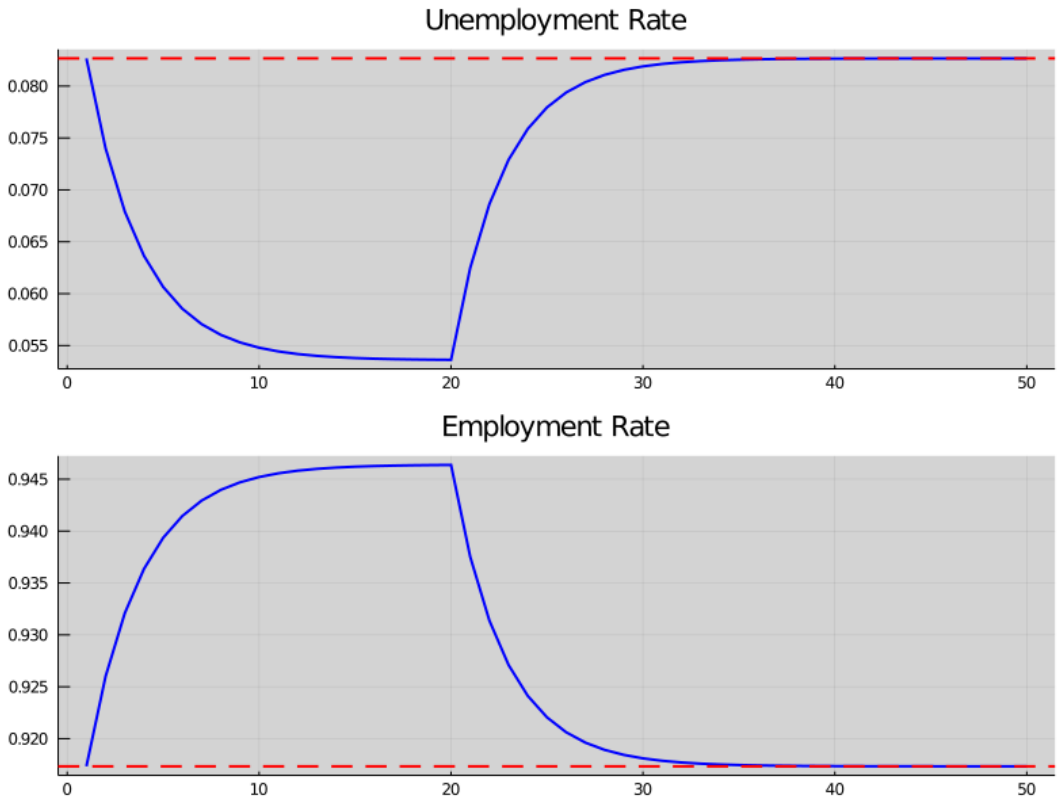


And the rates

```
In [30]: plt_unemp = plot(title = "Unemployment Rate", 1:T, x_path[1,:], color = :
↪blue, grid =
        true,
                        label = "", bg_inside = :lightgrey, lw = 2)
        plot!(plt_unemp, [x0[1]], linetype = :hline, linestyle = :dash, color =:
↪red, label = "",
        lw = 2)

        plt_emp = plot(title = "Employment Rate", 1:T, x_path[2,:], color = :
↪blue, grid = true,
                       label = "", bg_inside = :lightgrey, lw = 2)
```

```
    plot!(plt_emp, [x0[2]], linetype = :hline, linestyle = :dash, color =:
↪red, label = "",
    lw = 2)

    plot(plt_unemp, plt_emp, layout = (2, 1), size = (800, 600))
```

Out[30]:



Chapter 45

Rational Expectations Equilibrium

45.1 Contents

> "If you're so smart, why aren't you rich?"

45.2 Overview

This lecture introduces the concept of *rational expectations equilibrium*.

To illustrate it, we describe a linear quadratic version of a famous and important model due to Lucas and Prescott [71].

This 1971 paper is one of a small number of research articles that kicked off the *rational expectations revolution*.

We follow Lucas and Prescott by employing a setting that is readily "Bellmanized" (i.e., capable of being formulated in terms of dynamic programming problems).

Because we use linear quadratic setups for demand and costs, we can adapt the LQ programming techniques described in this lecture.

We will learn about how a representative agent's problem differs from a planner's, and how a planning problem can be used to compute rational expectations quantities.

We will also learn about how a rational expectations equilibrium can be characterized as a fixed point of a mapping from a *perceived law of motion* to an *actual law of motion*.

Equality between a perceived and an actual law of motion for endogenous market-wide objects captures in a nutshell what the rational expectations equilibrium concept is all about.

Finally, we will learn about the important "Big K, little k" trick, a modeling device widely used in macroeconomics.

Except that for us

- Instead of "Big K" it will be "Big Y"
- Instead of "little k" it will be "little y"

45.2.1 The Big Y, little y trick

This widely used method applies in contexts in which a "representative firm" or agent is a "price taker" operating within a competitive equilibrium.

We want to impose that

- The representative firm or individual takes *aggregate* Y as given when it chooses individual y, but ....
- At the end of the day, $Y = y$, so that the representative firm is indeed representative.

The Big Y, little y trick accomplishes these two goals by

- Taking Y as beyond control when posing the choice problem of who chooses y; but ....
- Imposing $Y = y$ *after* having solved the individual's optimization problem.

Please watch for how this strategy is applied as the lecture unfolds.

We begin by applying the Big Y, little y trick in a very simple static context.

A simple static example of the Big Y, little y trick

Consider a static model in which a collection of n firms produce a homogeneous good that is sold in a competitive market.

Each of these n firms sells output y.

The price p of the good lies on an inverse demand curve

$$p = a_0 - a_1 Y \tag{1}$$

where

- $a_i > 0$ for $i = 0, 1$
- $Y = ny$ is the market-wide level of output

Each firm has total cost function

$$c(y) = c_1 y + 0.5 c_2 y^2, \qquad c_i > 0 \text{ for } i = 1, 2$$

The profits of a representative firm are $py - c(y)$.

Using (1), we can express the problem of the representative firm as

$$\max_y \Big[(a_0 - a_1 Y) y - c_1 y - 0.5 c_2 y^2 \Big] \tag{2}$$

In posing problem (2), we want the firm to be a *price taker*.

We do that by regarding p and therefore Y as exogenous to the firm.

The essence of the Big Y, little y trick is *not* to set $Y = ny$ *before* taking the first-order condition with respect to y in problem (2).

This assures that the firm is a price taker.

The first order condition for problem (2) is

$$a_0 - a_1 Y - c_1 - c_2 y = 0 \tag{3}$$

At this point, *but not before*, we substitute $Y = ny$ into (3) to obtain the following linear equation

$$a_0 - c_1 - (a_1 + n^{-1} c_2) Y = 0 \tag{4}$$

to be solved for the competitive equilibrium market wide output Y.

After solving for Y, we can compute the competitive equilibrium price p from the inverse demand curve (1).

45.2.2 Further Reading

References for this lecture include

- [71]
- [94], chapter XIV
- [68], chapter 7

45.2.3 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

45.3 Defining Rational Expectations Equilibrium

Our first illustration of a rational expectations equilibrium involves a market with n firms, each of which seeks to maximize the discounted present value of profits in the face of adjustment costs.

The adjustment costs induce the firms to make gradual adjustments, which in turn requires consideration of future prices.

Individual firms understand that, via the inverse demand curve, the price is determined by the amounts supplied by other firms.

Hence each firm wants to forecast future total industry supplies.

In our context, a forecast is generated by a belief about the law of motion for the aggregate state.

Rational expectations equilibrium prevails when this belief coincides with the actual law of motion generated by production choices induced by this belief.

We formulate a rational expectations equilibrium in terms of a fixed point of an operator that maps beliefs into optimal beliefs.

45.3.1 Competitive Equilibrium with Adjustment Costs

To illustrate, consider a collection of n firms producing a homogeneous good that is sold in a competitive market.

Each of these n firms sells output y_t.

The price p_t of the good lies on the inverse demand curve

$$p_t = a_0 - a_1 Y_t \tag{5}$$

where

- $a_i > 0$ for $i = 0, 1$
- $Y_t = n y_t$ is the market-wide level of output

The Firm's Problem

Each firm is a price taker.

While it faces no uncertainty, it does face adjustment costs

In particular, it chooses a production plan to maximize

$$\sum_{t=0}^{\infty} \beta^t r_t \tag{6}$$

where

$$r_t := p_t y_t - \frac{\gamma (y_{t+1} - y_t)^2}{2}, \qquad y_0 \text{ given} \tag{7}$$

Regarding the parameters,

- $\beta \in (0, 1)$ is a discount factor
- $\gamma > 0$ measures the cost of adjusting the rate of output

Regarding timing, the firm observes p_t and y_t when it chooses y_{t+1} at at time t.

To state the firm's optimization problem completely requires that we specify dynamics for all state variables.

This includes ones that the firm cares about but does not control like p_t.

We turn to this problem now.

Prices and Aggregate Output

In view of (5), the firm's incentive to forecast the market price translates into an incentive to forecast aggregate output Y_t.

Aggregate output depends on the choices of other firms.

We assume that n is such a large number that the output of any single firm has a negligible effect on aggregate output.

That justifies firms in regarding their forecasts of aggregate output as being unaffected by their own output decisions.

The Firm's Beliefs

We suppose the firm believes that market-wide output Y_t follows the law of motion

$$Y_{t+1} = H(Y_t) \tag{8}$$

where Y_0 is a known initial condition.

The *belief function* H is an equilibrium object, and hence remains to be determined.

Optimal Behavior Given Beliefs

For now let's fix a particular belief H in (8) and investigate the firm's response to it.

Let v be the optimal value function for the firm's problem given H.

The value function satisfies the Bellman equation

$$v(y, Y) = \max_{y'} \left\{ a_0 y - a_1 y Y - \frac{\gamma(y' - y)^2}{2} + \beta v(y', H(Y)) \right\} \tag{9}$$

Let's denote the firm's optimal policy function by h, so that

$$y_{t+1} = h(y_t, Y_t) \tag{10}$$

where

$$h(y, Y) := \arg\max_{y'} \left\{ a_0 y - a_1 y Y - \frac{\gamma(y' - y)^2}{2} + \beta v(y', H(Y)) \right\} \tag{11}$$

Evidently v and h both depend on H.

First-Order Characterization of h

In what follows it will be helpful to have a second characterization of h, based on first order conditions.

The first-order necessary condition for choosing y' is

$$-\gamma(y' - y) + \beta v_y(y', H(Y)) = 0 \tag{12}$$

An important useful envelope result of Benveniste-Scheinkman [10] implies that to differentiate v with respect to y we can naively differentiate the right side of (9), giving

$$v_y(y, Y) = a_0 - a_1 Y + \gamma(y' - y)$$

Substituting this equation into (12) gives the *Euler equation*

$$-\gamma(y_{t+1} - y_t) + \beta[a_0 - a_1 Y_{t+1} + \gamma(y_{t+2} - y_{t+1})] = 0 \tag{13}$$

The firm optimally sets an output path that satisfies (13), taking (8) as given, and subject to

- the initial conditions for (y_0, Y_0)
- the terminal condition $\lim_{t\to\infty} \beta^t y_t v_y(y_t, Y_t) = 0$

This last condition is called the *transversality condition*, and acts as a first-order necessary condition "at infinity".

The firm's decision rule solves the difference equation (13) subject to the given initial condition y_0 and the transversality condition.

Note that solving the Bellman equation (9) for v and then h in (11) yields a decision rule that automatically imposes both the Euler equation (13) and the transversality condition.

The Actual Law of Motion for $\{Y_t\}$

As we've seen, a given belief translates into a particular decision rule h.

Recalling that $Y_t = n y_t$, the *actual law of motion* for market-wide output is then

$$Y_{t+1} = nh(Y_t/n, Y_t) \tag{14}$$

Thus, when firms believe that the law of motion for market-wide output is (8), their optimizing behavior makes the actual law of motion be (14).

45.3.2 Definition of Rational Expectations Equilibrium

A *rational expectations equilibrium* or *recursive competitive equilibrium* of the model with adjustment costs is a decision rule h and an aggregate law of motion H such that

1. Given belief H, the map h is the firm's optimal policy function.
2. The law of motion H satisfies $H(Y) = nh(Y/n, Y)$ for all. Y

Thus, a rational expectations equilibrium equates the perceived and actual laws of motion (8) and (14).

Fixed point characterization

As we've seen, the firm's optimum problem induces a mapping Φ from a perceived law of motion H for market-wide output to an actual law of motion $\Phi(H)$.

The mapping Φ is the composition of two operations, taking a perceived law of motion into a decision rule via (9)–(11), and a decision rule into an actual law via (14).

The H component of a rational expectations equilibrium is a fixed point of Φ.

45.4 Computation of an Equilibrium

Now let's consider the problem of computing the rational expectations equilibrium.

45.4.1 Misbehavior of Φ

Readers accustomed to dynamic programming arguments might try to address this problem by choosing some guess H_0 for the aggregate law of motion and then iterating with Φ.

Unfortunately, the mapping Φ is not a contraction.

In particular, there is no guarantee that direct iterations on Φ converge Section **??**.

Fortunately, there is another method that works here.

The method exploits a general connection between equilibrium and Pareto optimality expressed in the fundamental theorems of welfare economics (see, e.g, [75]).

Lucas and Prescott [71] used this method to construct a rational expectations equilibrium.

The details follow.

45.4.2 A Planning Problem Approach

Our plan of attack is to match the Euler equations of the market problem with those for a single-agent choice problem.

As we'll see, this planning problem can be solved by LQ control (linear regulator).

The optimal quantities from the planning problem are rational expectations equilibrium quantities.

The rational expectations equilibrium price can be obtained as a shadow price in the planning problem.

For convenience, in this section we set $n = 1$.

We first compute a sum of consumer and producer surplus at time t

$$s(Y_t, Y_{t+1}) := \int_0^{Y_t} (a_0 - a_1 x)\, dx - \frac{\gamma (Y_{t+1} - Y_t)^2}{2} \tag{15}$$

The first term is the area under the demand curve, while the second measures the social costs of changing output.

The *planning problem* is to choose a production plan $\{Y_t\}$ to maximize

$$\sum_{t=0}^{\infty} \beta^t s(Y_t, Y_{t+1})$$

subject to an initial condition for Y_0.

45.4.3 Solution of the Planning Problem

Evaluating the integral in (15) yields the quadratic form $a_0 Y_t - a_1 Y_t^2/2$.

As a result, the Bellman equation for the planning problem is

$$V(Y) = \max_{Y'} \left\{ a_0 Y - \frac{a_1}{2} Y^2 - \frac{\gamma (Y' - Y)^2}{2} + \beta V(Y') \right\} \tag{16}$$

The associated first order condition is

$$-\gamma (Y' - Y) + \beta V'(Y') = 0 \tag{17}$$

Applying the same Benveniste-Scheinkman formula gives

$$V'(Y) = a_0 - a_1 Y + \gamma (Y' - Y)$$

Substituting this into equation (17) and rearranging leads to the Euler equation

$$\beta a_0 + \gamma Y_t - [\beta a_1 + \gamma (1 + \beta)] Y_{t+1} + \gamma \beta Y_{t+2} = 0 \tag{18}$$

45.4.4 The Key Insight

Return to equation (13) and set $y_t = Y_t$ for all t.

(Recall that for this section we've set $n = 1$ to simplify the calculations)

A small amount of algebra will convince you that when $y_t = Y_t$, equations (18) and (13) are identical.

Thus, the Euler equation for the planning problem matches the second-order difference equation that we derived by

1. finding the Euler equation of the representative firm and
2. substituting into it the expression $Y_t = n y_t$ that "makes the representative firm be representative"

If it is appropriate to apply the same terminal conditions for these two difference equations, which it is, then we have verified that a solution of the planning problem is also a rational expectations equilibrium quantity sequence

It follows that for this example we can compute equilibrium quantities by forming the optimal linear regulator problem corresponding to the Bellman equation (16).

The optimal policy function for the planning problem is the aggregate law of motion H that the representative firm faces within a rational expectations equilibrium.

Structure of the Law of Motion

As you are asked to show in the exercises, the fact that the planner's problem is an LQ problem implies an optimal policy — and hence aggregate law of motion — taking the form

$$Y_{t+1} = \kappa_0 + \kappa_1 Y_t \tag{19}$$

for some parameter pair κ_0, κ_1.

Now that we know the aggregate law of motion is linear, we can see from the firm's Bellman equation (9) that the firm's problem can also be framed as an LQ problem.

As you're asked to show in the exercises, the LQ formulation of the firm's problem implies a law of motion that looks as follows

$$y_{t+1} = h_0 + h_1 y_t + h_2 Y_t \tag{20}$$

Hence a rational expectations equilibrium will be defined by the parameters $(\kappa_0, \kappa_1, h_0, h_1, h_2)$ in (19)–(20).

45.5 Exercises

45.5.1 Exercise 1

Consider the firm problem described above.

Let the firm's belief function H be as given in (19).

Formulate the firm's problem as a discounted optimal linear regulator problem, being careful to describe all of the objects needed.

Use the type `LQ` from the QuantEcon.jl package to solve the firm's problem for the following parameter values:

$$a_0 = 100, a_1 = 0.05, \beta = 0.95, \gamma = 10, \kappa_0 = 95.5, \kappa_1 = 0.95$$

Express the solution of the firm's problem in the form (20) and give the values for each h_j.

If there were n identical competitive firms all behaving according to (20), what would (20) imply for the *actual* law of motion (8) for market supply.

45.5.2 Exercise 2

Consider the following κ_0, κ_1 pairs as candidates for the aggregate law of motion component of a rational expectations equilibrium (see (19)).

Extending the program that you wrote for exercise 1, determine which if any satisfy the definition of a rational expectations equilibrium

- (94.0886298678, 0.923409232937)
- (93.2119845412, 0.984323478873)
- (95.0818452486, 0.952459076301)

Describe an iterative algorithm that uses the program that you wrote for exercise 1 to compute a rational expectations equilibrium.

(You are not being asked actually to use the algorithm you are suggesting)

45.5.3 Exercise 3

Recall the planner's problem described above

1. Formulate the planner's problem as an LQ problem.
2. Solve it using the same parameter values in exercise 1

- $a_0 = 100, a_1 = 0.05, \beta = 0.95, \gamma = 10$

1. Represent the solution in the form $Y_{t+1} = \kappa_0 + \kappa_1 Y_t$.
2. Compare your answer with the results from exercise 2.

45.5.4 Exercise 4

A monopolist faces the industry demand curve (5) and chooses $\{Y_t\}$ to maximize $\sum_{t=0}^{\infty} \beta^t r_t$ where

$$r_t = p_t Y_t - \frac{\gamma (Y_{t+1} - Y_t)^2}{2}$$

Formulate this problem as an LQ problem.

Compute the optimal policy using the same parameters as the previous exercise.

In particular, solve for the parameters in

$$Y_{t+1} = m_0 + m_1 Y_t$$

Compare your results with the previous exercise. Comment.

45.6 Solutions

45.6.1 Exercise 1

```
In [3]: using QuantEcon, Printf, LinearAlgebra
```

To map a problem into a discounted optimal linear control problem, we need to define

- state vector x_t and control vector u_t
- matrices A, B, Q, R that define preferences and the law of motion for the state

For the state and control vectors we choose

$$x_t = \begin{bmatrix} y_t \\ Y_t \\ 1 \end{bmatrix}, \qquad u_t = y_{t+1} - y_t$$

For $, B, Q, R$ we set

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \kappa_1 & \kappa_0 \\ 0 & 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad R = \begin{bmatrix} 0 & a_1/2 & -a_0/2 \\ a_1/2 & 0 & 0 \\ -a_0/2 & 0 & 0 \end{bmatrix}, \quad Q = \gamma/2$$

By multiplying out you can confirm that

- $x_t' R x_t + u_t' Q u_t = -r_t$
- $x_{t+1} = A x_t + B u_t$

We'll use the module `lqcontrol.jl` to solve the firm's problem at the stated parameter values.

This will return an LQ policy F with the interpretation $u_t = -F x_t$, or

$$y_{t+1} - y_t = -F_0 y_t - F_1 Y_t - F_2$$

Matching parameters with $y_{t+1} = h_0 + h_1 y_t + h_2 Y_t$ leads to

$$h_0 = -F_2, \quad h_1 = 1 - F_0, \quad h_2 = -F_1$$

Here's our solution

In [4]:
```
# model parameters
a0 = 100
a1 = 0.05
β = 0.95
γ = 10.0

# beliefs
κ0 = 95.5
κ1 = 0.95

# formulate the LQ problem
A = [1  0  0
     0 κ1 κ0
     0  0  1]

B = [1.0, 0.0, 0.0]

R = [    0   a1/2 -a0/2
      a1/2      0     0
     -a0/2      0     0]

Q = 0.5 * γ

# solve for the optimal policy
lq = QuantEcon.LQ(Q, R, A, B; bet = β)
P, F, d = stationary_values(lq)

hh = h0, h1, h2 = -F[3], 1 - F[1], -F[2]

@printf("F = [%.3f, %.3f, %.3f]\n", F[1], F[2], F[3])
@printf("(h0, h1, h2) = [%.3f, %.3f, %.3f]\n", h0, h1, h2)
```

```
   F = [-0.000, 0.046, -96.949]
(h0, h1, h2) = [96.949, 1.000, -0.046]
```

The implication is that

$$y_{t+1} = 96.949 + y_t - 0.046\, Y_t$$

For the case $n > 1$, recall that $Y_t = ny_t$, which, combined with the previous equation, yields

$$Y_{t+1} = n\left(96.949 + y_t - 0.046\, Y_t\right) = n96.949 + (1 - n0.046)Y_t$$

45.6.2 Exercise 2

To determine whether a κ_0, κ_1 pair forms the aggregate law of motion component of a rational expectations equilibrium, we can proceed as follows:

- Determine the corresponding firm law of motion $y_{t+1} = h_0 + h_1 y_t + h_2 Y_t$.
- Test whether the associated aggregate law :$Y_{t+1} = nh(Y_t/n, Y_t)$ evaluates to $Y_{t+1} = \kappa_0 + \kappa_1 Y_t$.

In the second step we can use $Y_t = ny_t = y_t$, so that $Y_{t+1} = nh(Y_t/n, Y_t)$ becomes

$$Y_{t+1} = h(Y_t, Y_t) = h_0 + (h_1 + h_2)Y_t$$

Hence to test the second step we can test $\kappa_0 = h_0$ and $\kappa_1 = h_1 + h_2$.

The following code implements this test

In [5]:
```
candidates = ([94.0886298678, 0.923409232937],
              [93.2119845412, 0.984323478873],
              [95.0818452486, 0.952459076301])

for (k0, k1) in candidates
    A = [1  0  0
         0 k1 k0
         0  0  1]
    lq = QuantEcon.LQ(Q, R, A, B; bet=β)
    P, F, d = stationary_values(lq)
    hh = h0, h1, h2 = -F[3], 1 - F[1], -F[2]

    if isapprox(k0, h0; atol = 1e-4) && isapprox(k1, h1 + h2; atol = 1e-4)
        @printf("Equilibrium pair = (%.6f, %.6f)\n", k0, k1)
        @printf("(h0, h1, h2) = [%.6f, %.6f, %.6f]\n", h0, h1, h2)
    end
end
```

```
   Equilibrium pair = (95.081845, 0.952459)
(h0, h1, h2) = [95.081891, 1.000000, -0.047541]
```

The output tells us that the answer is pair (iii), which implies $(h_0, h_1, h_2) = (95.0819, 1.0000, -.0475)$.

(Notice we use `isapprox` to test equality of floating point numbers, since exact equality is too strict)

Regarding the iterative algorithm, one could loop from a given (κ_0, κ_1) pair to the associated firm law and then to a new (κ_0, κ_1) pair.

This amounts to implementing the operator Φ described in the lecture.

(There is in general no guarantee that this iterative process will converge to a rational expectations equilibrium)

45.6.3 Exercise 3

We are asked to write the planner problem as an LQ problem.

For the state and control vectors we choose

$$x_t = \begin{bmatrix} Y_t \\ 1 \end{bmatrix}, \quad u_t = Y_{t+1} - Y_t$$

For the LQ matrices we set

$$A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad R = \begin{bmatrix} a_1/2 & -a_0/2 \\ -a_0/2 & 0 \end{bmatrix}, \quad Q = \gamma/2$$

By multiplying out you can confirm that

- $x_t' R x_t + u_t' Q u_t = -s(Y_t, Y_{t+1})$
- $x_{t+1} = A x_t + B u_t$

By obtaining the optimal policy and using $u_t = -F x_t$ or

$$Y_{t+1} - Y_t = -F_0 Y_t - F_1$$

we can obtain the implied aggregate law of motion via $\kappa_0 = -F_1$ and $\kappa_1 = 1 - F_0$

In [6]:
```
# formulate the planner's LQ problem
A = I + zeros(2, 2)
B = [1.0, 0.0]

R = [ a1 / 2.0  -a0 / 2.0
     -a0 / 2.0        0.0]

Q = γ / 2.0

# solve for the optimal policy
lq = QuantEcon.LQ(Q, R, A, B; bet=β)
P, F, d = stationary_values(lq)

# print the results
κ0, κ1 = -F[2], 1 - F[1]
println("κ0=$κ0\tκ1=$κ1")
```

```
κ0=95.08187459215002    κ1=0.9524590627039248
```

The output yields the same (κ_0, κ_1) pair obtained as an equilibrium from the previous exercise.

45.6.4 Exercise 4

The monopolist's LQ problem is almost identical to the planner's problem from the previous exercise, except that

$$R = \begin{bmatrix} a_1 & -a_0/2 \\ -a_0/2 & 0 \end{bmatrix}$$

The problem can be solved as follows

```
In [7]: # formulate the monopolist's LQ problem
        A = I + zeros(2, 2)
        B = [1.0, 0.0]

        R = [       a1   -a0 / 2.0
             -a0 / 2.0          0.0]

        Q = γ / 2.0

        # solve for the optimal policy
        lq = QuantEcon.LQ(Q, R, A, B; bet=β)
        P, F, d = stationary_values(lq)

        # print the results
        m0, m1 = -F[2], 1 - F[1]
        println("m0=$m0\tm1=$m1")
```

```
m0=73.47294403502833    m1=0.9265270559649701
```

We see that the law of motion for the monopolist is approximately $Y_{t+1} = 73.4729 + 0.9265 Y_t$.

In the rational expectations case the law of motion was approximately $Y_{t+1} = 95.0819 + 0.9525 Y_t$.

One way to compare these two laws of motion is by their fixed points, which give long run equilibrium output in each case.

For laws of the form $Y_{t+1} = c_0 + c_1 Y_t$, the fixed point is $c_0/(1 - c_1)$.

If you crunch the numbers, you will see that the monopolist adopts a lower long run quantity than obtained by the competitive market, implying a higher market price.

This is analogous to the elementary static-case results

Footnotes

[1] A literature that studies whether models populated with agents who learn can converge to rational expectations equilibria features iterations on a modification of the mapping Φ that can be approximated as $\gamma\Phi + (1 - \gamma)I$. Here I is the identity operator and $\gamma \in (0, 1)$ is a *relaxation parameter*. See [73] and [29] for statements and applications of this approach to establish conditions under which collections of adaptive agents who use least squares learning converge to a rational expectations equilibrium.

Chapter 46

Markov Perfect Equilibrium

46.1 Contents

46.2 Overview

This lecture describes the concept of Markov perfect equilibrium.

Markov perfect equilibrium is a key notion for analyzing economic problems involving dynamic strategic interaction, and a cornerstone of applied game theory.

In this lecture we teach Markov perfect equilibrium by example.

We will focus on settings with

- two players
- quadratic payoff functions
- linear transition rules for the state

Other references include chapter 7 of [68].

46.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
  ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics, QuantEcon
```

46.3 Background

Markov perfect equilibrium is a refinement of the concept of Nash equilibrium.

It is used to study settings where multiple decision makers interact non-cooperatively over time, each seeking to pursue its own objective.

The agents in the model face a common state vector, the time path of which is influenced by – and influences – their decisions.

In particular, the transition law for the state that confronts each agent is affected by decision rules of other agents.

Individual payoff maximization requires that each agent solve a dynamic programming problem that includes this transition law.

Markov perfect equilibrium prevails when no agent wishes to revise its policy, taking as given the policies of all other agents.

Well known examples include

- Choice of price, output, location or capacity for firms in an industry (e.g., [28], [93], [24]).
- Rate of extraction from a shared natural resource, such as a fishery (e.g., [67], [105]).

Let's examine a model of the first type.

46.3.1 Example: A duopoly model

Two firms are the only producers of a good the demand for which is governed by a linear inverse demand function

$$p = a_0 - a_1(q_1 + q_2) \tag{1}$$

Here $p = p_t$ is the price of the good, $q_i = q_{it}$ is the output of firm $i = 1, 2$ at time t and $a_0 > 0, a_1 > 0$.

In (1) and what follows,

- the time subscript is suppressed when possible to simplify notation
- $\hat{x}$ denotes a next period value of variable x

Each firm recognizes that its output affects total output and therefore the market price.

The one-period payoff function of firm i is price times quantity minus adjustment costs:

$$\pi_i = pq_i - \gamma(\hat{q}_i - q_i)^2, \quad \gamma > 0, \tag{2}$$

Substituting the inverse demand curve (1) into (2) lets us express the one-period payoff as

$$\pi_i(q_i, q_{-i}, \hat{q}_i) = a_0 q_i - a_1 q_i^2 - a_1 q_i q_{-i} - \gamma(\hat{q}_i - q_i)^2, \tag{3}$$

where q_{-i} denotes the output of the firm other than i.

The objective of the firm is to maximize $\sum_{t=0}^{\infty} \beta^t \pi_{it}$.

Firm i chooses a decision rule that sets next period quantity $\hat{q}_i$ as a function f_i of the current state (q_i, q_{-i}).

An essential aspect of a Markov perfect equilibrium is that each firm takes the decision rule of the other firm as known and given.

Given f_{-i}, the Bellman equation of firm i is

$$v_i(q_i, q_{-i}) = \max_{\hat{q}_i} \{\pi_i(q_i, q_{-i}, \hat{q}_i) + \beta v_i(\hat{q}_i, f_{-i}(q_{-i}, q_i))\} \tag{4}$$

Definition A *Markov perfect equilibrium* of the duopoly model is a pair of value functions (v_1, v_2) and a pair of policy functions (f_1, f_2) such that, for each $i \in \{1, 2\}$ and each possible state,

- The value function v_i satisfies the Bellman equation (4).
- The maximizer on the right side of (4) is equal to $f_i(q_i, q_{-i})$.

The adjective "Markov" denotes that the equilibrium decision rules depend only on the current values of the state variables, not other parts of their histories.

"Perfect" means complete, in the sense that the equilibrium is constructed by backward induction and hence builds in optimizing behavior for each firm at all possible future states.

- These include many states that will not be reached when we iterate forward on the pair of equilibrium strategies f_i starting from a given initial state.

46.3.2 Computation

One strategy for computing a Markov perfect equilibrium is iterating to convergence on pairs of Bellman equations and decision rules.

In particular, let v_i^j, f_i^j be the value function and policy function for firm i at the j-th iteration.

Imagine constructing the iterates

$$v_i^{j+1}(q_i, q_{-i}) = \max_{\hat{q}_i} \left\{\pi_i(q_i, q_{-i}, \hat{q}_i) + \beta v_i^j(\hat{q}_i, f_{-i}(q_{-i}, q_i))\right\} \tag{5}$$

These iterations can be challenging to implement computationally.

However, they simplify for the case in which the one-period payoff functions are quadratic and the transition laws are linear — which takes us to our next topic.

46.4 Linear Markov perfect equilibria

As we saw in the duopoly example, the study of Markov perfect equilibria in games with two players leads us to an interrelated pair of Bellman equations.

In linear quadratic dynamic games, these "stacked Bellman equations" become "stacked Riccati equations" with a tractable mathematical structure.

We'll lay out that structure in a general setup and then apply it to some simple problems.

46.4.1 Coupled linear regulator problems

We consider a general linear quadratic regulator game with two players.

For convenience, we'll start with a finite horizon formulation, where t_0 is the initial date and t_1 is the common terminal date.

Player i takes $\{u_{-it}\}$ as given and minimizes

$$\sum_{t=t_0}^{t_1-1} \beta^{t-t_0} \{x_t' R_i x_t + u_{it}' Q_i u_{it} + u_{-it}' S_i u_{-it} + 2x_t' W_i u_{it} + 2u_{-it}' M_i u_{it}\} \tag{6}$$

while the state evolves according to

$$x_{t+1} = Ax_t + B_1 u_{1t} + B_2 u_{2t} \tag{7}$$

Here

- x_t is an $n \times 1$ state vector and u_{it} is a $k_i \times 1$ vector of controls for player i
- R_i is $n \times n$
- S_i is $k_{-i} \times k_{-i}$
- Q_i is $k_i \times k_i$
- W_i is $n \times k_i$
- M_i is $k_{-i} \times k_i$
- A is $n \times n$
- B_i is $n \times k_i$

46.4.2 Computing Equilibrium

We formulate a linear Markov perfect equilibrium as follows.

Player i employs linear decision rules $u_{it} = -F_{it} x_t$, where F_{it} is a $k_i \times n$ matrix.

A Markov perfect equilibrium is a pair of sequences $\{F_{1t}, F_{2t}\}$ over $t = t_0, \ldots, t_1 - 1$ such that

- $\{F_{1t}\}$ solves player 1's problem, taking $\{F_{2t}\}$ as given, and
- $\{F_{2t}\}$ solves player 2's problem, taking $\{F_{1t}\}$ as given

If we take $u_{2t} = -F_{2t} x_t$ and substitute it into (6) and (7), then player 1's problem becomes minimization of

$$\sum_{t=t_0}^{t_1-1} \beta^{t-t_0} \{x_t' \Pi_{1t} x_t + u_{1t}' Q_1 u_{1t} + 2u_{1t}' \Gamma_{1t} x_t\} \tag{8}$$

subject to

$$x_{t+1} = \Lambda_{1t} x_t + B_1 u_{1t}, \tag{9}$$

where

- $\Lambda_{it} := A - B_{-i} F_{-it}$
- $\Pi_{it} := R_i + F_{-it}' S_i F_{-it}$
- $\Gamma_{it} := W_i' - M_i' F_{-it}$

This is an LQ dynamic programming problem that can be solved by working backwards.

The policy rule that solves this problem is

$$F_{1t} = (Q_1 + \beta B_1' P_{1t+1} B_1)^{-1} (\beta B_1' P_{1t+1} \Lambda_{1t} + \Gamma_{1t}) \tag{10}$$

where P_{1t} solves the matrix Riccati difference equation

$$P_{1t} = \Pi_{1t} - (\beta B_1' P_{1t+1} \Lambda_{1t} + \Gamma_{1t})' (Q_1 + \beta B_1' P_{1t+1} B_1)^{-1} (\beta B_1' P_{1t+1} \Lambda_{1t} + \Gamma_{1t}) + \beta \Lambda_{1t}' P_{1t+1} \Lambda_{1t} \tag{11}$$

Similarly, the policy that solves player 2's problem is

$$F_{2t} = (Q_2 + \beta B_2' P_{2t+1} B_2)^{-1} (\beta B_2' P_{2t+1} \Lambda_{2t} + \Gamma_{2t}) \tag{12}$$

where P_{2t} solves

$$P_{2t} = \Pi_{2t} - (\beta B_2' P_{2t+1} \Lambda_{2t} + \Gamma_{2t})' (Q_2 + \beta B_2' P_{2t+1} B_2)^{-1} (\beta B_2' P_{2t+1} \Lambda_{2t} + \Gamma_{2t}) + \beta \Lambda_{2t}' P_{2t+1} \Lambda_{2t} \tag{13}$$

Here in all cases $t = t_0, \ldots, t_1 - 1$ and the terminal conditions are $P_{it_1} = 0$.

The solution procedure is to use equations (10), (11), (12), and (13), and "work backwards" from time $t_1 - 1$.

Since we're working backwards, P_{1t+1} and P_{2t+1} are taken as given at each stage.

Moreover, since

- some terms on the right hand side of (10) contain F_{2t}
- some terms on the right hand side of (12) contain F_{1t}

we need to solve these $k_1 + k_2$ equations simultaneously.

Key insight

A key insight is that equations (10) and (12) are linear in F_{1t} and F_{2t}.

After these equations have been solved, we can take F_{it} and solve for P_{it} in (11) and (13).

Infinite horizon

We often want to compute the solutions of such games for infinite horizons, in the hope that the decision rules F_{it} settle down to be time invariant as $t_1 \to +\infty$.

In practice, we usually fix t_1 and compute the equilibrium of an infinite horizon game by driving $t_0 \to -\infty$.

This is the approach we adopt in the next section.

46.4.3 Implementation

We use the function nnash from QuantEcon.jl that computes a Markov perfect equilibrium of the infinite horizon linear quadratic dynamic game in the manner described above.

46.5 Application

Let's use these procedures to treat some applications, starting with the duopoly model.

46.5.1 A duopoly model

To map the duopoly model into coupled linear-quadratic dynamic programming problems, define the state and controls as

$$x_t := \begin{bmatrix} 1 \\ q_{1t} \\ q_{2t} \end{bmatrix} \quad \text{and} \quad u_{it} := q_{i,t+1} - q_{it}, \quad i = 1, 2$$

If we write

$$x_t' R_i x_t + u_{it}' Q_i u_{it}$$

where $Q_1 = Q_2 = \gamma$,

$$R_1 := \begin{bmatrix} 0 & -\frac{a_0}{2} & 0 \\ -\frac{a_0}{2} & a_1 & \frac{a_1}{2} \\ 0 & \frac{a_1}{2} & 0 \end{bmatrix} \quad \text{and} \quad R_2 := \begin{bmatrix} 0 & 0 & -\frac{a_0}{2} \\ 0 & 0 & \frac{a_1}{2} \\ -\frac{a_0}{2} & \frac{a_1}{2} & a_1 \end{bmatrix}$$

then we recover the one-period payoffs in expression (3).

The law of motion for the state x_t is $x_{t+1} = Ax_t + B_1 u_{1t} + B_2 u_{2t}$ where

$$A := \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad B_1 := \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad B_2 := \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

The optimal decision rule of firm i will take the form $u_{it} = -F_i x_t$, inducing the following closed loop system for the evolution of x in the Markov perfect equilibrium:

$$x_{t+1} = (A - B_1 F_1 - B_1 F_2) x_t \tag{14}$$

46.5.2 Parameters and Solution

Consider the previously presented duopoly model with parameter values of:

- $a_0 = 10$
- $a_1 = 2$
- $\beta = 0.96$
- $\gamma = 12$

From these we compute the infinite horizon MPE using the following code

```
In [3]: using QuantEcon, LinearAlgebra

        # parameters
```

```
a0 = 10.0
a1 = 2.0
β = 0.96
γ = 12.0

# in LQ form
A  = I + zeros(3, 3)
B1 = [0.0, 1.0, 0.0]
B2 = [0.0, 0.0, 1.0]

R1 = [      0.0    -a0 / 2.0          0.0;
     -a0 / 2.0           a1     a1 / 2.0;
            0.0     a1 / 2.0          0.0]

R2 = [      0.0          0.0       -a0 / 2.0;
            0.0          0.0        a1 / 2.0;
     -a0 / 2.0      a1 / 2.0             a1]

Q1 = Q2 = γ
S1 = S2 = W1 = W2 = M1 = M2 = 0.0

# solve using QE's nnash function
F1, F2, P1, P2 = nnash(A, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2,
                       beta=β)

# display policies
println("Computed policies for firm 1 and firm 2:")
println("F1 = $F1")
println("F2 = $F2")
```

```
   Computed policies for firm 1 and firm 2:
F1 = [-0.6684661455442794 0.295124817744414 0.07584666305807419]
F2 = [-0.6684661455442794 0.07584666305807419 0.295124817744414]
```

Running the code produces the following output.

One way to see that F_i is indeed optimal for firm i taking F_2 as given is to use QuantEcon.jl's LQ type.

In particular, let's take F2 as computed above, plug it into (8) and (9) to get firm 1's problem and solve it using LQ.

We hope that the resulting policy will agree with F1 as computed above

In [4]:
```
Λ1 = A - (B2 * F2)
lq1 = QuantEcon.LQ(Q1, R1, Λ1, B1, bet=β)
P1_ih, F1_ih, d = stationary_values(lq1)
F1_ih
```

Out[4]:
```
1×3 Array{Float64,2}:
 -0.668466  0.295125  0.0758467
```

This is close enough for rock and roll, as they say in the trade.

Indeed, isapprox agrees with our assessment

```
In [5]: isapprox(F1, F1_ih, atol=1e-7)
```

```
Out[5]: true
```

46.5.3 Dynamics

Let's now investigate the dynamics of price and output in this simple duopoly model under the MPE policies.

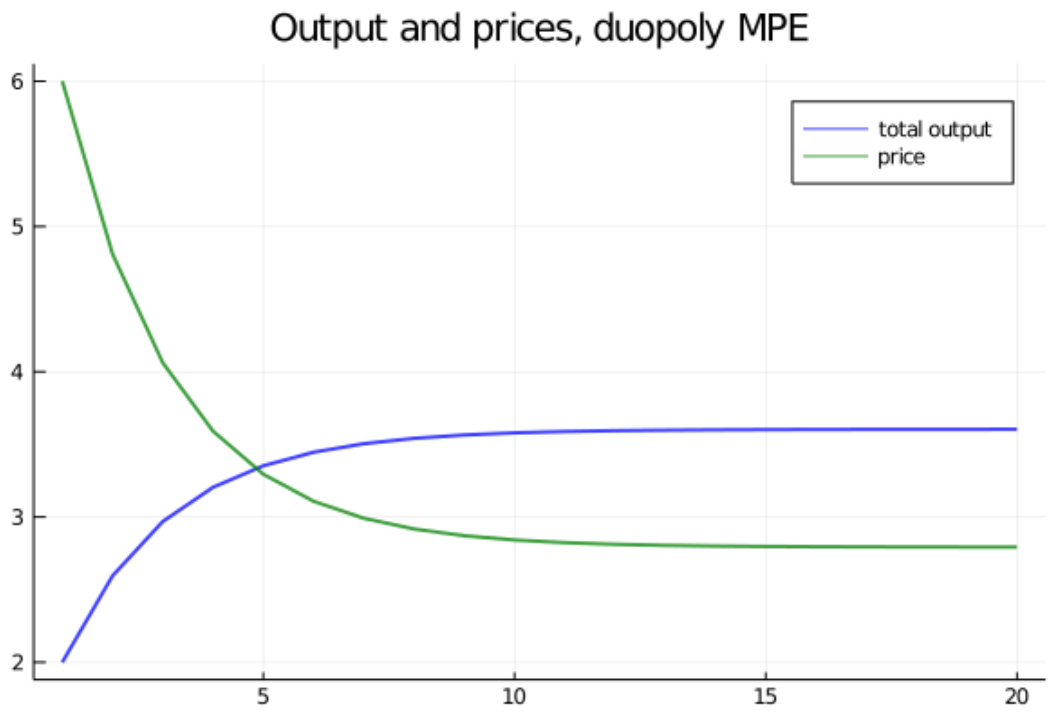
Given our optimal policies $F1$ and $F2$, the state evolves according to (14).

The following program

- imports $F1$ and $F2$ from the previous program along with all parameters
- computes the evolution of x_t using (14)
- extracts and plots industry output $q_t = q_{1t} + q_{2t}$ and price $p_t = a_0 - a_1 q_t$

```
In [6]: using Plots
        gr(fmt=:png);

        AF = A - B1 * F1 - B2 * F2
        n = 20
        x = zeros(3, n)
        x[:, 1] = [1 1 1]
        for t in 1:n-1
            x[:, t+1] = AF * x[:, t]
        end
        q1 = x[2, :]
        q2 = x[3, :]
        q = q1 + q2          # total output, MPE
        p = a0 .- a1 * q     # price, MPE

        plt = plot(q, color=:blue, lw=2, alpha=0.75, label="total output")
        plot!(plt, p, color=:green, lw=2, alpha=0.75, label="price")
        plot!(plt, title="Output and prices, duopoly MPE")
```

```
Out[6]:
```

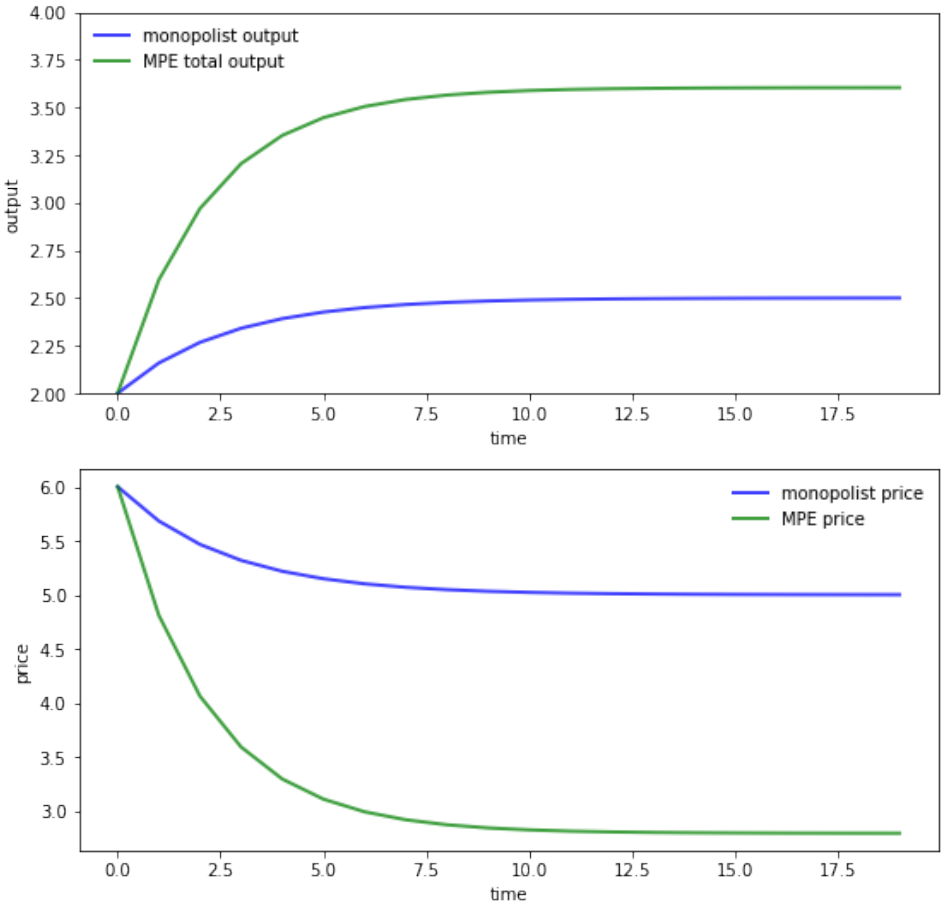


Note that the initial condition has been set to $q_{10} = q_{20} = 1.0$.

To gain some perspective we can compare this to what happens in the monopoly case.

The first panel in the next figure compares output of the monopolist and industry output under the MPE, as a function of time.

The second panel shows analogous curves for price



Here parameters are the same as above for both the MPE and monopoly solutions.

The monopolist initial condition is $q_0 = 2.0$ to mimic the industry initial condition $q_{10} = q_{20} = 1.0$ in the MPE case.

As expected, output is higher and prices are lower under duopoly than monopoly.

46.6 Exercises

46.6.1 Exercise 1

Replicate the pair of figures showing the comparison of output and prices for the monopolist and duopoly under MPE.

Parameters are as in duopoly_mpe.jl and you can use that code to compute MPE policies under duopoly.

The optimal policy in the monopolist case can be computed using QuantEcon.jl's LQ type.

46.6.2 Exercise 2

In this exercise we consider a slightly more sophisticated duopoly problem.

It takes the form of infinite horizon linear quadratic game proposed by Judd [59].

Two firms set prices and quantities of two goods interrelated through their demand curves.

Relevant variables are defined as follows:

- I_{it} = inventories of firm i at beginning of t
- q_{it} = production of firm i during period t
- p_{it} = price charged by firm i during period t
- S_{it} = sales made by firm i during period t
- E_{it} = costs of production of firm i during period t
- C_{it} = costs of carrying inventories for firm i during t

The firms' cost functions are

- $C_{it} = c_{i1} + c_{i2} I_{it} + 0.5 c_{i3} I_{it}^2$
- $E_{it} = e_{i1} + e_{i2} q_{it} + 0.5 e_{i3} q_{it}^2$ where e_{ij}, c_{ij} are positive scalars

Inventories obey the laws of motion

$$I_{i,t+1} = (1 - \delta) I_{it} + q_{it} - S_{it}$$

Demand is governed by the linear schedule

$$S_t = D p_{it} + b$$

where

- $S_t = \begin{bmatrix} S_{1t} & S_{2t} \end{bmatrix}'$
- D is a 2×2 negative definite matrix and
- b is a vector of constants

Firm i maximizes the undiscounted sum

$$\lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T} (p_{it} S_{it} - E_{it} - C_{it})$$

We can convert this to a linear quadratic problem by taking

$$u_{it} = \begin{bmatrix} p_{it} \\ q_{it} \end{bmatrix} \quad \text{and} \quad x_t = \begin{bmatrix} I_{1t} \\ I_{2t} \\ 1 \end{bmatrix}$$

Decision rules for price and quantity take the form $u_{it} = -F_i x_t$.

The Markov perfect equilibrium of Judd's model can be computed by filling in the matrices appropriately.

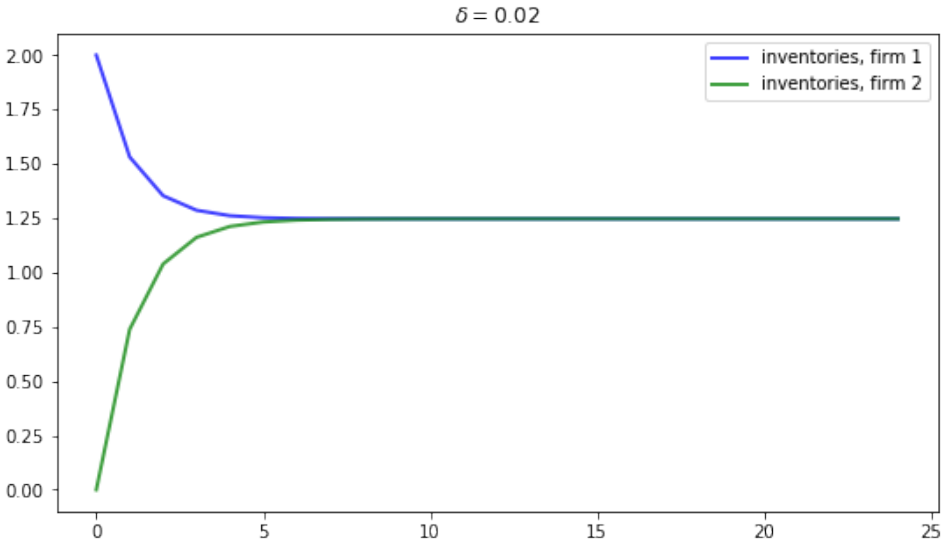
The exercise is to calculate these matrices and compute the following figures.

The first figure shows the dynamics of inventories for each firm when the parameters are

In [7]:
```
δ = 0.02
D = [ -1  0.5;
      0.5   -1]
b = [25, 25]
```

```
c1 = c2 = [1, -2, 1]
e1 = e2 = [10, 10, 3]
```

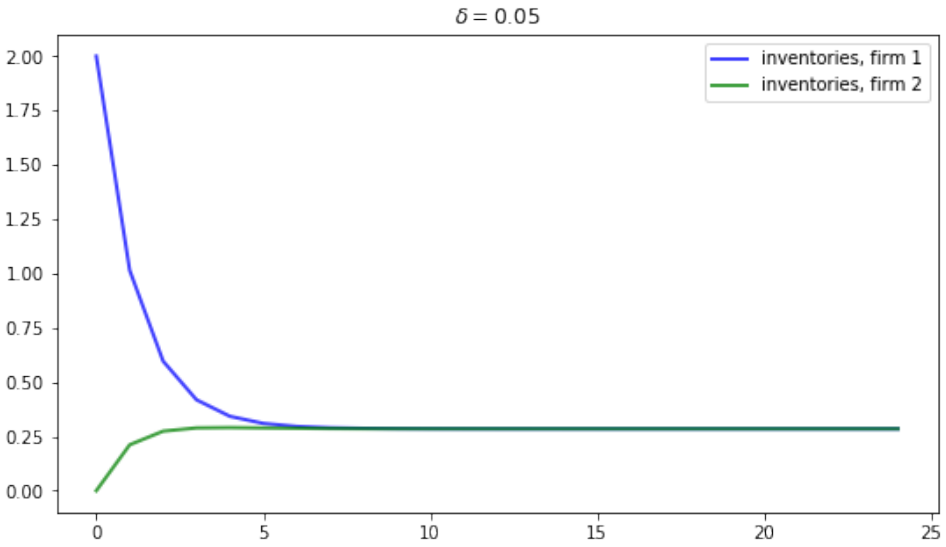
```
Out[7]: 3-element Array{Int64,1}:
         10
         10
          3
```



Inventories trend to a common steady state.

If we increase the depreciation rate to $\delta = 0.05$, then we expect steady state inventories to fall.

This is indeed the case, as the next figure shows



46.7 Solutions

46.7.1 Exercise 1

First let's compute the duopoly MPE under the stated parameters

```
In [8]: # parameters
        a0 = 10.0
        a1 = 2.0
        β = 0.96
        γ = 12.0

        # in LQ form
        A = I + zeros(3, 3)
        B1 = [0.0, 1.0, 0.0]
        B2 = [0.0, 0.0, 1.0]

        R1 = [      0.0   -a0 / 2.0         0.0;
              -a0 / 2.0          a1    a1 / 2.0;
                    0.0    a1 / 2.0         0.0]

        R2 = [      0.0         0.0    -a0 / 2.0;
                    0.0         0.0     a1 / 2.0;
              -a0 / 2.0   a1 / 2.0           a1]

        Q1 = Q2 = γ
        S1 = S2 = W1 = W2 = M1 = M2 = 0.0

        # solve using QE's nnash function
        F1, F2, P1, P2 = nnash(A, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2,
                               beta=β)
```

```
Out[8]: ([-0.6684661455442794 0.295124817744414 0.07584666305807419], [-0.
        ↪6684661455442794
              0.07584666305807419 0.295124817744414], [-100.74013291681779 -13.
        ↪28370101134053
              2.435873888234418; -13.283701011340526 5.441368457863284 1.
        ↪9305445296892967;
              2.4358738882344166 1.9305445296892967 -0.18944247543524873], [-100.
        ↪74013291681771
              2.435873888234418 -13.283701011340526; 2.435873888234417 -0.
        ↪18944247543524873
              1.9305445296892967; -13.283701011340526 1.9305445296892967 5.
        ↪441368457863284])
```

Now we evaluate the time path of industry output and prices given initial condition $q_{10} = q_{20} = 1$

```
In [9]: AF = A - B1 * F1 - B2 * F2
        n = 20
        x = zeros(3, n)
        x[:, 1] = [1  1  1]
        for t in 1:(n-1)
            x[:, t+1] = AF * x[:, t]
        end
```

```
q1 = x[2, :]
q2 = x[3, :]
q = q1 + q2       # Total output, MPE
p = a0 .- a1 * q   # Price, MPE
```

Next let's have a look at the monopoly solution.

For the state and control we take

$$x_t = q_t - \bar{q} \quad \text{and} \quad u_t = q_{t+1} - q_t$$

To convert to an LQ problem we set

$$R = a_1 \quad \text{and} \quad Q = \gamma$$

in the payoff function $x_t' R x_t + u_t' Q u_t$ and

$$A = B = 1$$

in the law of motion $x_{t+1} = Ax_t + Bu_t$.

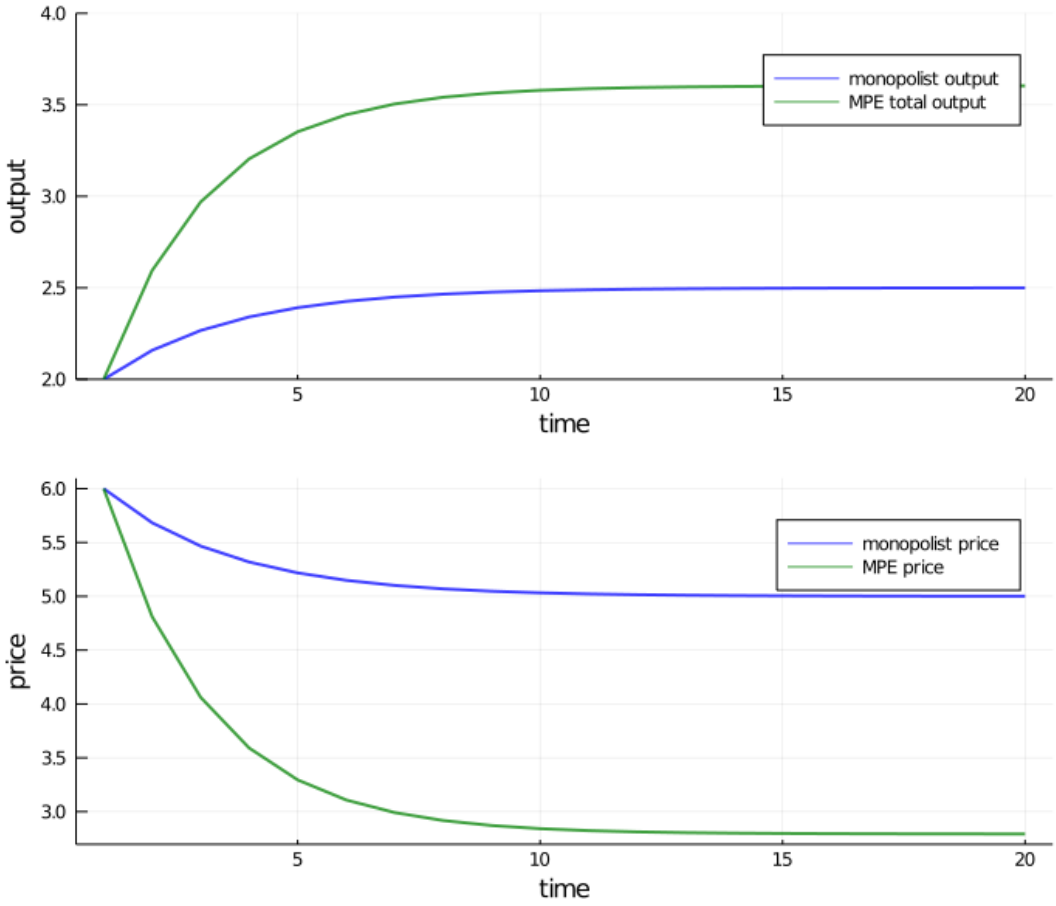
We solve for the optimal policy $u_t = -Fx_t$ and track the resulting dynamics of $\{q_t\}$, starting at $q_0 = 2.0$.

In [10]:
```
R = a1
Q = γ
A = B = 1
lq_alt = QuantEcon.LQ(Q, R, A, B, bet=β)
P, F, d = stationary_values(lq_alt)

q = a0 / (2.0 * a1)
qm = zeros(n)
qm[1] = 2

x0 = qm[1]-q
x = x0
for i in 2:n
    x = A * x - B * F[1] * x

    qm[i] = float(x) + q
end
pm = a0 .- a1 * qm
```

Let's have a look at the different time paths

In [11]:
```
plt_q = plot(qm, color=:blue, lw=2, alpha=0.75, label="monopolist output")
plot!(plt_q, q, color=:green, lw=2, alpha=0.75, label="MPE total output")
plot!(plt_q, xlabel="time", ylabel="output", ylim=(2,4),legend=:topright)

plt_p = plot(pm, color=:blue, lw=2, alpha=0.75, label="monopolist price")
plot!(plt_p, p, color=:green, lw=2, alpha=0.75, label="MPE price")
plot!(plt_p, xlabel="time", ylabel="price",legend=:topright)

plot(plt_q, plt_p, layout=(2,1), size=(700,600))
```

Out[11]:



46.7.2 Exercise 2

We treat the case $\delta = 0.02$

In [12]:
```
δ = 0.02
D = [-1  0.5;
      0.5 -1]
b = [25, 25]
c1 = c2 = [1, -2, 1]
e1 = e2 = [10, 10, 3]
δ_1 = 1-δ
```

Out[12]: 0.98

Recalling that the control and state are

$$u_{it} = \begin{bmatrix} p_{it} \\ q_{it} \end{bmatrix} \quad \text{and} \quad x_t = \begin{bmatrix} I_{1t} \\ I_{2t} \\ 1 \end{bmatrix}$$

we set up the matrices as follows:

In [13]:
```
# create matrices needed to compute the Nash feedback equilibrium
A = [δ_1     0   -δ_1 * b[1];
       0   δ_1   -δ_1 * b[2];
       0     0             1]

B1 = δ_1 * [1 -D[1, 1];
            0 -D[2, 1];
            0        0]
B2 = δ_1 * [0 -D[1, 2];
            1 -D[2, 2];
            0        0]

R1 = -[0.5 * c1[3]   0    0.5 * c1[2];
                 0   0              0;
       0.5 * c1[2]   0          c1[1]]

R2 = -[0             0              0;
       0   0.5 * c2[3]      0.5*c2[2];
       0   0.5 * c2[2]          c2[1]]

Q1 = [-0.5*e1[3]          0;
                0    D[1, 1]]
Q2 = [-0.5*e2[3]          0;
                0    D[2, 2]]

S1 = zeros(2, 2)
S2 = copy(S1)

W1 = [         0.0           0.0;
               0.0           0.0;
      -0.5 * e1[2]    b[1] / 2.0]
W2 = [         0.0           0.0;
               0.0           0.0;
      -0.5 * e2[2]    b[2] / 2.0]

M1 = [0.0            0.0;
      0.0  D[1, 2] / 2.0]
M2 = copy(M1)
```

Out[13]:
```
2×2 Array{Float64,2}:
 0.0  0.0
 0.0  0.25
```

We can now compute the equilibrium using `qe.nnash`

In [14]:
```
F1, F2, P1, P2 = nnash(A, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2)

println("\nFirm 1's feedback rule:\n")
println(F1)

println("\nFirm 2's feedback rule:\n")
println(F2)
```

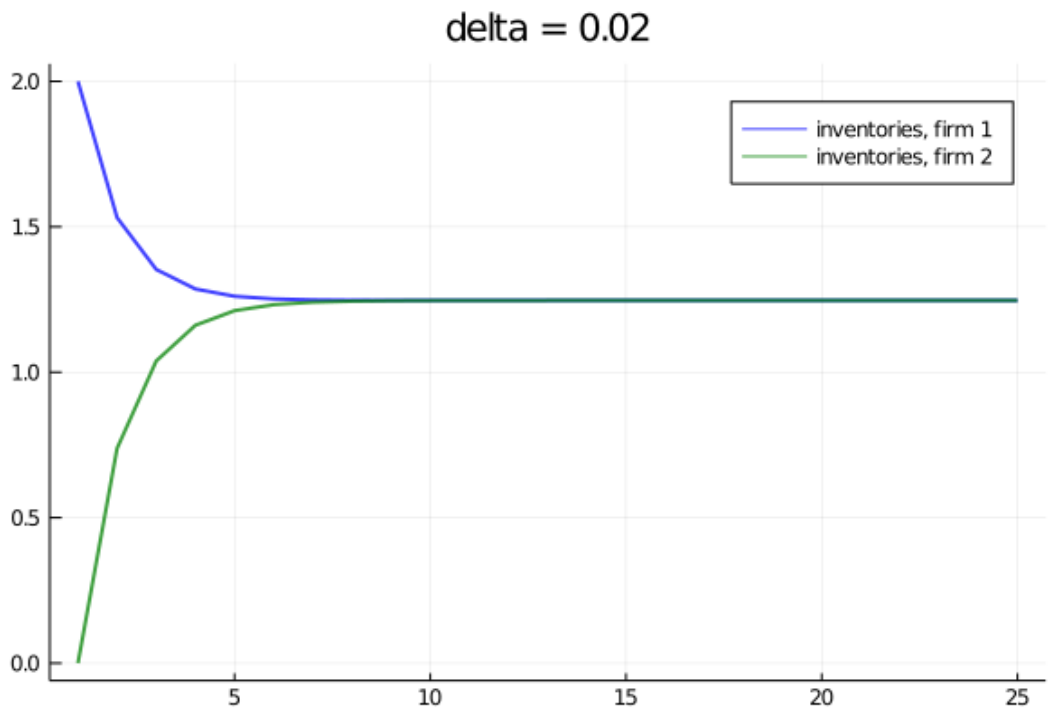
```
Firm 1's feedback rule:
```

```
[0.24366658220856505 0.02723606266195122 -6.827882926030329; 0.3923707338756386
0.13969645088599783 -37.734107288592014]

Firm 2's feedback rule:

[0.027236062661951208 0.243666582208565 -6.827882926030323; 0.1396964508859978
0.39237073387563864 -37.73410728859201]
```

Now let's look at the dynamics of inventories, and reproduce the graph corresponding to $\delta = 0.02$

In [15]:
```
AF = A - B1 * F1 - B2 * F2
n = 25
x = zeros(3, n)
x[:, 1] = [2  0  1]
for t in 1:(n-1)
    x[:, t+1] = AF * x[:, t]
end
I1 = x[1, :]
I2 = x[2, :]

plot(I1, color=:blue, lw=2, alpha=0.75, label="inventories, firm 1")
plot!(I2, color=:green, lw=2, alpha=0.75, label="inventories, firm 2")
plot!(title="delta = 0.02")
```

Out[15]:



Chapter 47

Asset Pricing I: Finite State Models

47.1 Contents

> "A little knowledge of geometric series goes a long way" – Robert E. Lucas, Jr.
>
> "Asset pricing is all about covariances" – Lars Peter Hansen

47.2 Overview

An asset is a claim on one or more future payoffs.

The spot price of an asset depends primarily on

- the anticipated dynamics for the stream of income accruing to the owners
- attitudes to risk
- rates of time preference

In this lecture we consider some standard pricing models and dividend stream specifications.

We study how prices and dividend-price ratios respond in these different scenarios.

We also look at creating and pricing *derivative* assets by repackaging income streams.

Key tools for the lecture are

- formulas for predicting future values of functions of a Markov state
- a formula for predicting the discounted sum of future values of a Markov state

47.3 Pricing Models

In what follows let $\{d_t\}_{t \geq 0}$ be a stream of dividends.

- A time-t **cum-dividend** asset is a claim to the stream $d_t, d_{t+1}, \ldots$.
- A time-t **ex-dividend** asset is a claim to the stream $d_{t+1}, d_{t+2}, \ldots$.

Let's look at some equations that we expect to hold for prices of assets under ex-dividend contracts (we will consider cum-dividend pricing in the exercises).

47.3.1 Risk Neutral Pricing

Our first scenario is risk-neutral pricing.

Let $\beta = 1/(1+\rho)$ be an intertemporal discount factor, where ρ is the rate at which agents discount the future.

The basic risk-neutral asset pricing equation for pricing one unit of an ex-dividend asset is.

$$p_t = \beta \mathbb{E}_t[d_{t+1} + p_{t+1}] \tag{1}$$

This is a simple "cost equals expected benefit" relationship.

Here $\mathbb{E}_t[y]$ denotes the best forecast of y, conditioned on information available at time t.

47.3.2 Pricing with Random Discount Factor

What happens if for some reason traders discount payouts differently depending on the state of the world?

Michael Harrison and David Kreps [49] and Lars Peter Hansen and Scott Richard [43] showed that in quite general settings the price of an ex-dividend asset obeys

$$p_t = \mathbb{E}_t\left[m_{t+1}(d_{t+1} + p_{t+1})\right] \tag{2}$$

for some **stochastic discount factor** m_{t+1}.

The fixed discount factor β in (1) has been replaced by the random variable m_{t+1}.

The way anticipated future payoffs are evaluated can now depend on various random outcomes.

One example of this idea is that assets that tend to have good payoffs in bad states of the world might be regarded as more valuable.

This is because they pay well when the funds are more urgently needed.

We give examples of how the stochastic discount factor has been modeled below.

47.3.3 Asset Pricing and Covariances

Recall that, from the definition of a conditional covariance $\operatorname{cov}_t(x_{t+1}, y_{t+1})$, we have

$$\mathbb{E}_t(x_{t+1} y_{t+1}) = \operatorname{cov}_t(x_{t+1}, y_{t+1}) + \mathbb{E}_t x_{t+1} \mathbb{E}_t y_{t+1} \tag{3}$$

If we apply this definition to the asset pricing equation (2) we obtain

$$p_t = \mathbb{E}_t m_{t+1} \mathbb{E}_t (d_{t+1} + p_{t+1}) + \text{cov}_t (m_{t+1}, d_{t+1} + p_{t+1}) \tag{4}$$

It is useful to regard equation (4) as a generalization of equation (1).

- In equation (1), the stochastic discount factor $m_{t+1} = \beta$, a constant.
- In equation (1), the covariance term $\text{cov}_t (m_{t+1}, d_{t+1} + p_{t+1})$ is zero because $m_{t+1} = \beta$.

Equation (4) asserts that the covariance of the stochastic discount factor with the one period payout $d_{t+1} + p_{t+1}$ is an important determinant of the price p_t.

We give examples of some models of stochastic discount factors that have been proposed later in this lecture and also in a later lecture.

47.3.4 The Price-Dividend Ratio

Aside from prices, another quantity of interest is the **price-dividend ratio** $v_t := p_t / d_t$.

Let's write down an expression that this ratio should satisfy.

We can divide both sides of (2) by d_t to get

$$v_t = \mathbb{E}_t \left[m_{t+1} \frac{d_{t+1}}{d_t} (1 + v_{t+1}) \right] \tag{5}$$

Below we'll discuss the implication of this equation.

47.4 Prices in the Risk Neutral Case

What can we say about price dynamics on the basis of the models described above?

The answer to this question depends on

1. the process we specify for dividends
2. the stochastic discount factor and how it correlates with dividends

For now let's focus on the risk neutral case, where the stochastic discount factor is constant, and study how prices depend on the dividend process.

47.4.1 Example 1: Constant dividends

The simplest case is risk neutral pricing in the face of a constant, non-random dividend stream $d_t = d > 0$.

Removing the expectation from (1) and iterating forward gives

$$\begin{aligned} p_t &= \beta(d + p_{t+1}) \\ &= \beta(d + \beta(d + p_{t+2})) \\ &\vdots \\ &= \beta(d + \beta d + \beta^2 d + \cdots + \beta^{k-2} d + \beta^{k-1} p_{t+k}) \end{aligned}$$

Unless prices explode in the future, this sequence converges to

$$\bar{p} := \frac{\beta d}{1 - \beta} \tag{6}$$

This price is the equilibrium price in the constant dividend case.

Indeed, simple algebra shows that setting $p_t = \bar{p}$ for all t satisfies the equilibrium condition $p_t = \beta(d + p_{t+1})$.

47.4.2 Example 2: Dividends with deterministic growth paths

Consider a growing, non-random dividend process $d_{t+1} = g d_t$ where $0 < g\beta < 1$.

While prices are not usually constant when dividends grow over time, the price dividend-ratio might be.

If we guess this, substituting $v_t = v$ into (5) as well as our other assumptions, we get $v = \beta g(1 + v)$.

Since $\beta g < 1$, we have a unique positive solution:

$$v = \frac{\beta g}{1 - \beta g}$$

The price is then

$$p_t = \frac{\beta g}{1 - \beta g} d_t$$

If, in this example, we take $g = 1 + \kappa$ and let $\rho := 1/\beta - 1$, then the price becomes

$$p_t = \frac{1 + \kappa}{\rho - \kappa} d_t$$

This is called the *Gordon formula*.

47.4.3 Example 3: Markov growth, risk neutral pricing

Next we consider a dividend process

$$d_{t+1} = g_{t+1} d_t \tag{7}$$

The stochastic growth factor $\{g_t\}$ is given by

$$g_t = g(X_t), \quad t = 1, 2, ...$$

where

1. $\{X_t\}$ is a finite Markov chain with state space S and transition probabilities

$$P(x, y) := \mathbb{P}\{X_{t+1} = y \,|\, X_t = x\} \qquad (x, y \in S)$$

1. g is a given function on S taking positive values

You can think of

- S as n possible "states of the world" and X_t as the current state
- g as a function that maps a given state X_t into a growth factor $g_t = g(X_t)$ for the endowment
- $\ln g_t = \ln(d_{t+1}/d_t)$ is the growth rate of dividends

(For a refresher on notation and theory for finite Markov chains see this lecture)

The next figure shows a simulation, where

- $\{X_t\}$ evolves as a discretized AR1 process produced using Tauchen's method
- $g_t = \exp(X_t)$, so that $\ln g_t = X_t$ is the growth rate

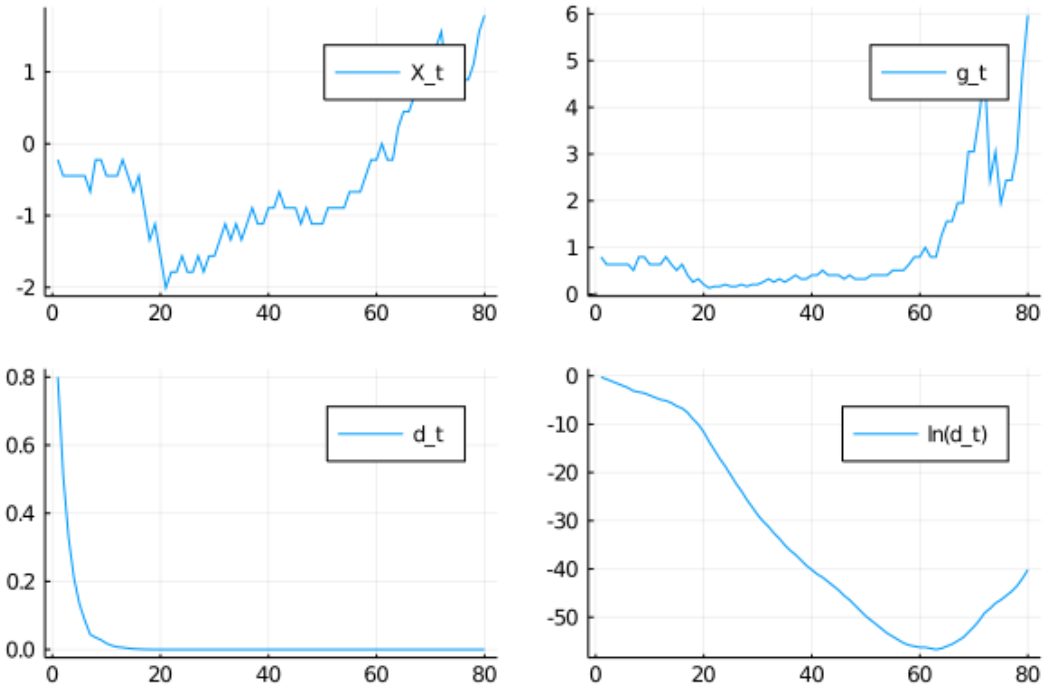
47.4.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Parameters, Plots, QuantEcon
        gr(fmt = :png);
```

```
In [3]: n = 25
        mc = tauchen(n, 0.96, 0.25)
        sim_length = 80

        x_series = simulate(mc, sim_length; init = round(Int, n / 2))
        g_series = exp.(x_series)
        d_series = cumprod(g_series) # assumes d_0 = 1

        series = [x_series g_series d_series log.(d_series)]
        labels = ["X_t" "g_t" "d_t" "ln(d_t)"]
        plot(series, layout = 4, labels = labels)
```

```
Out[3]:
```



Pricing

To obtain asset prices in this setting, let's adapt our analysis from the case of deterministic growth.

In that case we found that v is constant.

This encourages us to guess that, in the current case, v_t is constant given the state X_t.

In other words, we are looking for a fixed function v such that the price-dividend ratio satisfies $v_t = v(X_t)$.

We can substitute this guess into (5) to get

$$v(X_t) = \beta \mathbb{E}_t[g(X_{t+1})(1 + v(X_{t+1}))]$$

If we condition on $X_t = x$, this becomes

$$v(x) = \beta \sum_{y \in S} g(y)(1 + v(y))P(x, y)$$

or

$$v(x) = \beta \sum_{y \in S} K(x, y)(1 + v(y)) \quad \text{where} \quad K(x, y) := g(y)P(x, y) \tag{8}$$

Suppose that there are n possible states $x_1, \ldots, x_n$.

We can then think of (8) as n stacked equations, one for each state, and write it in matrix form as

$$v = \beta K(\mathbb{1} + v) \tag{9}$$

Here

- v is understood to be the column vector $(v(x_1), \ldots, v(x_n))'$
- K is the matrix $(K(x_i, x_j))_{1 \leq i,j \leq n}$
- $\mathbb{1}$ is a column vector of ones

When does (9) have a unique solution?

From the Neumann series lemma and Gelfand's formula, this will be the case if βK has spectral radius strictly less than one.

In other words, we require that the eigenvalues of K be strictly less than β^{-1} in modulus.

The solution is then

$$v = (I - \beta K)^{-1} \beta K \mathbb{1} \tag{10}$$

47.4.5 Code

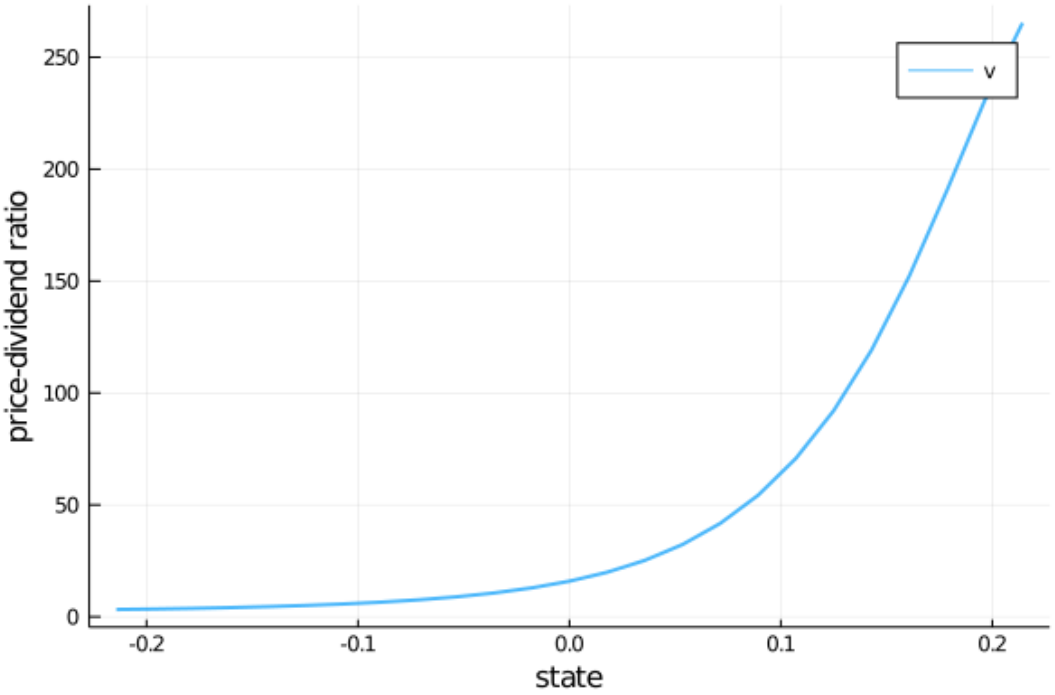
Let's calculate and plot the price-dividend ratio at a set of parameters.

As before, we'll generate $\{X_t\}$ as a discretized AR1 process and set $g_t = \exp(X_t)$.

Here's the code, including a test of the spectral radius condition

In [4]:
```
n = 25  # size of state space
β = 0.9
mc = tauchen(n, 0.96, 0.02)

K = mc.p .* exp.(mc.state_values)'

v = (I - β * K) \  (β * K * ones(n, 1))

plot(mc.state_values,
     v,
     lw = 2,
     ylabel = "price-dividend ratio",
     xlabel = "state",
     alpha = 0.7,
     label = "v")
```

Out[4]:



Why does the price-dividend ratio increase with the state?

The reason is that this Markov process is positively correlated, so high current states suggest high future states.

Moreover, dividend growth is increasing in the state.

Anticipation of high future dividend growth leads to a high price-dividend ratio.

47.5 Asset Prices under Risk Aversion

Now let's turn to the case where agents are risk averse.

We'll price several distinct assets, including

- The price of an endowment stream.
- A consol (a variety of bond issued by the UK government in the 19th century).
- Call options on a consol.

47.5.1 Pricing a Lucas tree

Let's start with a version of the celebrated asset pricing model of Robert E. Lucas, Jr. [69].

As in [69], suppose that the stochastic discount factor takes the form

$$m_{t+1} = \beta \frac{u'(c_{t+1})}{u'(c_t)} \tag{11}$$

where u is a concave utility function and c_t is time t consumption of a representative consumer.

(A derivation of this expression is given in a later lecture)

Assume the existence of an endowment that follows (7).

The asset being priced is a claim on the endowment process.

Following [69], suppose further that in equilibrium, consumption is equal to the endowment, so that $d_t = c_t$ for all t.

For utility, we'll assume the **constant relative risk aversion** (CRRA) specification

$$u(c) = \frac{c^{1-\gamma}}{1-\gamma} \text{ with } \gamma > 0 \tag{12}$$

When $\gamma = 1$ we let $u(c) = \ln c$.

Inserting the CRRA specification into (11) and using $c_t = d_t$ gives

$$m_{t+1} = \beta \left(\frac{c_{t+1}}{c_t} \right)^{-\gamma} = \beta g_{t+1}^{-\gamma} \tag{13}$$

Substituting this into (5) gives the price-dividend ratio formula

$$v(X_t) = \beta \mathbb{E}_t \left[g(X_{t+1})^{1-\gamma} (1 + v(X_{t+1})) \right]$$

Conditioning on $X_t = x$, we can write this as

$$v(x) = \beta \sum_{y \in S} g(y)^{1-\gamma} (1 + v(y)) P(x, y)$$

If we let

$$J(x, y) := g(y)^{1-\gamma} P(x, y)$$

then we can rewrite in vector form as

$$v = \beta J (\mathbb{1} + v)$$

Assuming that the spectral radius of J is strictly less than β^{-1}, this equation has the unique solution

$$v = (I - \beta J)^{-1} \beta J \mathbb{1} \tag{14}$$

We will define a function tree_price to solve for v given parameters stored in the AssetPriceModel objects

```
In [5]: # A default Markov chain for the state process
        ρ = 0.9
        σ = 0.02
        n = 25
        default_mc = tauchen(n, ρ, σ)

        AssetPriceModel = @with_kw (β = 0.96,
                                    γ = 2.0,
```

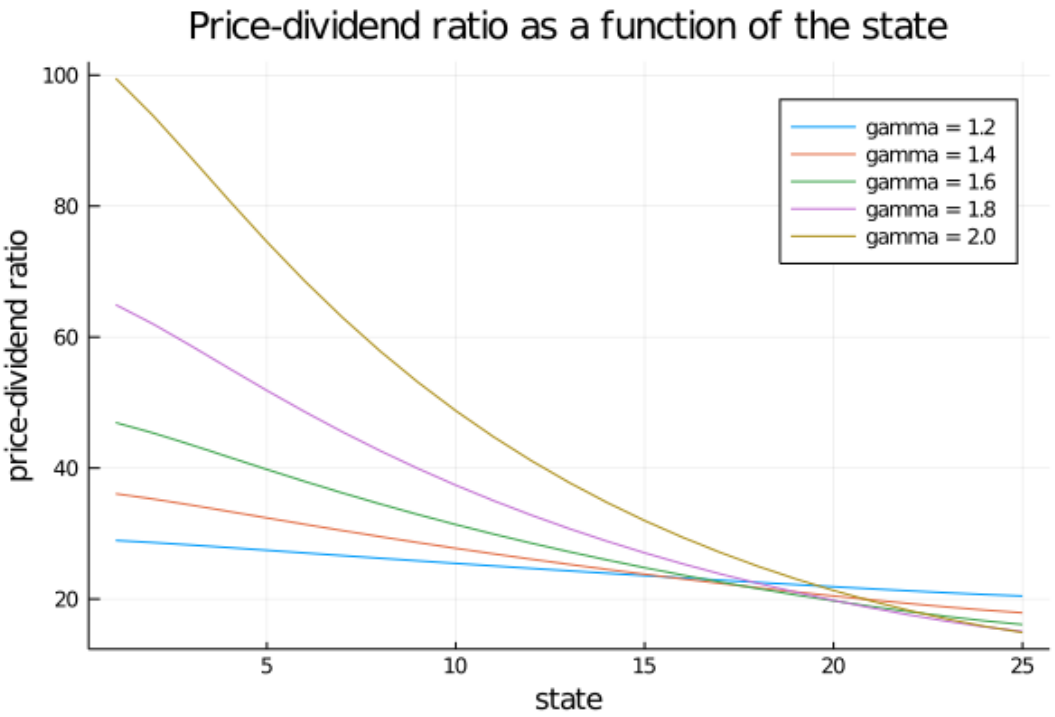
```
                                mc = default_mc,
                                n = size(mc.p)[1],
                                g = exp)

    # test stability of matrix Q
    function test_stability(ap, Q)
        sr = maximum(abs, eigvals(Q))
        if sr ≥ 1 / ap.β
            msg = "Spectral radius condition failed with radius = $sr"
            throw(ArgumentError(msg))
        end
    end

    # price/dividend ratio of the Lucas tree
    function tree_price(ap; γ = ap.γ)
        # Simplify names, set up matrices
        @unpack β, mc = ap
        P, y = mc.p, mc.state_values
        y = reshape(y, 1, ap.n)
        J = P .* ap.g.(y).^(1 - γ)

        # Make sure that a unique solution exists
        test_stability(ap, J)

        # Compute v
        v = (I - β * J) \ sum(β * J, dims = 2)

        return v
    end
```

```
Out[5]: tree_price (generic function with 1 method)
```

Here's a plot of v as a function of the state for several values of γ, with a positively correlated Markov process and $g(x) = \exp(x)$

```
In [6]: γs = [1.2, 1.4, 1.6, 1.8, 2.0]
        ap = AssetPriceModel()
        states = ap.mc.state_values

        lines = []
        labels = []

        for γ in γs
            v = tree_price(ap, γ = γ)
            label = "gamma = $γ"
            push!(labels, label)
            push!(lines, v)
        end

        plot(lines,
             labels = reshape(labels, 1, length(labels)),
             title = "Price-dividend ratio as a function of the state",
             ylabel = "price-dividend ratio",
             xlabel = "state")
```

```
Out[6]:
```



Notice that v is decreasing in each case.

This is because, with a positively correlated state process, higher states suggest higher future consumption growth.

In the stochastic discount factor (13), higher growth decreases the discount factor, lowering the weight placed on future returns.

Special cases

In the special case $\gamma = 1$, we have $J = P$.

Recalling that $P^i \mathbb{1} = \mathbb{1}$ for all i and applying Neumann's geometric series lemma, we are led to

$$v = \beta(I - \beta P)^{-1} \mathbb{1} = \beta \sum_{i=0}^{\infty} \beta^i P^i \mathbb{1} = \beta \frac{1}{1-\beta} \mathbb{1}$$

Thus, with log preferences, the price-dividend ratio for a Lucas tree is constant.

Alternatively, if $\gamma = 0$, then $J = K$ and we recover the risk neutral solution (10).

This is as expected, since $\gamma = 0$ implies $u(c) = c$ (and hence agents are risk neutral).

47.5.2 A Risk-Free Consol

Consider the same pure exchange representative agent economy.

A risk-free consol promises to pay a constant amount $\zeta > 0$ each period.

Recycling notation, let p_t now be the price of an ex-coupon claim to the consol.

An ex-coupon claim to the consol entitles the owner at the end of period t to

- ζ in period $t+1$, plus
- the right to sell the claim for p_{t+1} next period

The price satisfies (2) with $d_t = \zeta$, or

$$p_t = \mathbb{E}_t \left[m_{t+1} (\zeta + p_{t+1}) \right]$$

We maintain the stochastic discount factor (13), so this becomes

$$p_t = \mathbb{E}_t \left[\beta g_{t+1}^{-\gamma} (\zeta + p_{t+1}) \right] \tag{15}$$

Guessing a solution of the form $p_t = p(X_t)$ and conditioning on $X_t = x$, we get

$$p(x) = \beta \sum_{y \in S} g(y)^{-\gamma} (\zeta + p(y)) P(x, y)$$

Letting $M(x, y) = P(x, y) g(y)^{-\gamma}$ and rewriting in vector notation yields the solution

$$p = (I - \beta M)^{-1} \beta M \zeta \mathbb{1} \tag{16}$$

The above is implemented in the function consol_price

```
In [7]: function consol_price(ap, ζ)
            # Simplify names, set up matrices
            @unpack β, γ, mc, g, n = ap
            P, y = mc.p, mc.state_values
            y = reshape(y, 1, n)
            M = P .* g.(y).^(-γ)

            # Make sure that a unique solution exists
            test_stability(ap, M)

            # Compute price
            return (I - β * M) \ sum(β * ζ * M, dims = 2)
        end
```

```
Out[7]: consol_price (generic function with 1 method)
```

47.5.3 Pricing an Option to Purchase the Consol

Let's now price options of varying maturity that give the right to purchase a consol at a price p_S.

An infinite horizon call option

We want to price an infinite horizon option to purchase a consol at a price p_S.

The option entitles the owner at the beginning of a period either to

1. purchase the bond at price p_S now, or

2. Not to exercise the option now but to retain the right to exercise it later

Thus, the owner either *exercises* the option now, or chooses *not to exercise* and wait until next period.

This is termed an infinite-horizon *call option* with *strike price* p_S.

The owner of the option is entitled to purchase the consol at the price p_S at the beginning of any period, after the coupon has been paid to the previous owner of the bond.

The fundamentals of the economy are identical with the one above, including the stochastic discount factor and the process for consumption.

Let $w(X_t, p_S)$ be the value of the option when the time t growth state is known to be X_t but *before* the owner has decided whether or not to exercise the option at time t (i.e., today).

Recalling that $p(X_t)$ is the value of the consol when the initial growth state is X_t, the value of the option satisfies

$$w(X_t, p_S) = \max\left\{\beta \, \mathbb{E}_t \frac{u'(c_{t+1})}{u'(c_t)} w(X_{t+1}, p_S), \; p(X_t) - p_S\right\}$$

The first term on the right is the value of waiting, while the second is the value of exercising now.

We can also write this as

$$w(x, p_S) = \max\left\{\beta \sum_{y \in S} P(x,y) g(y)^{-\gamma} w(y, p_S), \; p(x) - p_S\right\} \tag{17}$$

With $M(x,y) = P(x,y)g(y)^{-\gamma}$ and w as the vector of values $(w(x_i), p_S)_{i=1}^n$, we can express (17) as the nonlinear vector equation

$$w = \max\{\beta M w, \; p - p_S \mathbb{1}\} \tag{18}$$

To solve (18), form the operator T mapping vector w into vector Tw via

$$Tw = \max\{\beta M w, \; p - p_S \mathbb{1}\}$$

Start at some initial w and iterate to convergence with T.

We can find the solution with the following function call_option

```
In [8]: # price of perpetual call on consol bond
        function call_option(ap, ζ, p_s, ϵ = 1e-7)

            # Simplify names, set up matrices
            @unpack β, γ, mc, g, n = ap
            P, y = mc.p, mc.state_values
            y = reshape(y, 1, n)
            M = P .* g.(y).^(-γ)

            # Make sure that a unique console price exists
            test_stability(ap, M)
```

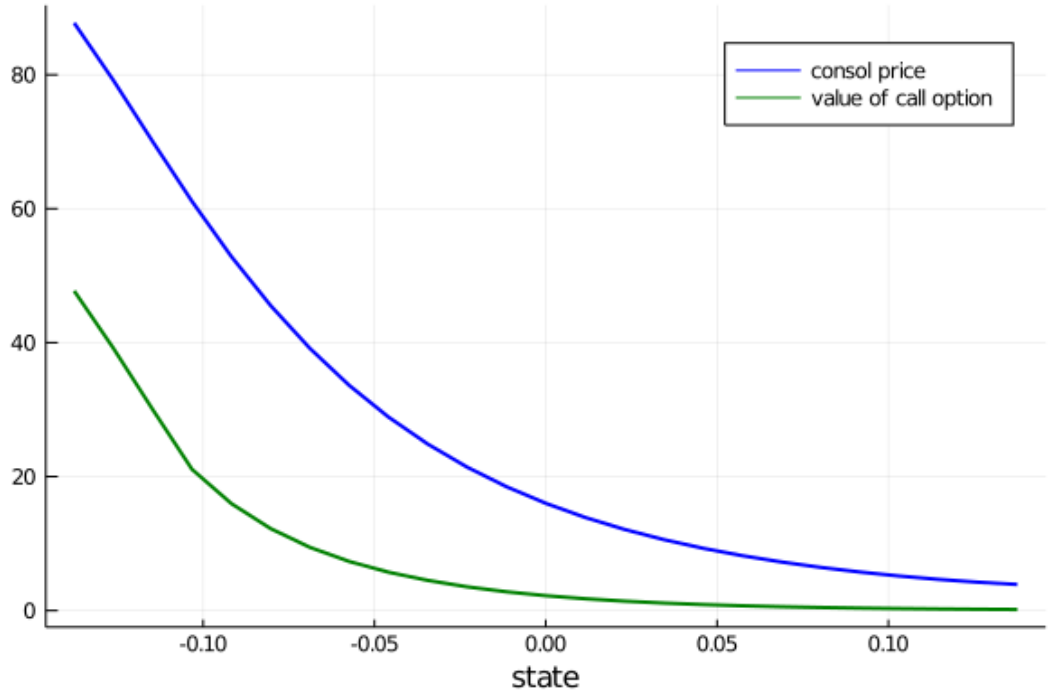
```
        # Compute option price
        p = consol_price(ap, ζ)
        w = zeros(ap.n, 1)
        error = ϵ + 1
        while (error > ϵ)
            # Maximize across columns
            w_new = max.(β * M * w, p .- p_s)
            # Find maximal difference of each component and update
            error = maximum(abs, w - w_new)
            w = w_new
        end

        return w
    end
```

```
Out[8]: call_option (generic function with 2 methods)
```

Here's a plot of w compared to the consol price when $P_S = 40$

```
In [9]: ap = AssetPriceModel(β=0.9)
        ζ = 1.0
        strike_price = 40.0

        x = ap.mc.state_values
        p = consol_price(ap, ζ)
        w = call_option(ap, ζ, strike_price)

        plot(x, p, color = "blue", lw = 2, xlabel = "state", label = "consol price")
        plot!(x, w, color = "green", lw = 2, label = "value of call option")
```

```
Out[9]:
```



In large states the value of the option is close to zero.

This is despite the fact the Markov chain is irreducible and low states — where the consol prices is high — will eventually be visited.

The reason is that $\beta = 0.9$, so the future is discounted relatively rapidly

47.5.4 Risk Free Rates

Let's look at risk free interest rates over different periods.

The one-period risk-free interest rate

As before, the stochastic discount factor is $m_{t+1} = \beta g_{t+1}^{-\gamma}$.

It follows that the reciprocal R_t^{-1} of the gross risk-free interest rate R_t in state x is

$$\mathbb{E}_t m_{t+1} = \beta \sum_{y \in S} P(x, y) g(y)^{-\gamma}$$

We can write this as

$$m_1 = \beta M \mathbb{1}$$

where the i-th element of m_1 is the reciprocal of the one-period gross risk-free interest rate in state x_i.

Other terms

Let m_j be an $n \times 1$ vector whose i th component is the reciprocal of the j -period gross risk-free interest rate in state x_i.

Then $m_1 = \beta M$, and $m_{j+1} = M m_j$ for $j \geq 1$.

47.6 Exercises

47.6.1 Exercise 1

In the lecture, we considered **ex-dividend assets**.

A **cum-dividend** asset is a claim to the stream $d_t, d_{t+1}, ...$

Following (1), find the risk-neutral asset pricing equation for one unit of a cum-dividend asset.

With a constant, non-random dividend stream $d_t = d > 0$, what is the equilibrium price of a cum-dividend asset?

With a growing, non-random dividend process $d_t = g d_t$ where $0 < g\beta < 1$, what is the equilibrium price of a cum-dividend asset?

47.6.2 Exercise 2

Consider the following primitives

```
In [10]: n = 5
         P = fill(0.0125, n, n) + (0.95 - 0.0125)I
         s = [1.05, 1.025, 1.0, 0.975, 0.95]
         γ = 2.0
         β = 0.94
         ζ = 1.0
```

```
Out[10]: 1.0
```

Let g be defined by $g(x) = x$ (that is, g is the identity map).

Compute the price of the Lucas tree.

Do the same for

- the price of the risk-free consol when $\zeta = 1$
- the call option on the consol when $\zeta = 1$ and $p_S = 150.0$

47.6.3 Exercise 3

Let's consider finite horizon call options, which are more common than the infinite horizon variety.

Finite horizon options obey functional equations closely related to (17).

A k period option expires after k periods.

If we view today as date zero, a k period option gives the owner the right to exercise the option to purchase the risk-free consol at the strike price p_S at dates $0, 1, \ldots, k-1$.

The option expires at time k.

Thus, for $k = 1, 2, ...$, let $w(x, k)$ be the value of a k-period option.

It obeys

$$w(x,k) = \max\left\{\beta \sum_{y \in S} P(x,y) g(y)^{-\gamma} w(y, k-1),\ p(x) - p_S\right\}$$

where $w(x, 0) = 0$ for all x.

We can express the preceding as the sequence of nonlinear vector equations

$$w_k = \max\{\beta M w_{k-1},\ p - p_S \mathbb{1}\} \quad k = 1, 2, \ldots \quad \text{with } w_0 = 0$$

Write a function that computes w_k for any given k.

Compute the value of the option with `k = 5` and `k = 25` using parameter values as in Exercise 1.

Is one higher than the other? Can you give intuition?

47.7 Solutions

47.7.1 Exercise 2

```
In [11]: n = 5
         P = fill(0.0125, n, n) + (0.95 - 0.0125)I
         s = [0.95, 0.975, 1.0, 1.025, 1.05]  # state values
         mc = MarkovChain(P, s)

         γ = 2.0
         β = 0.94
         ζ = 1.0
         p_s = 150.0
```

```
Out[11]: 150.0
```

Next we'll create an instance of AssetPriceModel to feed into the functions.

```
In [12]: ap = AssetPriceModel(β = β, mc = mc, γ = γ, g = x -> x)
```

```
Out[12]: (β = 0.94, γ = 2.0, mc = Discrete Markov Chain
         stochastic matrix of type Array{Float64,2}:
         [0.95 0.0125 … 0.0125 0.0125; 0.0125 0.95 … 0.0125 0.0125; … ; 0.0125 0.
        ↪0125 … 0.95
         0.0125; 0.0125 0.0125 … 0.0125 0.95], n = 5, g = var"#5#6"())
```

```
In [13]: v = tree_price(ap)
         println("Lucas Tree Prices: $v\n")
```

```
Lucas Tree Prices: [29.474015777145; 21.935706611219704; 17.571422357262904;
14.725150017725884; 12.722217630644252]
```

```
In [14]: v_consol = consol_price(ap, 1.0)
         println("Consol Bond Prices: $(v_consol)\n")
```

```
Consol Bond Prices: [753.8710047641987; 242.55144081989457; 148.67554548466478;
109.25108965024712; 87.56860138531121]
```

```
In [15]: w = call_option(ap, ζ, p_s)
```

```
Out[15]: 5×1 Array{Float64,2}:
          603.8710047641987
          176.839334301913
          108.67734499337003
           80.05179254233045
           64.30843748377002
```

47.7.2 Exercise 3

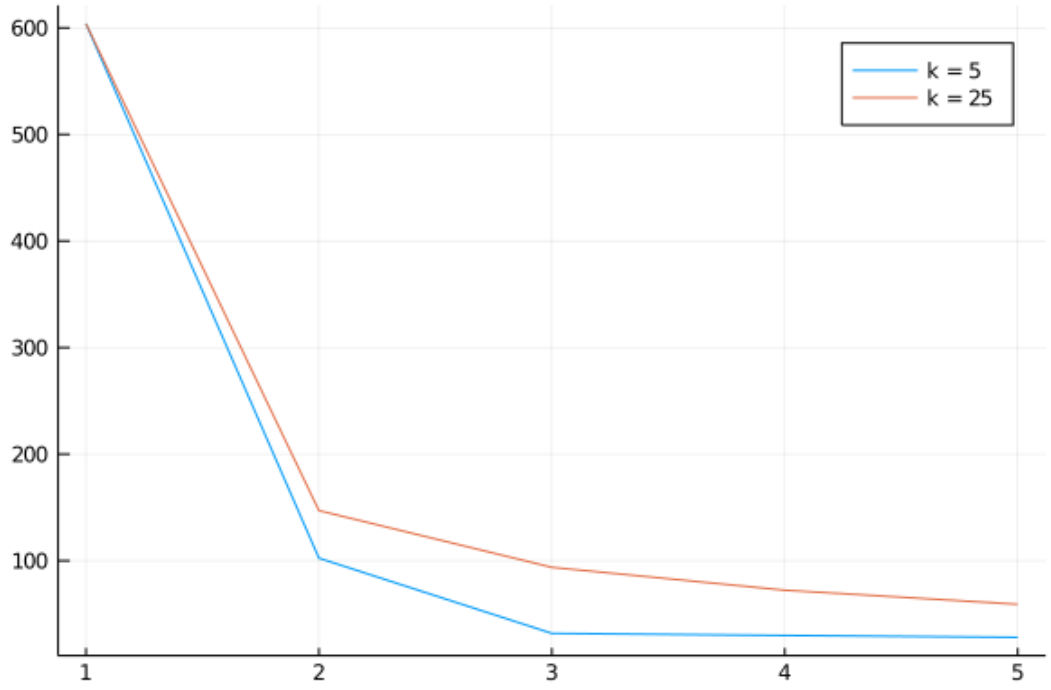
Here's a suitable function:

In [16]:
```
function finite_horizon_call_option(ap, ζ, p_s, k)

    # Simplify names, set up matrices
    @unpack β, γ, mc = ap
    P, y = mc.p, mc.state_values
    y = y'
    M = P .* ap.g.(y).^(- γ)

    # Make sure that a unique console price exists
    test_stability(ap, M)

    # Compute option price
    p = consol_price(ap, ζ)
    w = zeros(ap.n, 1)
    for i in 1:k
        # Maximize across columns
        w = max.(β * M * w, p .- p_s)
    end

    return w
end
```

Out[16]:
```
finite_horizon_call_option (generic function with 1 method)
```

In [17]:
```
lines = []
labels = []
for k in [5, 25]
    w = finite_horizon_call_option(ap, ζ, p_s, k)
    push!(lines, w)
    push!(labels, "k = $k")
end
plot(lines, labels = reshape(labels, 1, length(labels)))
```

Out[17]:



Not surprisingly, the option has greater value with larger k. This is because the owner has a longer time horizon over which he or she may exercise the option.

Chapter 48

Asset Pricing II: The Lucas Asset Pricing Model

48.1 Contents

48.2 Overview

As stated in an earlier lecture, an asset is a claim on a stream of prospective payments.

What is the correct price to pay for such a claim?

The elegant asset pricing model of Lucas [69] attempts to answer this question in an equilibrium setting with risk averse agents.

While we mentioned some consequences of Lucas' model earlier, it is now time to work through the model more carefully, and try to understand where the fundamental asset pricing equation comes from.

A side benefit of studying Lucas' model is that it provides a beautiful illustration of model building in general and equilibrium pricing in competitive models in particular.

Another difference to our first asset pricing lecture is that the state space and shock will be continous rather than discrete.

48.3 The Lucas Model

Lucas studied a pure exchange economy with a representative consumer (or household), where

- *Pure exchange* means that all endowments are exogenous.
- *Representative* consumer means that either
  - there is a single consumer (sometimes also referred to as a household), or
  - all consumers have identical endowments and preferences

Either way, the assumption of a representative agent means that prices adjust to eradicate desires to trade.

This makes it very easy to compute competitive equilibrium prices.

48.3.1 Basic Setup

Let's review the set up.

Assets

There is a single "productive unit" that costlessly generates a sequence of consumption goods $\{y_t\}_{t=0}^{\infty}$.

Another way to view $\{y_t\}_{t=0}^{\infty}$ is as a *consumption endowment* for this economy.

We will assume that this endowment is Markovian, following the exogenous process

$$y_{t+1} = G(y_t, \xi_{t+1})$$

Here $\{\xi_t\}$ is an iid shock sequence with known distribution ϕ and $y_t \geq 0$.

An asset is a claim on all or part of this endowment stream.

The consumption goods $\{y_t\}_{t=0}^{\infty}$ are nonstorable, so holding assets is the only way to transfer wealth into the future.

For the purposes of intuition, it's common to think of the productive unit as a "tree" that produces fruit.

Based on this idea, a "Lucas tree" is a claim on the consumption endowment.

Consumers

A representative consumer ranks consumption streams $\{c_t\}$ according to the time separable utility functional

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t u(c_t) \tag{1}$$

Here

- $\beta \in (0, 1)$ is a fixed discount factor
- u is a strictly increasing, strictly concave, continuously differentiable period utility function
- $\mathbb{E}$ is a mathematical expectation

48.3.2 Pricing a Lucas Tree

What is an appropriate price for a claim on the consumption endowment?

We'll price an *ex dividend* claim, meaning that

- the seller retains this period's dividend
- the buyer pays p_t today to purchase a claim on
  - y_{t+1} and
  - the right to sell the claim tomorrow at price p_{t+1}

Since this is a competitive model, the first step is to pin down consumer behavior, taking prices as given.

Next we'll impose equilibrium constraints and try to back out prices.

In the consumer problem, the consumer's control variable is the share π_t of the claim held in each period.

Thus, the consumer problem is to maximize (1) subject to

$$c_t + \pi_{t+1} p_t \leq \pi_t y_t + \pi_t p_t$$

along with $c_t \geq 0$ and $0 \leq \pi_t \leq 1$ at each t.

The decision to hold share π_t is actually made at time $t-1$.

But this value is inherited as a state variable at time t, which explains the choice of subscript.

The dynamic program

We can write the consumer problem as a dynamic programming problem.

Our first observation is that prices depend on current information, and current information is really just the endowment process up until the current period.

In fact the endowment process is Markovian, so that the only relevant information is the current state $y \in \mathbb{R}_+$ (dropping the time subscript).

This leads us to guess an equilibrium where price is a function p of y.

Remarks on the solution method

- Since this is a competitive (read: price taking) model, the consumer will take this function p as .
- In this way we determine consumer behavior given p and then use equilibrium conditions to recover p.
- This is the standard way to solve competitive equilibrum models.

Using the assumption that price is a given function p of y, we write the value function and constraint as

$$v(\pi, y) = \max_{c, \pi'} \left\{ u(c) + \beta \int v(\pi', G(y, z)) \phi(dz) \right\}$$

subject to

$$c + \pi' p(y) \leq \pi y + \pi p(y) \tag{2}$$

We can invoke the fact that utility is increasing to claim equality in (2) and hence eliminate the constraint, obtaining

$$v(\pi, y) = \max_{\pi'} \left\{ u[\pi(y + p(y)) - \pi' p(y)] + \beta \int v(\pi', G(y, z))\phi(dz) \right\} \tag{3}$$

The solution to this dynamic programming problem is an optimal policy expressing either π' or c as a function of the state (π, y).

- Each one determines the other, since $c(\pi, y) = \pi(y + p(y)) - \pi'(\pi, y)p(y)$.

Next steps

What we need to do now is determine equilibrium prices.

It seems that to obtain these, we will have to

1. Solve this two dimensional dynamic programming problem for the optimal policy.
2. Impose equilibrium constraints.
3. Solve out for the price function $p(y)$ directly.

However, as Lucas showed, there is a related but more straightforward way to do this.

Equilibrium constraints

Since the consumption good is not storable, in equilibrium we must have $c_t = y_t$ for all t.

In addition, since there is one representative consumer (alternatively, since all consumers are identical), there should be no trade in equilibrium.

In particular, the representative consumer owns the whole tree in every period, so $\pi_t = 1$ for all t.

Prices must adjust to satisfy these two constraints.

The equilibrium price function

Now observe that the first order condition for (3) can be written as

$$u'(c)p(y) = \beta \int v_1'(\pi', G(y, z))\phi(dz)$$

where v_1' is the derivative of v with respect to its first argument.

To obtain v_1' we can simply differentiate the right hand side of (3) with respect to π, yielding

$$v_1'(\pi, y) = u'(c)(y + p(y))$$

Next we impose the equilibrium constraints while combining the last two equations to get

$$p(y) = \beta \int \frac{u'[G(y, z)]}{u'(y)} [G(y, z) + p(G(y, z))]\phi(dz) \tag{4}$$

In sequential rather than functional notation, we can also write this as

$$p_t = \mathbb{E}_t \left[\beta \frac{u'(c_{t+1})}{u'(c_t)} (y_{t+1} + p_{t+1}) \right] \tag{5}$$

This is the famous consumption-based asset pricing equation.

Before discussing it further we want to solve out for prices.

48.3.3 Solving the Model

Equation (4) is a *functional equation* in the unknown function p.

The solution is an equilibrium price function p^*.

Let's look at how to obtain it.

Setting up the problem

Instead of solving for it directly we'll follow Lucas' indirect approach, first setting

$$f(y) := u'(y)p(y) \tag{6}$$

so that (4) becomes

$$f(y) = h(y) + \beta \int f[G(y,z)]\phi(dz) \tag{7}$$

Here $h(y) := \beta \int u'[G(y,z)]G(y,z)\phi(dz)$ is a function that depends only on the primitives.

Equation (7) is a functional equation in f.

The plan is to solve out for f and convert back to p via (6).

To solve (7) we'll use a standard method: convert it to a fixed point problem.

First we introduce the operator T mapping f into Tf as defined by

$$(Tf)(y) = h(y) + \beta \int f[G(y,z)]\phi(dz) \tag{8}$$

The reason we do this is that a solution to (7) now corresponds to a function f^* satisfying $(Tf^*)(y) = f^*(y)$ for all y.

In other words, a solution is a *fixed point* of T.

This means that we can use fixed point theory to obtain and compute the solution.

A little fixed point theory

Let $cb\mathbb{R}_+$ be the set of continuous bounded functions $f \colon \mathbb{R}_+ \to \mathbb{R}_+$.

We now show that

1. T has exactly one fixed point f^* in $cb\mathbb{R}_+$.
2. For any $f \in cb\mathbb{R}_+$, the sequence $T^k f$ converges uniformly to f^*.

(Note: If you find the mathematics heavy going you can take 1–2 as given and skip to the next section)

Recall the Banach contraction mapping theorem.

It tells us that the previous statements will be true if we can find an $\alpha < 1$ such that

$$\|Tf - Tg\| \leq \alpha \|f - g\|, \qquad \forall\, f, g \in cb\mathbb{R}_+ \tag{9}$$

Here $\|h\| := \sup_{x \in \mathbb{R}_+} |h(x)|$.

To see that (9) is valid, pick any $f, g \in cb\mathbb{R}_+$ and any $y \in \mathbb{R}_+$.

Observe that, since integrals get larger when absolute values are moved to the inside,

$$\begin{aligned} |Tf(y) - Tg(y)| &= \left| \beta \int f[G(y,z)]\phi(dz) - \beta \int g[G(y,z)]\phi(dz) \right| \\ &\leq \beta \int |f[G(y,z)] - g[G(y,z)]|\, \phi(dz) \\ &\leq \beta \int \|f - g\| \phi(dz) \\ &= \beta \|f - g\| \end{aligned}$$

Since the right hand side is an upper bound, taking the sup over all y on the left hand side gives (9) with $\alpha := \beta$.

48.3.4 Computation – An Example

The preceding discussion tells that we can compute f^* by picking any arbitrary $f \in cb\mathbb{R}_+$ and then iterating with T.

The equilibrium price function p^* can then be recovered by $p^*(y) = f^*(y)/u'(y)$.

Let's try this when $\ln y_{t+1} = \alpha \ln y_t + \sigma \epsilon_{t+1}$ where $\{\epsilon_t\}$ is iid and standard normal.

Utility will take the isoelastic form $u(c) = c^{1-\gamma}/(1-\gamma)$, where $\gamma > 0$ is the coefficient of relative risk aversion.

Some code to implement the iterative computational procedure can be found below:

48.3.5 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Interpolations, Parameters, Plots, QuantEcon, Random
        gr(fmt = :png);
```

```
In [3]: # model
        function LucasTree(;γ = 2.0,
                            β = 0.95,
                            α = 0.9,
                            σ = 0.1,
                            grid_size = 100)

            ϕ = LogNormal(0.0, σ)
            shocks = rand(ϕ, 500)

            # build a grid with mass around stationary distribution
            ssd = σ / sqrt(1 - α^2)
            grid_min, grid_max = exp(-4ssd), exp(4ssd)
            grid = range(grid_min, grid_max, length = grid_size)

            # set h(y) = β * int u'(G(y,z)) G(y,z) ☒(dz)
            h = similar(grid)
            for (i, y) in enumerate(grid)
                h[i] = β * mean((y^α .* shocks).^(1 - γ))
            end

           return (γ = γ, β = β, α = α, σ = σ, ϕ = ϕ, grid = grid, shocks = shocks,
        ↪h = h)
        end

        # approximate Lucas operator, which returns the updated function Tf on the
        ↪grid
        function lucas_operator(lt, f)

            # unpack input
            @unpack grid, α, β, h = lt
            z = lt.shocks

            Af = LinearInterpolation(grid, f, extrapolation_bc=Line())

            Tf = [ h[i] + β * mean(Af.(grid[i]^α .* z)) for i in 1:length(grid) ]
            return Tf
        end

        # get equilibrium price for Lucas tree
        function solve_lucas_model(lt;
                                   tol = 1e-6,
                                   max_iter = 500)

            @unpack grid, γ = lt

            i = 0
            f = zero(grid)  # Initial guess of f
            error = tol + 1

            while (error > tol) && (i < max_iter)
                f_new = lucas_operator(lt, f)
                error = maximum(abs, f_new - f)
                f = f_new
                i += 1
            end

            # p(y) = f(y) * y ^ γ
```

```
    price = f .* grid.^γ

    return price
end
```

```
Out[3]: solve_lucas_model (generic function with 1 method)
```

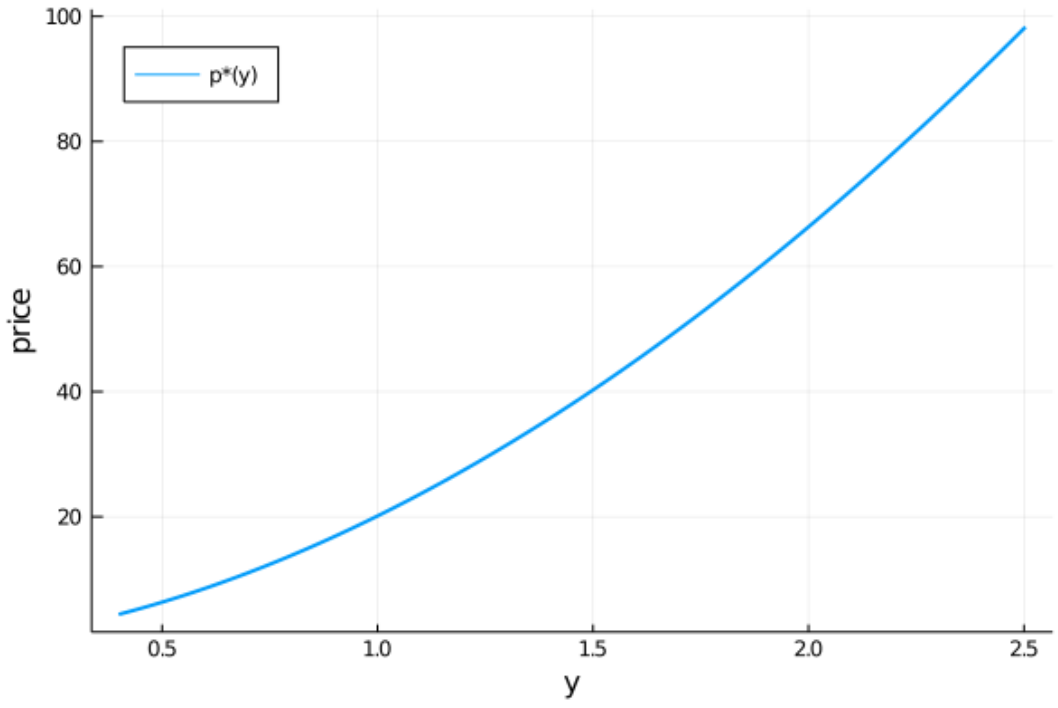
An example of usage is given in the docstring and repeated here

```
In [4]: Random.seed!(42) # For reproducible results.

        tree = LucasTree(γ = 2.0, β = 0.95, α = 0.90, σ = 0.1)
        price_vals = solve_lucas_model(tree);
```

Here's the resulting price function

```
In [5]: plot(tree.grid, price_vals, lw = 2, label = "p*(y)")
        plot!(xlabel = "y", ylabel = "price", legend = :topleft)
```

Out[5]:



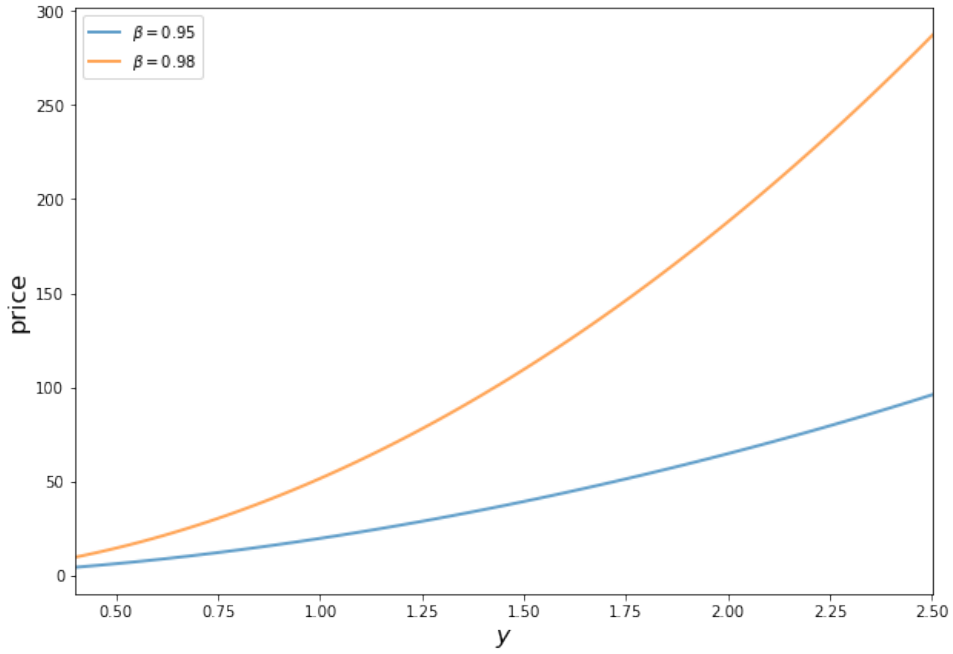
The price is increasing, even if we remove all serial correlation from the endowment process.

The reason is that a larger current endowment reduces current marginal utility.

The price must therefore rise to induce the household to consume the entire endowment (and hence satisfy the resource constraint).

What happens with a more patient consumer?

Here the orange line corresponds to the previous parameters and the green line is price when $\beta = 0.98$.



We see that when consumers are more patient the asset becomes more valuable, and the price of the Lucas tree shifts up.

Exercise 1 asks you to replicate this figure.

48.4 Exercises

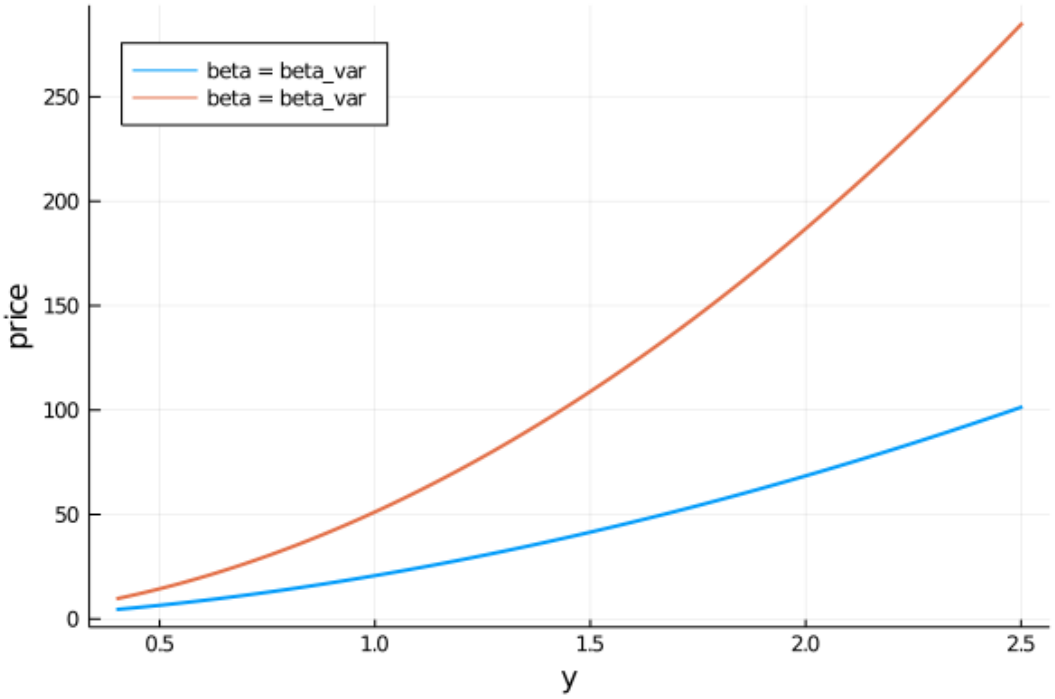
48.4.1 Exercise 1

Replicate the figure to show how discount rates affect prices.

48.5 Solutions

In [6]:
```
plot()
for β in (.95, 0.98)
    tree = LucasTree(;β = β)
    grid = tree.grid
    price_vals = solve_lucas_model(tree)
    plot!(grid, price_vals, lw = 2, label = "beta = beta_var")
end

plot!(xlabel = "y", ylabel = "price", legend = :topleft)
```

Out[6]:


beta = beta_var
beta = beta_var
price
y
0
50
100
150
200
250
0.5
1.0
1.5
2.0
2.5

Chapter 49

Asset Pricing III: Incomplete Markets

49.1 Contents

49.2 Overview

This lecture describes a version of a model of Harrison and Kreps [48].

The model determines the price of a dividend-yielding asset that is traded by two types of self-interested investors.

The model features

- heterogeneous beliefs
- incomplete markets
- short sales constraints, and possibly ...
- (leverage) limits on an investor's ability to borrow in order to finance purchases of a risky asset

49.2.1 References

Prior to reading the following you might like to review our lectures on

- Markov chains
- Asset pricing with finite state space

49.2.2 Bubbles

Economists differ in how they define a *bubble*.

The Harrison-Kreps model illustrates the following notion of a bubble that attracts many economists:

> *A component of an asset price can be interpreted as a bubble when all investors agree that the current price of the asset exceeds what they believe the asset's underlying dividend stream justifies.*

49.2.3 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

49.3 Structure of the Model

The model simplifies by ignoring alterations in the distribution of wealth among investors having different beliefs about the fundamentals that determine asset payouts.

There is a fixed number A of shares of an asset.

Each share entitles its owner to a stream of dividends $\{d_t\}$ governed by a Markov chain defined on a state space $S \in \{0, 1\}$.

The dividend obeys

$$d_t = \begin{cases} 0 & \text{if } s_t = 0 \\ 1 & \text{if } s_t = 1 \end{cases}$$

The owner of a share at the beginning of time t is entitled to the dividend paid at time t.

The owner of the share at the beginning of time t is also entitled to sell the share to another investor during time t.

Two types $h = a, b$ of investors differ only in their beliefs about a Markov transition matrix P with typical element

$$P(i, j) = \mathbb{P}\{s_{t+1} = j \mid s_t = i\}$$

Investors of type a believe the transition matrix

$$P_a = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{2}{3} & \frac{1}{3} \end{bmatrix}$$

Investors of type b think the transition matrix is

$$P_b = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} \\ \frac{1}{4} & \frac{3}{4} \end{bmatrix}$$

The stationary (i.e., invariant) distributions of these two matrices can be calculated as follows:

```
In [3]: using QuantEcon

        qa = [1/2 1/2; 2/3 1/3]
        qb = [2/3 1/3; 1/4 3/4]
        mcA = MarkovChain(qa)
        mcB = MarkovChain(qb)
        stA = stationary_distributions(mcA)
```

```
Out[3]: 1-element Array{Array{Float64,1},1}:
         [0.5714285714285715, 0.4285714285714286]
```

```
In [4]: stB = stationary_distributions(mcB)
```

```
Out[4]: 1-element Array{Array{Float64,1},1}:
         [0.42857142857142855, 0.5714285714285714]
```

The stationary distribution of P_a is approximately $\pi_A = \begin{bmatrix} .57 & .43 \end{bmatrix}$.

The stationary distribution of P_b is approximately $\pi_B = \begin{bmatrix} .43 & .57 \end{bmatrix}$.

49.3.1 Ownership Rights

An owner of the asset at the end of time t is entitled to the dividend at time $t+1$ and also has the right to sell the asset at time $t+1$.

Both types of investors are risk-neutral and both have the same fixed discount factor $\beta \in (0, 1)$.

In our numerical example, we'll set $\beta = .75$, just as Harrison and Kreps did.

We'll eventually study the consequences of two different assumptions about the number of shares A relative to the resources that our two types of investors can invest in the stock.

1. Both types of investors have enough resources (either wealth or the capacity to borrow) so that they can purchase the entire available stock of the asset Section **??**.
2. No single type of investor has sufficient resources to purchase the entire stock.

Case 1 is the case studied in Harrison and Kreps.

In case 2, both types of investor always hold at least some of the asset.

49.3.2 Short Sales Prohibited

No short sales are allowed.

This matters because it limits pessimists from expressing their opinions

- They can express their views by selling their shares.
- They cannot express their pessimism more loudly by artificially "manufacturing shares" – that is, they cannot borrow shares from more optimistic investors and sell them immediately.

49.3.3 Optimism and Pessimism

The above specifications of the perceived transition matrices P_a and P_b, taken directly from Harrison and Kreps, build in stochastically alternating temporary optimism and pessimism.

Remember that state 1 is the high dividend state.

- In state 0, a type a agent is more optimistic about next period's dividend than a type b agent.
- In state 1, a type b agent is more optimistic about next period's dividend.

However, the stationary distributions $\pi_A = \begin{bmatrix} .57 & .43 \end{bmatrix}$ and $\pi_B = \begin{bmatrix} .43 & .57 \end{bmatrix}$ tell us that a type B person is more optimistic about the dividend process in the long run than is a type A person.

Transition matrices for the temporarily optimistic and pessimistic investors are constructed as follows.

Temporarily optimistic investors (i.e., the investor with the most optimistic beliefs in each state) believe the transition matrix

$$P_o = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{4} & \frac{3}{4} \end{bmatrix}$$

Temporarily pessimistic believe the transition matrix

$$P_p = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{4} & \frac{3}{4} \end{bmatrix}$$

We'll return to these matrices and their significance in the exercise.

49.3.4 Information

Investors know a price function mapping the state s_t at t into the equilibrium price $p(s_t)$ that prevails in that state.

This price function is endogenous and to be determined below.

When investors choose whether to purchase or sell the asset at t, they also know s_t.

49.4 Solving the Model

Now let's turn to solving the model.

This amounts to determining equilibrium prices under the different possible specifications of beliefs and constraints listed above.

In particular, we compare equilibrium price functions under the following alternative assumptions about beliefs:

1. There is only one type of agent, either a or b.
2. There are two types of agent differentiated only by their beliefs. Each type of agent has sufficient resources to purchase all of the asset (Harrison and Kreps's setting).

3. There are two types of agent with different beliefs, but because of limited wealth and/or limited leverage, both types of investors hold the asset each period.

49.4.1 Summary Table

The following table gives a summary of the findings obtained in the remainder of the lecture (you will be asked to recreate the table in an exercise).

It records implications of Harrison and Kreps's specifications of P_a, P_b, β.

s_t	0	1
p_a	1.33	1.22
p_b	1.45	1.91
p_o	1.85	2.08
p_p	1	1
$\hat{p}_a$	1.85	1.69
$\hat{p}_b$	1.69	2.08

Here

- p_a is the equilibrium price function under homogeneous beliefs P_a
- p_b is the equilibrium price function under homogeneous beliefs P_b
- p_o is the equilibrium price function under heterogeneous beliefs with optimistic marginal investors
- p_p is the equilibrium price function under heterogeneous beliefs with pessimistic marginal investors
- $\hat{p}_a$ is the amount type a investors are willing to pay for the asset
- $\hat{p}_b$ is the amount type b investors are willing to pay for the asset

We'll explain these values and how they are calculated one row at a time.

49.4.2 Single Belief Prices

We'll start by pricing the asset under homogeneous beliefs.

(This is the case treated in the lecture on asset pricing with finite Markov states)

Suppose that there is only one type of investor, either of type a or b, and that this investor always "prices the asset".

Let $p_h = \begin{bmatrix} p_h(0) \\ p_h(1) \end{bmatrix}$ be the equilibrium price vector when all investors are of type h.

The price today equals the expected discounted value of tomorrow's dividend and tomorrow's price of the asset:

$$p_h(s) = \beta \left(P_h(s,0)(0 + p_h(0)) + P_h(s,1)(1 + p_h(1)) \right), \quad s = 0, 1$$

These equations imply that the equilibrium price vector is

$$\begin{bmatrix} p_h(0) \\ p_h(1) \end{bmatrix} = \beta [I - \beta P_h]^{-1} P_h \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{1}$$

The first two rows of of the table report $p_a(s)$ and $p_b(s)$.

Here's a function that can be used to compute these values

In [5]:
```
using LinearAlgebra

function price_single_beliefs(transition, dividend_payoff;
                              β=.75)
    # First compute inverse piece
    imbq_inv = inv(I - β * transition)

    # Next compute prices
    prices = β * ((imbq_inv * transition) * dividend_payoff)

    return prices
end
```

Out[5]:
```
price_single_beliefs (generic function with 1 method)
```

Single belief prices as benchmarks

These equilibrium prices under homogeneous beliefs are important benchmarks for the subsequent analysis.

- $p_h(s)$ tells what investor h thinks is the "fundamental value" of the asset.
- Here "fundamental value" means the expected discounted present value of future dividends.

We will compare these fundamental values of the asset with equilibrium values when traders have different beliefs.

49.4.3 Pricing under Heterogeneous Beliefs

There are several cases to consider.

The first is when both types of agent have sufficient wealth to purchase all of the asset themselves.

In this case the marginal investor who prices the asset is the more optimistic type, so that the equilibrium price $\bar{p}$ satisfies Harrison and Kreps's key equation:

$$\bar{p}(s) = \beta \max \left\{ P_a(s,0)\bar{p}(0) + P_a(s,1)(1+\bar{p}(1)),\ P_b(s,0)\bar{p}(0) + P_b(s,1)(1+\bar{p}(1)) \right\} \tag{2}$$

for $s = 0, 1$.

The marginal investor who prices the asset in state s is of type a if

$$P_a(s,0)\bar{p}(0) + P_a(s,1)(1+\bar{p}(1)) > P_b(s,0)\bar{p}(0) + P_b(s,1)(1+\bar{p}(1))$$

The marginal investor is of type b if

$$P_a(s,1)\bar{p}(0) + P_a(s,1)(1+\bar{p}(1)) < P_b(s,1)\bar{p}(0) + P_b(s,1)(1+\bar{p}(1))$$

Thus the marginal investor is the (temporarily) optimistic type.

Equation (2) is a functional equation that, like a Bellman equation, can be solved by

- starting with a guess for the price vector $\bar{p}$ and
- iterating to convergence on the operator that maps a guess $\bar{p}^j$ into an updated guess $\bar{p}^{j+1}$ defined by the right side of (2), namely

$$\bar{p}^{j+1}(s) = \beta \max \left\{ P_a(s,0)\bar{p}^j(0) + P_a(s,1)(1+\bar{p}^j(1)),\ P_b(s,0)\bar{p}^j(0) + P_b(s,1)(1+\bar{p}^j(1)) \right\} \quad (3)$$

for $s = 0, 1$.

The third row of the table reports equilibrium prices that solve the functional equation when $\beta = .75$.

Here the type that is optimistic about s_{t+1} prices the asset in state s_t.

It is instructive to compare these prices with the equilibrium prices for the homogeneous belief economies that solve under beliefs P_a and P_b.

Equilibrium prices $\bar{p}$ in the heterogeneous beliefs economy exceed what any prospective investor regards as the fundamental value of the asset in each possible state.

Nevertheless, the economy recurrently visits a state that makes each investor want to purchase the asset for more than he believes its future dividends are worth.

The reason is that he expects to have the option to sell the asset later to another investor who will value the asset more highly than he will.

- Investors of type a are willing to pay the following price for the asset

$$\hat{p}_a(s) = \begin{cases} \bar{p}(0) & \text{if } s_t = 0 \\ \beta(P_a(1,0)\bar{p}(0) + P_a(1,1)(1+\bar{p}(1))) & \text{if } s_t = 1 \end{cases}$$

- Investors of type b are willing to pay the following price for the asset

$$\hat{p}_b(s) = \begin{cases} \beta(P_b(0,0)\bar{p}(0) + P_b(0,1)(1+\bar{p}(1))) & \text{if } s_t = 0 \\ \bar{p}(1) & \text{if } s_t = 1 \end{cases}$$

Evidently, $\hat{p}_a(1) < \bar{p}(1)$ and $\hat{p}_b(0) < \bar{p}(0)$.

Investors of type a want to sell the asset in state 1 while investors of type b want to sell it in state 0.

- The asset changes hands whenever the state changes from 0 to 1 or from 1 to 0.
- The valuations $\hat{p}_a(s)$ and $\hat{p}_b(s)$ are displayed in the fourth and fifth rows of the table.
- Even the pessimistic investors who don't buy the asset think that it is worth more than they think future dividends are worth.

Here's code to solve for $\bar{p}$, $\hat{p}_a$ and $\hat{p}_b$ using the iterative method described above

```
In [6]: function price_optimistic_beliefs(transitions,
                                          dividend_payoff;
                                          β=.75, max_iter=50000,
                                          tol=1e-16)
```

```
    # We will guess an initial price vector of [0, 0]
    p_new = [0,0]
    p_old = [10.0,10.0]

    # We know this is a contraction mapping, so we can iterate to conv
    for i  1:max_iter
        p_old = p_new
        temp = [maximum((q * p_old) + (q * dividend_payoff))
                              for q in transitions]
        p_new = β * temp

        # If we succed in converging, break out of for loop
        if maximum(sqrt, ((p_new - p_old).^2)) < 1e-12
            break
        end
    end

   temp=[minimum((q * p_old) + (q * dividend_payoff)) for q in transitions]
    ptwiddle = β * temp

    phat_a = [p_new[1], ptwiddle[2]]
    phat_b = [ptwiddle[1], p_new[2]]

    return p_new, phat_a, phat_b
end
```

```
Out[6]: price_optimistic_beliefs (generic function with 1 method)
```

49.4.4 Insufficient Funds

Outcomes differ when the more optimistic type of investor has insufficient wealth — or insufficient ability to borrow enough — to hold the entire stock of the asset.

In this case, the asset price must adjust to attract pessimistic investors.

Instead of equation (2), the equilibrium price satisfies

$$\check{p}(s) = \beta \min \{P_a(s,1)\check{p}(0) + P_a(s,1)(1+\check{p}(1)),\ P_b(s,1)\check{p}(0) + P_b(s,1)(1+\check{p}(1))\} \tag{4}$$

and the marginal investor who prices the asset is always the one that values it *less* highly than does the other type.

Now the marginal investor is always the (temporarily) pessimistic type.

Notice from the sixth row of that the pessimistic price $\underline{p}$ is lower than the homogeneous belief prices p_a and p_b in both states.

When pessimistic investors price the asset according to (4), optimistic investors think that the asset is underpriced.

If they could, optimistic investors would willingly borrow at the one-period gross interest rate β^{-1} to purchase more of the asset.

Implicit constraints on leverage prohibit them from doing so.

When optimistic investors price the asset as in equation (2), pessimistic investors think that the asset is overpriced and would like to sell the asset short.

Constraints on short sales prevent that.

Here's code to solve for $\check{p}$ using iteration

```
In [7]: function price_pessimistic_beliefs(transitions,
                                           dividend_payoff;
                                           β=.75, max_iter=50000,
                                           tol=1e-16)
            # We will guess an initial price vector of [0, 0]
            p_new = [0, 0]
            p_old = [10.0, 10.0]

            # We know this is a contraction mapping, so we can iterate to conv
            for i  1:max_iter
                p_old = p_new
                temp=[minimum((q * p_old) + (q* dividend_payoff)) for q in
 ↪transitions]
                p_new = β * temp

                # If we succed in converging, break out of for loop
                if maximum(sqrt, ((p_new - p_old).^2)) < 1e-12
                    break
                end
            end

            return p_new
        end
```

```
Out[7]: price_pessimistic_beliefs (generic function with 1 method)
```

49.4.5 Further Interpretation

[96] interprets the Harrison-Kreps model as a model of a bubble — a situation in which an asset price exceeds what every investor thinks is merited by the asset's underlying dividend stream.

Scheinkman stresses these features of the Harrison-Kreps model:

- Compared to the homogeneous beliefs setting leading to the pricing formula, high volume occurs when the Harrison-Kreps pricing formula prevails.

Type a investors sell the entire stock of the asset to type b investors every time the state switches from $s_t = 0$ to $s_t = 1$.

Type b investors sell the asset to type a investors every time the state switches from $s_t = 1$ to $s_t = 0$.

Scheinkman takes this as a strength of the model because he observes high volume during *famous bubbles*.

- If the *supply* of the asset is increased sufficiently either physically (more "houses" are built) or artificially (ways are invented to short sell "houses"), bubbles end when the supply has grown enough to outstrip optimistic investors' resources for purchasing the asset.
- If optimistic investors finance purchases by borrowing, tightening leverage constraints can extinguish a bubble.

Scheinkman extracts insights about effects of financial regulations on bubbles.

He emphasizes how limiting short sales and limiting leverage have opposite effects.

49.5 Exercises

49.5.1 Exercise 1

Recreate the summary table using the functions we have built above.

s_t	0	1
p_a	1.33	1.22
p_b	1.45	1.91
p_o	1.85	2.08
p_p	1	1
$\hat{p}_a$	1.85	1.69
$\hat{p}_b$	1.69	2.08

You will first need to define the transition matrices and dividend payoff vector.

49.6 Solutions

49.6.1 Exercise 1

First we will obtain equilibrium price vectors with homogeneous beliefs, including when all investors are optimistic or pessimistic

```
In [8]: qa = [1/2 1/2; 2/3 1/3]     # Type a transition matrix
        qb = [2/3 1/3; 1/4 3/4]     # Type b transition matrix
        qopt = [1/2 1/2; 1/4 3/4]   # Optimistic investor transition matrix
        qpess = [2/3 1/3; 2/3 1/3]  # Pessimistic investor transition matrix

        dividendreturn = [0; 1]

        transitions = [qa, qb, qopt, qpess]
        labels = ["p_a", "p_b", "p_optimistic", "p_pessimistic"]

        for (transition, label) in zip(transitions, labels)
            println(label)
            println(repeat("=", 20))
            s0, s1 = round.(price_single_beliefs(transition, dividendreturn),
    ↪digits=2)
            println("State 0: $s0")
            println("State 1: $s1")
            println(repeat("-", 20))
        end
```

```
    p_a
====================
State 0: 1.33
```

```
State 1: 1.22
--------------------
p_b
====================
State 0: 1.45
State 1: 1.91
--------------------
p_optimistic
====================
State 0: 1.85
State 1: 2.08
--------------------
p_pessimistic
====================
State 0: 1.0
State 1: 1.0
--------------------
```

We will use the price_optimistic_beliefs function to find the price under heterogeneous beliefs.

```
In [9]: opt_beliefs = price_optimistic_beliefs([qa, qb], dividendreturn)
        labels = ["p_optimistic", "p_hat_a", "p_hat_b"]

        for (p, label)  zip(opt_beliefs, labels)
            println(label)
            println(repeat("=", 20))
            s0, s1 = round.(p, digits = 2)
            println("State 0: $s0")
            println("State 1: $s1")
            println(repeat("-", 20))
        end
```

```
   p_optimistic
====================
State 0: 1.85
State 1: 2.08
--------------------
p_hat_a
====================
State 0: 1.85
State 1: 1.69
--------------------
p_hat_b
====================
State 0: 1.69
State 1: 2.08
--------------------
```

Notice that the equilibrium price with heterogeneous beliefs is equal to the price under single beliefs with optimistic investors - this is due to the marginal investor being the temporarily optimistic type.

Footnotes

[1] By assuming that both types of agent always have "deep enough pockets" to purchase all of the asset, the model takes wealth dynamics off the table. The Harrison-Kreps model generates high trading volume when the state changes either from 0 to 1 or from 1 to 0.

Chapter 50

Uncertainty Traps

50.1 Contents

50.2 Overview

In this lecture we study a simplified version of an uncertainty traps model of Fajgelbaum, Schaal and Taschereau-Dumouchel [30].

The model features self-reinforcing uncertainty that has big impacts on economic activity.

In the model,

- Fundamentals vary stochastically and are not fully observable.
- At any moment there are both active and inactive entrepreneurs; only active entrepreneurs produce.
- Agents – active and inactive entrepreuneurs – have beliefs about the fundamentals expressed as probability distributions.
- Greater uncertainty means greater dispersions of these distributions.
- Entrepreneurs are risk averse and hence less inclined to be active when uncertainty is high.
- The output of active entrepreneurs is observable, supplying a noisy signal that helps everyone inside the model infer fundamentals.
- Entrepreneurs update their beliefs about fundamentals using Bayes' Law, implemented via Kalman filtering.

Uncertainty traps emerge because:

- High uncertainty discourages entrepreneurs from becoming active.
- A low level of participation – i.e., a smaller number of active entrepreneurs – diminishes the flow of information about fundamentals.

- Less information translates to higher uncertainty, further discouraging entrepreneurs from choosing to be active, and so on.

Uncertainty traps stem from a positive externality: high aggregate economic activity levels generates valuable information.

50.3 The Model

The original model described in [30] has many interesting moving parts.

Here we examine a simplified version that nonetheless captures many of the key ideas.

50.3.1 Fundamentals

The evolution of the fundamental process $\{\theta_t\}$ is given by

$$\theta_{t+1} = \rho\theta_t + \sigma_\theta w_{t+1}$$

where

- $\sigma_\theta > 0$ and $0 < \rho < 1$
- $\{w_t\}$ is IID and standard normal

The random variable θ_t is not observable at any time.

50.3.2 Output

There is a total $\bar{M}$ of risk averse entrepreneurs.

Output of the m-th entrepreneur, conditional on being active in the market at time t, is equal to

$$x_m = \theta + \epsilon_m \quad \text{where} \quad \epsilon_m \sim N\left(0, \gamma_x^{-1}\right) \tag{1}$$

Here the time subscript has been dropped to simplify notation.

The inverse of the shock variance, γ_x, is called the shock's **precision**.

The higher is the precision, the more informative x_m is about the fundamental.

Output shocks are independent across time and firms.

50.3.3 Information and Beliefs

All entrepreneurs start with identical beliefs about θ_0.

Signals are publicly observable and hence all agents have identical beliefs always.

Dropping time subscripts, beliefs for current θ are represented by the normal distribution $N(\mu, \gamma^{-1})$.

Here γ is the precision of beliefs; its inverse is the degree of uncertainty.

These parameters are updated by Kalman filtering.

Let

- $\mathbb{M} \subset \{1, \ldots, \bar{M}\}$ denote the set of currently active firms
- $M := |\mathbb{M}|$ denote the number of currently active firms
- X be the average output $\frac{1}{M} \sum_{m \in \mathbb{M}} x_m$ of the active firms

With this notation and primes for next period values, we can write the updating of the mean and precision via

$$\mu' = \rho \frac{\gamma \mu + M \gamma_x X}{\gamma + M \gamma_x} \tag{2}$$

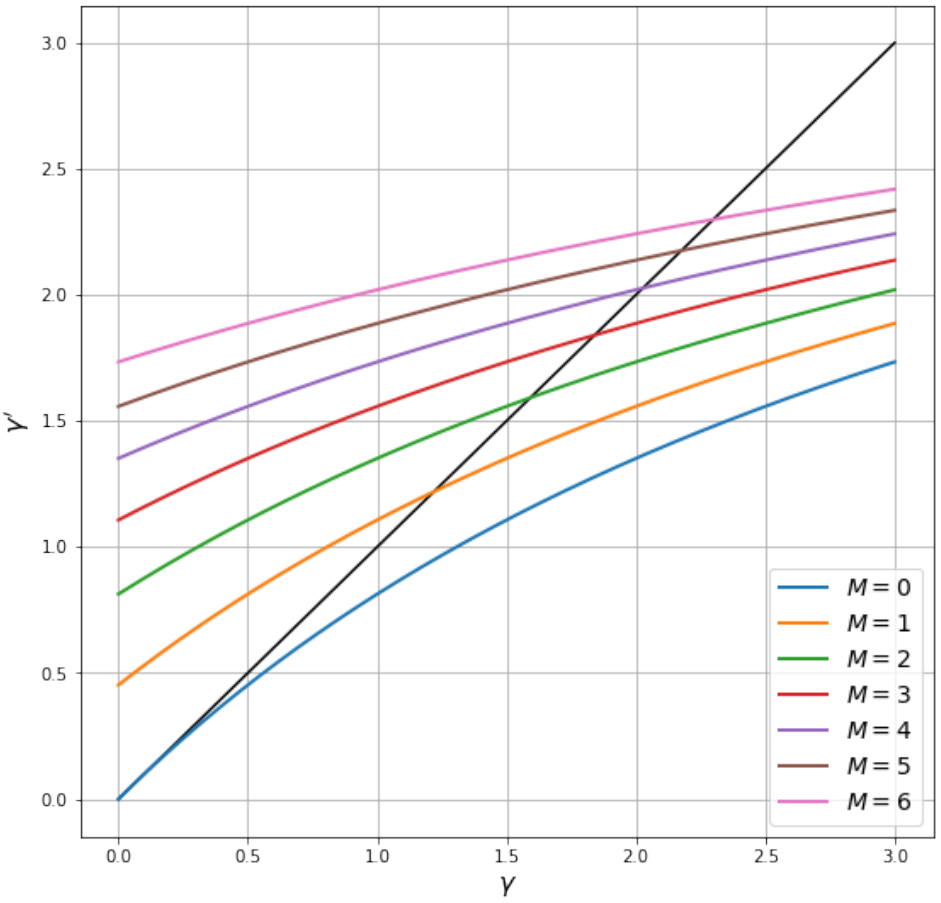
$$\gamma' = \left(\frac{\rho^2}{\gamma + M \gamma_x} + \sigma_\theta^2 \right)^{-1} \tag{3}$$

These are standard Kalman filtering results applied to the current setting.

Exercise 1 provides more details on how (2) and (3) are derived, and then asks you to fill in remaining steps.

The next figure plots the law of motion for the precision in (3) as a 45 degree diagram, with one curve for each $M \in \{0, \ldots, 6\}$.

The other parameter values are $\rho = 0.99, \gamma_x = 0.5, \sigma_\theta = 0.5$



Points where the curves hit the 45 degree lines are long run steady states for precision for dif-

ferent values of M.

Thus, if one of these values for M remains fixed, a corresponding steady state is the equilibrium level of precision

- high values of M correspond to greater information about the fundamental, and hence more precision in steady state
- low values of M correspond to less information and more uncertainty in steady state

In practice, as we'll see, the number of active firms fluctuates stochastically.

50.3.4 Participation

Omitting time subscripts once more, entrepreneurs enter the market in the current period if

$$\mathbb{E}[u(x_m - F_m)] > c \tag{4}$$

Here

- the mathematical expectation of x_m is based on (1) and beliefs $N(\mu, \gamma^{-1})$ for θ
- F_m is a stochastic but previsible fixed cost, independent across time and firms
- c is a constant reflecting opportunity costs

The statement that F_m is previsible means that it is realized at the start of the period and treated as a constant in (4).

The utility function has the constant absolute risk aversion form

$$u(x) = \frac{1}{a}\left(1 - \exp(-ax)\right) \tag{5}$$

where a is a positive parameter.

Combining (4) and (5), entrepreneur m participates in the market (or is said to be active) when

$$\frac{1}{a}\left\{1 - \mathbb{E}[\exp\left(-a(\theta + \epsilon_m - F_m)\right)]\right\} > c$$

Using standard formulas for expectations of lognormal random variables, this is equivalent to the condition

$$\psi(\mu, \gamma, F_m) := \frac{1}{a}\left(1 - \exp\left(-a\mu + aF_m + \frac{a^2\left(\frac{1}{\gamma} + \frac{1}{\gamma_x}\right)}{2}\right)\right) - c > 0 \tag{6}$$

50.4 Implementation

We want to simulate this economy.

We'll want a named tuple generator of the kind that we've seen before.

And we need methods to update θ, μ and γ, as well as to determine the number of active firms and their outputs.

The updating methods follow the laws of motion for θ, μ and γ given above.

The method to evaluate the number of active firms generates $F_1, \ldots, F_{\bar{M}}$ and tests condition (6) for each firm.

50.4.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using DataFrames, Parameters, Plots
        gr(fmt = :png);
```

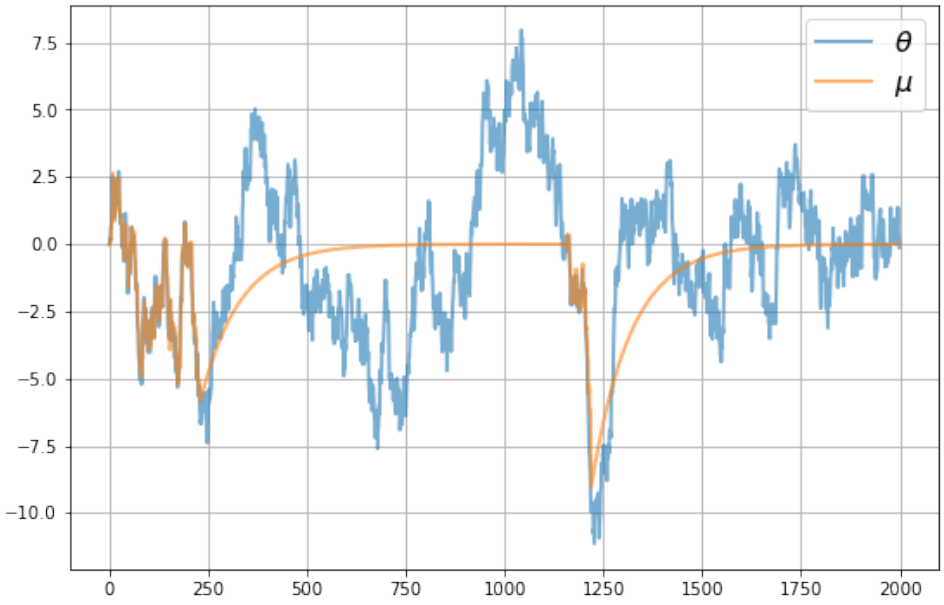
```
In [3]: UncertaintyTrapEcon = @with_kw (a = 1.5, # risk aversion
                                       γ_x = 0.5, # production shock precision
                                       ρ = 0.99, # correlation coefficient for ϑ
                                       σ_θ = 0.5, # standard dev. of ϑ shock
                                       num_firms = 100, # number of firms
                                       σ_F = 1.5, # standard dev. of fixed costs
                                       c = -420.0, # external opportunity cost
                                       μ_init = 0.0, # initial value for μ
                                       γ_init = 4.0, # initial value for γ
                                       θ_init = 0.0, # initial value for ϑ
                                      σ_x = sqrt(a / γ_x)) # standard dev. of shock
```

```
Out[3]: ##NamedTuple_kw#253 (generic function with 2 methods)
```

In the results below we use this code to simulate time series for the major variables.

50.5 Results

Let's look first at the dynamics of μ, which the agents use to track θ



We see that μ tracks θ well when there are sufficient firms in the market.

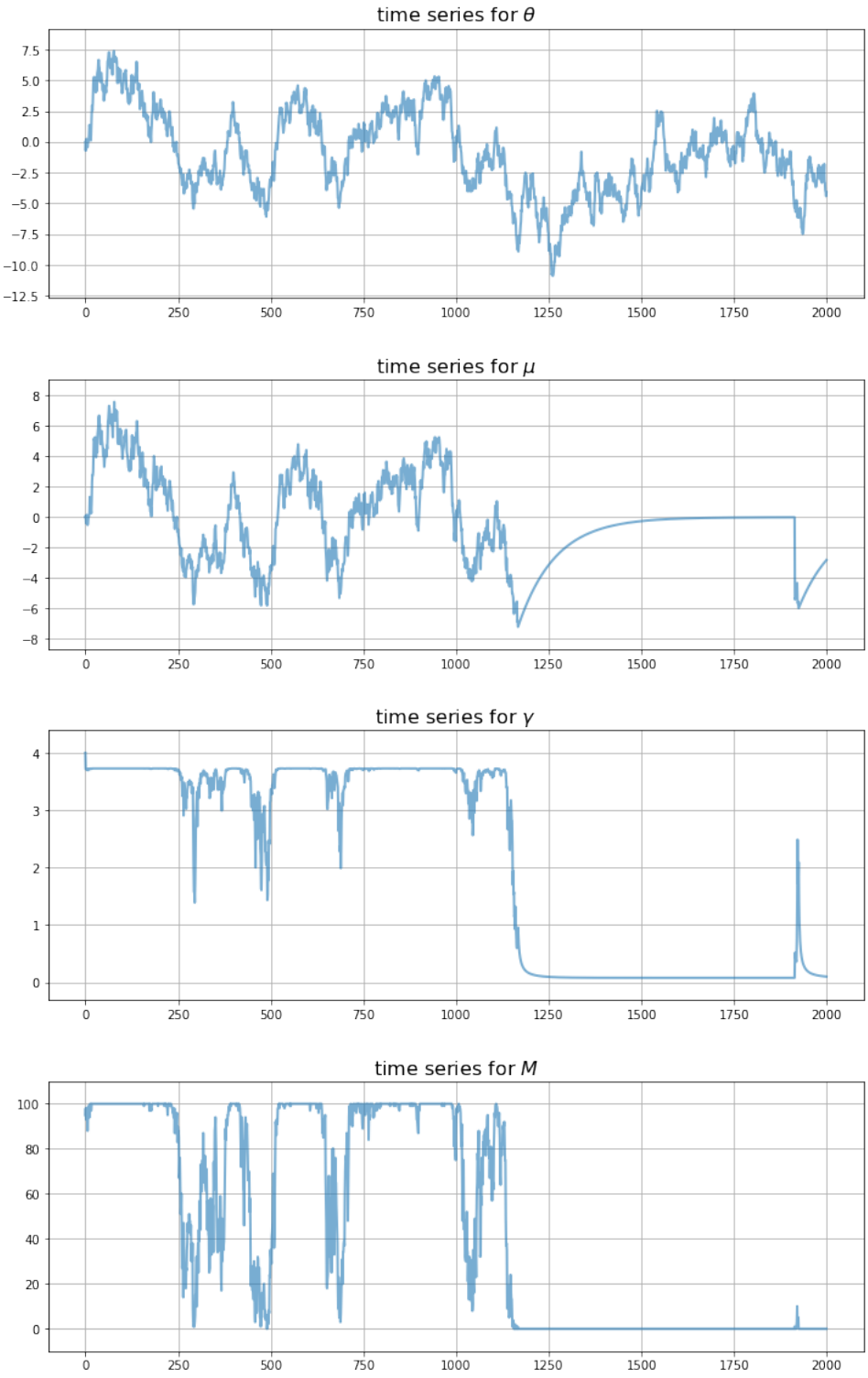
However, there are times when μ tracks θ poorly due to insufficient information.

These are episodes where the uncertainty traps take hold.

During these episodes

- precision is low and uncertainty is high
- few firms are in the market

To get a clearer idea of the dynamics, let's look at all the main time series at once, for a given set of shocks



Notice how the traps only take hold after a sequence of bad draws for the fundamental.

Thus, the model gives us a *propagation mechanism* that maps bad random draws into long downturns in economic activity.

50.6 Exercises

50.6.1 Exercise 1

Fill in the details behind (2) and (3) based on the following standard result (see, e.g., p. 24 of [109]).

Fact Let $\mathbf{x} = (x_1, \ldots, x_M)$ be a vector of IID draws from common distribution $N(\theta, 1/\gamma_x)$ and let $\bar{x}$ be the sample mean. If γ_x is known and the prior for θ is $N(\mu, 1/\gamma)$, then the posterior distribution of θ given $\mathbf{x}$ is

$$\pi(\theta \,|\, \mathbf{x}) = N(\mu_0, 1/\gamma_0)$$

where

$$\mu_0 = \frac{\mu\gamma + M\bar{x}\gamma_x}{\gamma + M\gamma_x} \quad \text{and} \quad \gamma_0 = \gamma + M\gamma_x$$

50.6.2 Exercise 2

Modulo randomness, replicate the simulation figures shown above

- Use the parameter values listed as defaults in the function UncertaintyTrapEcon.

50.7 Solutions

50.7.1 Exercise 1

This exercise asked you to validate the laws of motion for γ and μ given in the lecture, based on the stated result about Bayesian updating in a scalar Gaussian setting.

The stated result tells us that after observing average output X of the M firms, our posterior beliefs will be

$$N(\mu_0, 1/\gamma_0)$$

where

$$\mu_0 = \frac{\mu\gamma + MX\gamma_x}{\gamma + M\gamma_x} \quad \text{and} \quad \gamma_0 = \gamma + M\gamma_x$$

If we take a random variable θ with this distribution and then evaluate the distribution of $\rho\theta + \sigma_\theta w$ where w is independent and standard normal, we get the expressions for μ' and γ' given in the lecture.

50.8 Exercise 2

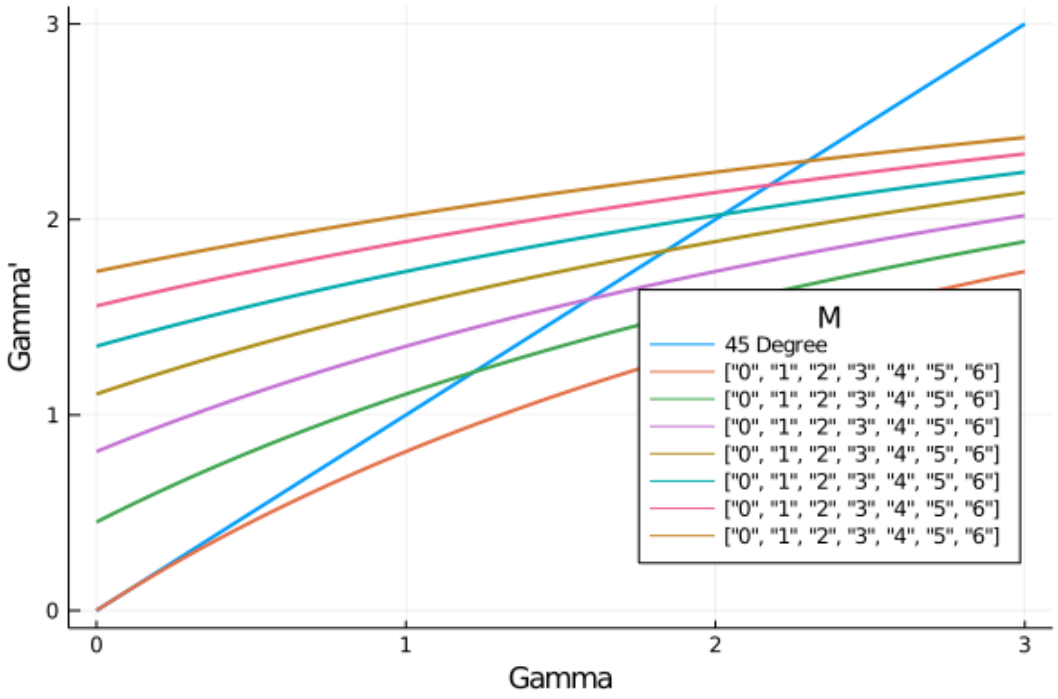
First let's replicate the plot that illustrates the law of motion for precision, which is

$$\gamma_{t+1} = \left(\frac{\rho^2}{\gamma_t + M\gamma_x} + \sigma_\theta^2 \right)^{-1}$$

Here M is the number of active firms. The next figure plots γ_{t+1} against γ_t on a 45 degree diagram for different values of M

In [4]:
```
econ = UncertaintyTrapEcon()
@unpack ρ, σ_θ, γ_x = econ # simplify names

# grid for γ and γ_{t+1}
γ = range(1e-10, 3, length = 200)
M_range = 0:6
γp = 1 ./ (ρ^2 ./ (γ .+ γ_x .* M_range') .+ σ_θ^2)

labels = ["0", "1", "2", "3", "4", "5", "6"]

plot(γ, γ, lw = 2, label = "45 Degree")
plot!(γ, γp, lw = 2, label = labels)
plot!(xlabel = "Gamma", ylabel = "Gamma'", legend_title = "M", legend = :
↪bottomright)
```

Out[4]:



The points where the curves hit the 45 degree lines are the long run steady states corresponding to each M, if that value of M was to remain fixed. As the number of firms falls, so does the long run steady state of precision.

Next let's generate time series for beliefs and the aggregates – that is, the number of active firms and average output

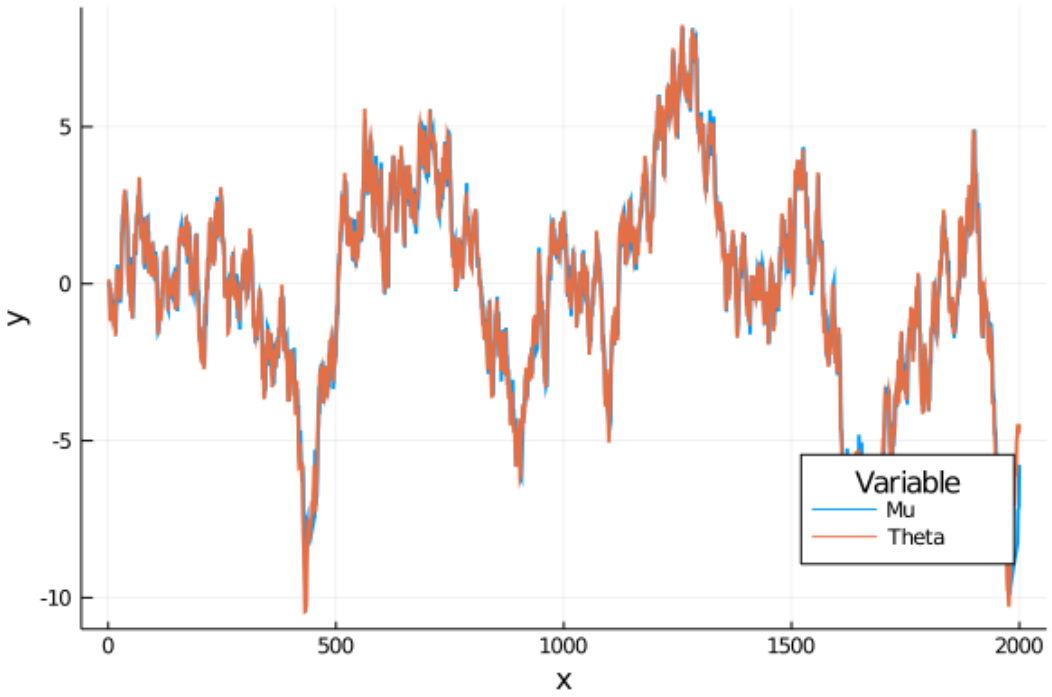
In [5]:
```
function simulate(uc, capT = 2_000)
    # unpack parameters
    @unpack a, γ_x, ρ, σ_θ, num_firms, σ_F, c, μ_init, γ_init, θ_init, σ_x = uc

    # draw standard normal shocks
    w_shocks = randn(capT)

    # aggregate functions
    # auxiliary function ψ
    function ψ(γ, μ, F)
        temp1 = -a * (μ - F)
        temp2 = 0.5 * a^2 / (γ + γ_x)
        return (1 - exp(temp1 + temp2)) / a - c
    end

    # compute X, M
    function gen_aggregates(γ, μ, θ)
        F_vals = σ_F * randn(num_firms)
        M = sum(ψ.(Ref(γ), Ref(μ), F_vals) .> 0) # counts number of active firms
        if any(ψ(γ, μ, f) > 0 for f in F_vals) #  an active firm
            x_vals = θ .+ σ_x * randn(M)
            X = mean(x_vals)
        else
            X = 0.0
        end
        return (X = X, M = M)
    end

    # initialize dataframe
    X_init, M_init = gen_aggregates(γ_init, μ_init, θ_init)
    df = DataFrame(γ = γ_init, μ = μ_init, θ = θ_init, X = X_init, M = M_init)

    # update dataframe
    for t in 2:capT
        # unpack old variables
        θ_old, γ_old, μ_old, X_old, M_old = (df.θ[end], df.γ[end], df.μ[end], df.X[end],
                                             df.M[end])

        # define new beliefs
        θ = ρ * θ_old + σ_θ * w_shocks[t-1]
        μ = (ρ * (γ_old * μ_old + M_old * γ_x * X_old))/(γ_old + M_old * γ_x)
        γ = 1 / (ρ^2 / (γ_old + M_old * γ_x) + σ_θ^2)

        # compute new aggregates
        X, M = gen_aggregates(γ, μ, θ)
        push!(df, (γ = γ, μ = μ, θ = θ, X = X, M = M))
    end

    # return
    return df
end
```

Out[5]:
```
simulate (generic function with 2 methods)
```

First let's see how well μ tracks θ in these simulations

In [6]:
```
df = simulate(econ)

plot(eachindex(df.μ), df.μ, lw = 2, label = "Mu")
plot!(eachindex(df.θ), df.θ, lw = 2, label = "Theta")
plot!(xlabel = "x", ylabel = "y", legend_title = "Variable", legend = :
↪bottomright)
```

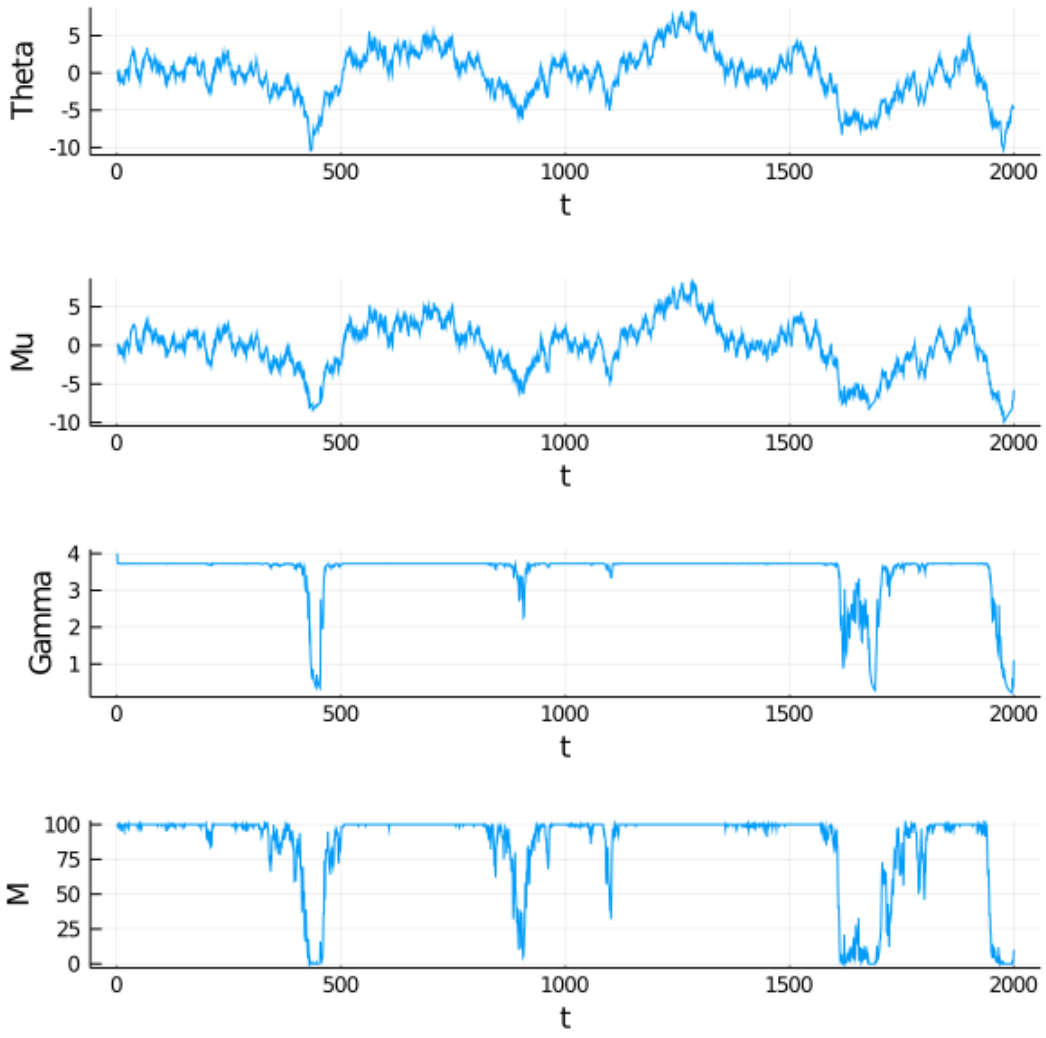
Out[6]:



Now let's plot the whole thing together

In [7]:
```
len = eachindex(df.θ)
yvals = [df.θ, df.μ, df.γ, df.M]
vars = ["Theta", "Mu", "Gamma", "M"]

plt = plot(layout = (4,1), size = (600, 600))

for i in 1:4
    plot!(plt[i], len, yvals[i], xlabel = "t", ylabel = vars[i], label = "")
end

plot(plt)
```

Out[7]:


Theta
5
0
-5
-10
0
500
1000
1500
2000
t
Mu
5
0
-5
-10
0
500
1000
1500
2000
t
Gamma
4
3
2
1
0
500
1000
1500
2000
t
M
100
75
50
25
0
0
500
1000
1500
2000
t

Chapter 51

The Aiyagari Model

51.1 Contents

51.2 Overview

In this lecture we describe the structure of a class of models that build on work by Truman Bewley [12].

We begin by discussing an example of a Bewley model due to Rao Aiyagari.

The model features

- Heterogeneous agents.
- A single exogenous vehicle for borrowing and lending.
- Limits on amounts individual agents may borrow.

The Aiyagari model has been used to investigate many topics, including

- precautionary savings and the effect of liquidity constraints [1]
- risk sharing and asset pricing [50]
- the shape of the wealth distribution [9]
- etc., etc., etc.

51.2.1 References

The primary reference for this lecture is [1].

A textbook treatment is available in chapter 18 of [68].

A continuous time version of the model by SeHyoun Ahn and Benjamin Moll can be found here.

51.3 The Economy

51.3.1 Households

Infinitely lived households / consumers face idiosyncratic income shocks.

A unit interval of *ex ante* identical households face a common borrowing constraint.

The savings problem faced by a typical household is

$$\max \mathbb{E} \sum_{t=0}^{\infty} \beta^t u(c_t)$$

subject to

$$a_{t+1} + c_t \leq w z_t + (1+r) a_t \quad c_t \geq 0, \quad \text{and} \quad a_t \geq -B$$

where

- c_t is current consumption
- a_t is assets
- z_t is an exogenous component of labor income capturing stochastic unemployment risk, etc.
- w is a wage rate
- r is a net interest rate
- B is the maximum amount that the agent is allowed to borrow

The exogenous process $\{z_t\}$ follows a finite state Markov chain with given stochastic matrix P.

The wage and interest rate are fixed over time.

In this simple version of the model, households supply labor inelastically because they do not value leisure.

51.4 Firms

Firms produce output by hiring capital and labor.

Firms act competitively and face constant returns to scale.

Since returns to scale are constant the number of firms does not matter.

Hence we can consider a single (but nonetheless competitive) representative firm.

The firm's output is

$$Y_t = A K_t^{\alpha} N^{1-\alpha}$$

where

- A and α are parameters with $A > 0$ and $\alpha \in (0, 1)$
- K_t is aggregate capital
- N is total labor supply (which is constant in this simple version of the model)

The firm's problem is

$$max_{K,N} \{AK_t^\alpha N^{1-\alpha} - (r+\delta)K - wN\}$$

The parameter δ is the depreciation rate.

From the first-order condition with respect to capital, the firm's inverse demand for capital is

$$r = A\alpha \left(\frac{N}{K}\right)^{1-\alpha} - \delta \tag{1}$$

Using this expression and the firm's first-order condition for labor, we can pin down the equilibrium wage rate as a function of r as

$$w(r) = A(1-\alpha)(A\alpha/(r+\delta))^{\alpha/(1-\alpha)} \tag{2}$$

51.4.1 Equilibrium

We construct a *stationary rational expectations equilibrium* (SREE).

In such an equilibrium

- prices induce behavior that generates aggregate quantities consistent with the prices
- aggregate quantities and prices are constant over time

In more detail, an SREE lists a set of prices, savings and production policies such that

- households want to choose the specified savings policies taking the prices as given
- firms maximize profits taking the same prices as given
- the resulting aggregate quantities are consistent with the prices; in particular, the demand for capital equals the supply
- aggregate quantities (defined as cross-sectional averages) are constant

In practice, once parameter values are set, we can check for an SREE by the following steps

1. pick a proposed quantity K for aggregate capital
2. determine corresponding prices, with interest rate r determined by (1) and a wage rate $w(r)$ as given in (2)
3. determine the common optimal savings policy of the households given these prices
4. compute aggregate capital as the mean of steady state capital given this savings policy

If this final quantity agrees with K then we have a SREE.

51.5 Code

Let's look at how we might compute such an equilibrium in practice.

To solve the household's dynamic programming problem we'll use the DiscreteDP type from QuantEcon.jl.

Our first task is the least exciting one: write code that maps parameters for a household problem into the `R` and `Q` matrices needed to generate an instance of `DiscreteDP`.

Below is a piece of boilerplate code that does just this.

In reading the code, the following information will be helpful

- `R` needs to be a matrix where `R[s, a]` is the reward at state `s` under action `a`.
- `Q` needs to be a three dimensional array where `Q[s, a, s']` is the probability of transitioning to state `s'` when the current state is `s` and the current action is `a`.

(For a detailed discussion of `DiscreteDP` see this lecture)

Here we take the state to be $s_t := (a_t, z_t)$, where a_t is assets and z_t is the shock.

The action is the choice of next period asset level a_{t+1}.

The object also includes a default set of parameters that we'll adopt unless otherwise specified.

51.5.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

```
In [3]: using Parameters, Plots, QuantEcon
        gr(fmt = :png);
```

```
In [4]: Household = @with_kw (r = 0.01,
                              w = 1.0,
                              σ = 1.0,
                              β = 0.96,
                             z_chain = MarkovChain([0.9 0.1; 0.1 0.9], [0.1; 1.0]),
                              a_min = 1e-10,
                              a_max = 18.0,
                              a_size = 200,
                              a_vals = range(a_min, a_max, length = a_size),
                              z_size = length(z_chain.state_values),
                              n = a_size * z_size,
                              s_vals = gridmake(a_vals, z_chain.state_values),
                              s_i_vals = gridmake(1:a_size, 1:z_size),
                           u = σ == 1 ? x -> log(x) : x -> (x^(1 - σ) - 1) / (1 - σ),
                              R = setup_R!(fill(-Inf, n, a_size), a_vals, s_vals,
        r, w, u),
                              # -Inf is the utility of dying (0 consumption)
                             Q = setup_Q!(zeros(n, a_size, n), s_i_vals, z_chain))

        function setup_Q!(Q, s_i_vals, z_chain)
            for next_s_i in 1:size(Q, 3)
                for a_i in 1:size(Q, 2)
                    for s_i in 1:size(Q, 1)
                        z_i = s_i_vals[s_i, 2]
                        next_z_i = s_i_vals[next_s_i, 2]
```

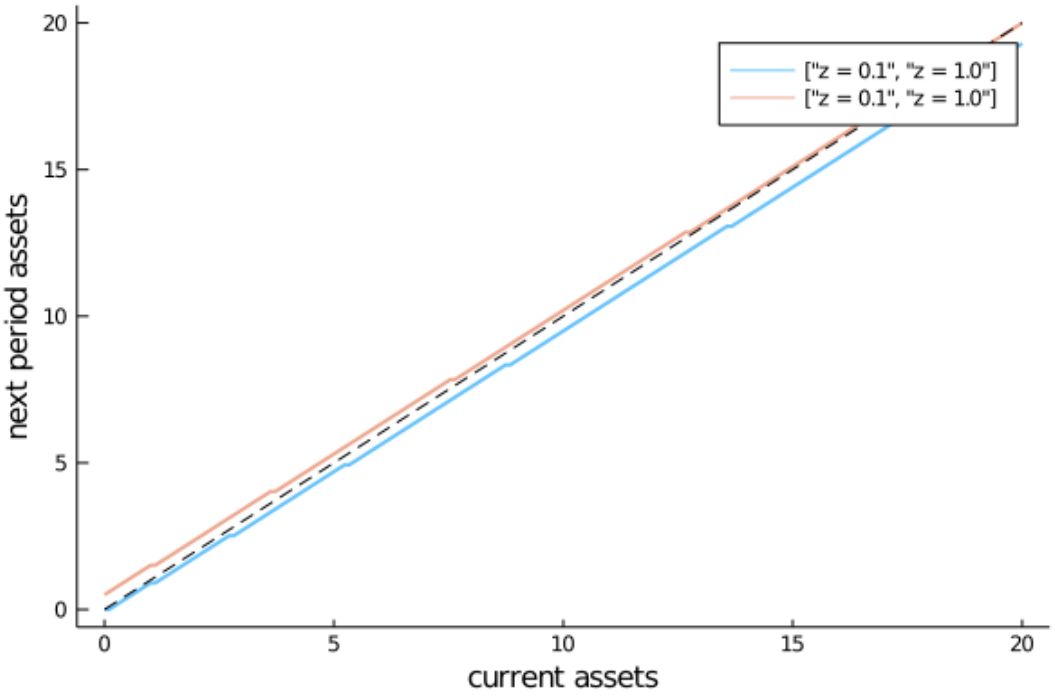
```
                    next_a_i = s_i_vals[next_s_i, 1]
                    if next_a_i == a_i
                        Q[s_i, a_i, next_s_i] = z_chain.p[z_i, next_z_i]
                    end
                end
            end
        end
        return Q
    end

    function setup_R!(R, a_vals, s_vals, r, w, u)
        for new_a_i in 1:size(R, 2)
            a_new = a_vals[new_a_i]
            for s_i in 1:size(R, 1)
                a = s_vals[s_i, 1]
                z = s_vals[s_i, 2]
                c = w * z + (1 + r) * a - a_new
                if c > 0
                    R[s_i, new_a_i] = u(c)
                end
            end
        end
        return R
    end
```

Out[4]: setup_R! (generic function with 1 method)

As a first example of what we can do, let's compute and plot an optimal accumulation policy at fixed prices

In [5]:
```
# Create an instance of Household
am = Household(a_max = 20.0, r = 0.03, w = 0.956)

# Use the instance to build a discrete dynamic program
am_ddp = DiscreteDP(am.R, am.Q, am.β)

# Solve using policy function iteration
results = solve(am_ddp, PFI)

# Simplify names
@unpack z_size, a_size, n, a_vals = am
z_vals = am.z_chain.state_values

# Get all optimal actions across the set of
# a indices with z fixed in each column
a_star = reshape([a_vals[results.sigma[s_i]] for s_i in 1:n], a_size,
↪z_size)

labels = ["z = $(z_vals[1])", "z = $(z_vals[2])"]
plot(a_vals, a_star, label = labels, lw = 2, alpha = 0.6)
plot!(a_vals, a_vals, label = "", color = :black, linestyle = :dash)
plot!(xlabel = "current assets", ylabel = "next period assets", grid =
↪false)
```

Out[5]:



The plot shows asset accumulation policies at different values of the exogenous state.

Now we want to calculate the equilibrium.

Let's do this visually as a first pass.

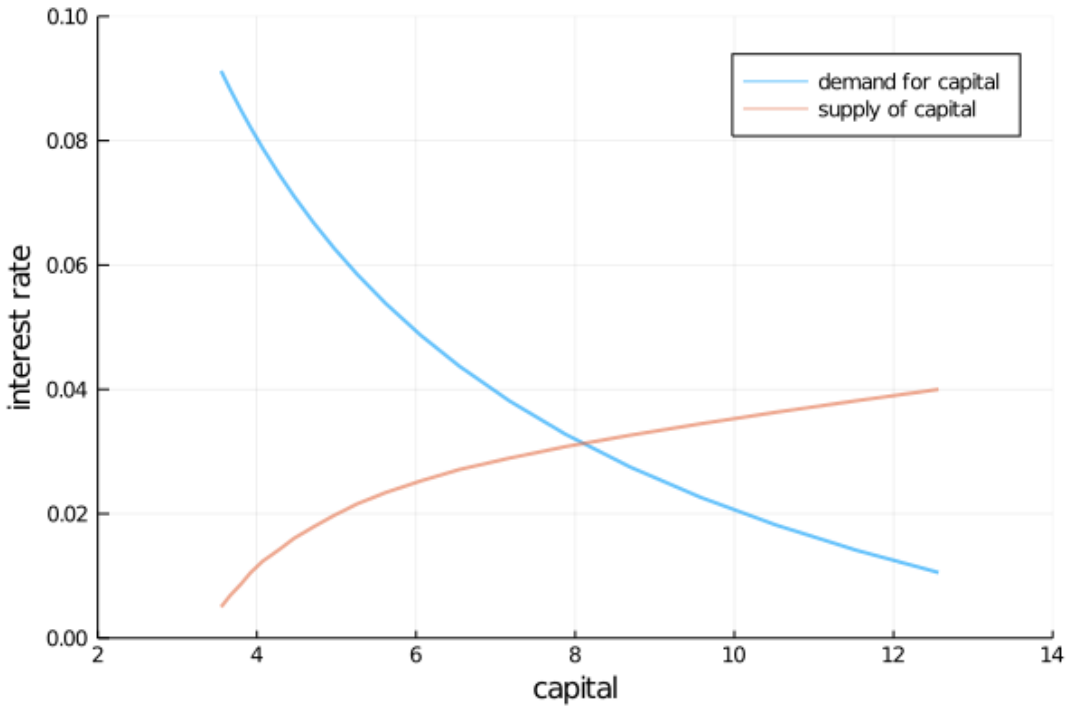
The following code draws aggregate supply and demand curves.

The intersection gives equilibrium interest rates and capital

```
In [6]: # Firms' parameters
        const A = 1
        const N = 1
        const α = 0.33
        const β = 0.96
        const δ = 0.05

        function r_to_w(r)
            return A * (1 - α) * (A * α / (r + δ)) ^ (α / (1 - α))
        end

        function rd(K)
            return A * α * (N / K) ^ (1 - α) - δ
        end

        function prices_to_capital_stock(am, r)

            # Set up problem
            w = r_to_w(r)
            @unpack a_vals, s_vals, u = am
            setup_R!(am.R, a_vals, s_vals, r, w, u)

            aiyagari_ddp = DiscreteDP(am.R, am.Q, am.β)

            # Compute the optimal policy
```

```
    results = solve(aiyagari_ddp, PFI)

    # Compute the stationary distribution
    stationary_probs = stationary_distributions(results.mc)[:, 1][1]

    # Return K
    return dot(am.s_vals[:, 1], stationary_probs)
end

# Create an instance of Household
am = Household(β = β, a_max = 20.0)

# Create a grid of r values at which to compute demand and supply of capital
r_vals = range(0.005, 0.04, length = 20)

# Compute supply of capital
k_vals = prices_to_capital_stock.(Ref(am), r_vals)

# Plot against demand for capital by firms
demand = rd.(k_vals)
labels =  ["demand for capital" "supply of capital"]
plot(k_vals, [demand r_vals], label = labels, lw = 2, alpha = 0.6)
plot!(xlabel = "capital", ylabel = "interest rate", xlim = (2, 14), ylim =
↪(0.0, 0.1))
```

Out[6]:



Chapter 52

Default Risk and Income Fluctuations

52.1 Contents

52.2 Overview

This lecture computes versions of Arellano's [5] model of sovereign default.

The model describes interactions among default risk, output, and an equilibrium interest rate that includes a premium for endogenous default risk.

The decision maker is a government of a small open economy that borrows from risk-neutral foreign creditors.

The foreign lenders must be compensated for default risk.

The government borrows and lends abroad in order to smooth the consumption of its citizens.

The government repays its debt only if it wants to, but declining to pay has adverse consequences.

The interest rate on government debt adjusts in response to the state-dependent default probability chosen by government.

The model yields outcomes that help interpret sovereign default experiences, including

- countercyclical interest rates on sovereign debt
- countercyclical trade balances
- high volatility of consumption relative to output

Notably, long recessions caused by bad draws in the income process increase the government's

incentive to default.

This can lead to

- spikes in interest rates
- temporary losses of access to international credit markets
- large drops in output, consumption, and welfare
- large capital outflows during recessions

Such dynamics are consistent with experiences of many countries.

52.3 Structure

In this section we describe the main features of the model.

52.3.1 Output, Consumption and Debt

A small open economy is endowed with an exogenous stochastically fluctuating potential output stream $\{y_t\}$.

Potential output is realized only in periods in which the government honors its sovereign debt.

The output good can be traded or consumed.

The sequence $\{y_t\}$ is described by a Markov process with stochastic density kernel $p(y, y')$.

Households within the country are identical and rank stochastic consumption streams according to

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t u(c_t) \tag{1}$$

Here

- $0 < \beta < 1$ is a time discount factor.
- u is an increasing and strictly concave utility function.

Consumption sequences enjoyed by households are affected by the government's decision to borrow or lend internationally.

The government is benevolent in the sense that its aim is to maximize (1).

The government is the only domestic actor with access to foreign credit.

Because household are averse to consumption fluctuations, the government will try to smooth consumption by borrowing from (and lending to) foreign creditors.

52.3.2 Asset Markets

The only credit instrument available to the government is a one-period bond traded in international credit markets.

The bond market has the following features

- The bond matures in one period and is not state contingent.

- A purchase of a bond with face value B' is a claim to B' units of the consumption good next period.
- To purchase B' next period costs qB' now, or, what is equivalent.
- For selling $-B'$ units of next period goods the seller earns $-qB'$ of today's goods
  - if $B' < 0$, then $-qB'$ units of the good are received in the current period, for a promise to repay $-B'$ units next period
  - there is an equilibrium price function $q(B', y)$ that makes q depend on both B' and y

Earnings on the government portfolio are distributed (or, if negative, taxed) lump sum to households.

When the government is not excluded from financial markets, the one-period national budget constraint is

$$c = y + B - q(B', y)B' \tag{2}$$

Here and below, a prime denotes a next period value or a claim maturing next period.

To rule out Ponzi schemes, we also require that $B \geq -Z$ in every period.

- Z is chosen to be sufficiently large that the constraint never binds in equilibrium.

52.3.3 Financial Markets

Foreign creditors

- are risk neutral
- know the domestic output stochastic process $\{y_t\}$ and observe $y_t, y_{t-1}, \ldots$, at time t
- can borrow or lend without limit in an international credit market at a constant international interest rate r
- receive full payment if the government chooses to pay
- receive zero if the government defaults on its one-period debt due

When a government is expected to default next period with probability δ, the expected value of a promise to pay one unit of consumption next period is $1 - \delta$.

Therefore, the discounted expected value of a promise to pay B next period is

$$q = \frac{1 - \delta}{1 + r} \tag{3}$$

Next we turn to how the government in effect chooses the default probability δ.

52.3.4 Government's decisions

At each point in time t, the government chooses between

1. defaulting

2. meeting its current obligations and purchasing or selling an optimal quantity of one-period sovereign debt

Defaulting means declining to repay all of its current obligations.

If the government defaults in the current period, then consumption equals current output.

But a sovereign default has two consequences:

1. Output immediately falls from y to $h(y)$, where $0 \leq h(y) \leq y$

- it returns to y only after the country regains access to international credit markets.

1. The country loses access to foreign credit markets.

52.3.5 Reentering international credit market

While in a state of default, the economy regains access to foreign credit in each subsequent period with probability θ.

52.4 Equilibrium

Informally, an equilibrium is a sequence of interest rates on its sovereign debt, a stochastic sequence of government default decisions and an implied flow of household consumption such that

1. Consumption and assets satisfy the national budget constraint.
2. The government maximizes household utility taking into account

- the resource constraint
- the effect of its choices on the price of bonds
- consequences of defaulting now for future net output and future borrowing and lending opportunities

1. The interest rate on the government's debt includes a risk-premium sufficient to make foreign creditors expect on average to earn the constant risk-free international interest rate.

To express these ideas more precisely, consider first the choices of the government, which

1. enters a period with initial assets B, or what is the same thing, initial debt to be repaid now of $-B$
2. observes current output y, and
3. chooses either
4. to default, or
5. to pay $-B$ and set next period's debt due to $-B'$

In a recursive formulation,

- state variables for the government comprise the pair (B, y)
- $v(B, y)$ is the optimum value of the government's problem when at the beginning of a period it faces the choice of whether to honor or default
- $v_c(B, y)$ is the value of choosing to pay obligations falling due
- $v_d(y)$ is the value of choosing to default

$v_d(y)$ does not depend on B because, when access to credit is eventually regained, net foreign assets equal 0.

Expressed recursively, the value of defaulting is

$$v_d(y) = u(h(y)) + \beta \int \{\theta v(0, y') + (1 - \theta) v_d(y')\} p(y, y') dy'$$

The value of paying is

$$v_c(B, y) = \max_{B' \geq -Z} \left\{ u(y - q(B', y)B' + B) + \beta \int v(B', y') p(y, y') dy' \right\}$$

The three value functions are linked by

$$v(B, y) = \max\{v_c(B, y), v_d(y)\}$$

The government chooses to default when

$$v_c(B, y) < v_d(y)$$

and hence given B' the probability of default next period is

$$\delta(B', y) := \int \mathbb{1}\{v_c(B', y') < v_d(y')\} p(y, y') dy' \tag{4}$$

Given zero profits for foreign creditors in equilibrium, we can combine (3) and (4) to pin down the bond price function:

$$q(B', y) = \frac{1 - \delta(B', y)}{1 + r} \tag{5}$$

52.4.1 Definition of equilibrium

An *equilibrium* is

- a pricing function $q(B', y)$,
- a triple of value functions $(v_c(B, y), v_d(y), v(B, y))$,
- a decision rule telling the government when to default and when to pay as a function of the state (B, y), and
- an asset accumulation rule that, conditional on choosing not to default, maps (B, y) into B'

such that

- The three Bellman equations for $(v_c(B, y), v_d(y), v(B, y))$ are satisfied.

- Given the price function $q(B', y)$, the default decision rule and the asset accumulation decision rule attain the optimal value function $v(B, y)$, and
- The price function $q(B', y)$ satisfies equation (5).

52.5 Computation

Let's now compute an equilibrium of Arellano's model.

The equilibrium objects are the value function $v(B, y)$, the associated default decision rule, and the pricing function $q(B', y)$.

We'll use our code to replicate Arellano's results.

After that we'll perform some additional simulations.

It uses a slightly modified version of the algorithm recommended by Arellano.

- The appendix to [5] recommends value function iteration until convergence, updating the price, and then repeating.
- Instead, we update the bond price at every value function iteration step.

The second approach is faster and the two different procedures deliver very similar results.

Here is a more detailed description of our algorithm:

1. Guess a value function $v(B, y)$ and price function $q(B', y)$.
2. At each pair (B, y),

- update the value of defaulting $v_d(y)$
- update the value of continuing $v_c(B, y)$

1. Update the value function v(B, y), the default rule, the implied ex ante default probability, and the price function.
2. Check for convergence. If converged, stop. If not, go to step 2.

We use simple discretization on a grid of asset holdings and income levels.

The output process is discretized using Tauchen's quadrature method.

The code can be found below:

(Results and discussion follow the code)

52.5.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Parameters, QuantEcon, DataFrames, Plots, Random
```

In [3]:
```
function ArellanoEconomy(;β = .953,
                          γ = 2.,
                          r = 0.017,
                          ρ = 0.945,
                          η = 0.025,
                          θ = 0.282,
                          ny = 21,
                          nB = 251)

    # create grids
    Bgrid = collect(range(-.4, .4, length = nB))
    mc = tauchen(ny, ρ, η)
    Π = mc.p
    ygrid = exp.(mc.state_values)
    ydefgrid = min.(.969 * mean(ygrid), ygrid)

    # define value functions
    # notice ordered different than Python to take
    # advantage of column major layout of Julia)
    vf = zeros(nB, ny)
    vd = zeros(1, ny)
    vc = zeros(nB, ny)
    policy = zeros(nB, ny)
    q = ones(nB, ny) .* (1 / (1 + r))
    defprob = zeros(nB, ny)

    return (β = β, γ = γ, r = r, ρ = ρ, η = η, θ = θ, ny = ny,
            nB = nB, ygrid = ygrid, ydefgrid = ydefgrid,
            Bgrid = Bgrid, Π = Π, vf = vf, vd = vd, vc = vc,
            policy = policy, q = q, defprob = defprob)
end

u(ae, c) = c^(1 - ae.γ) / (1 - ae.γ)

function one_step_update!(ae,
                          EV,
                          EVd,
                          EVc)

    # unpack stuff
    @unpack β, γ, r, ρ, η, θ, ny, nB = ae
    @unpack ygrid, ydefgrid, Bgrid, Π, vf, vd, vc, policy, q, defprob = ae
    zero_ind = searchsortedfirst(Bgrid, 0.)

    for iy in 1:ny
        y = ae.ygrid[iy]
        ydef = ae.ydefgrid[iy]

        # value of being in default with income y
        defval = u(ae, ydef) + β * (θ * EVc[zero_ind, iy] + (1-θ) * EVd[1,
↪iy])
        ae.vd[1, iy] = defval

        for ib in 1:nB
            B = ae.Bgrid[ib]

            current_max = -1e14
            pol_ind = 0
```

```
            for ib_next=1:nB
                c = max(y - ae.q[ib_next, iy]*Bgrid[ib_next] + B, 1e-14)
                m = u(ae, c) + β * EV[ib_next, iy]

                if m > current_max
                    current_max = m
                    pol_ind = ib_next
                end

            end

            # update value and policy functions
            ae.vc[ib, iy] = current_max
            ae.policy[ib, iy] = pol_ind
            ae.vf[ib, iy] = defval > current_max ? defval : current_max
        end
    end
end

function compute_prices!(ae)
    # unpack parameters
    @unpack β, γ, r, ρ, η, θ, ny, nB = ae

    # create default values with a matching size
    vd_compat = repeat(ae.vd, nB)
    default_states = vd_compat .> ae.vc

    # update default probabilities and prices
    copyto!(ae.defprob, default_states * ae.Π')
    copyto!(ae.q, (1 .- ae.defprob) / (1 + r))
    return
end

function vfi!(ae; tol = 1e-8, maxit = 10000)

    # unpack stuff
    @unpack β, γ, r, ρ, η, θ, ny, nB = ae
    @unpack ygrid, ydefgrid, Bgrid, Π, vf, vd, vc, policy, q, defprob = ae
    Πt = Π'

    # Iteration stuff
    it = 0
    dist = 10.

    # allocate memory for update
    V_upd = similar(ae.vf)

    while dist > tol && it < maxit
        it += 1

        # compute expectations for this iterations
        # (we need Π' because of order value function dimensions)
        copyto!(V_upd, ae.vf)
        EV = ae.vf * Πt
        EVd = ae.vd * Πt
        EVc = ae.vc * Πt

        # update value function
```

```
        one_step_update!(ae, EV, EVd, EVc)

        # update prices
        compute_prices!(ae)

        dist = maximum(abs(x - y) for (x, y) in zip(V_upd, ae.vf))

        if it % 25 == 0
            println("Finished iteration $(it) with dist of $(dist)")
        end
    end
end

function QuantEcon.simulate(ae,
                            capT = 5000;
                            y_init = mean(ae.ygrid),
                            B_init = mean(ae.Bgrid),
                            )

    # get initial indices
    zero_index = searchsortedfirst(ae.Bgrid, 0.)
    y_init_ind = searchsortedfirst(ae.ygrid, y_init)
    B_init_ind = searchsortedfirst(ae.Bgrid, B_init)

    # create a QE MarkovChain
    mc = MarkovChain(ae.Π)
    y_sim_indices = simulate(mc, capT + 1; init = y_init_ind)

    # allocate and fill output
    y_sim_val = zeros(capT+1)
    B_sim_val, q_sim_val = similar(y_sim_val), similar(y_sim_val)
    B_sim_indices = fill(0, capT + 1)
    default_status = fill(false, capT + 1)
    B_sim_indices[1], default_status[1] = B_init_ind, false
    y_sim_val[1], B_sim_val[1] = ae.ygrid[y_init_ind], ae.Bgrid[B_init_ind]

    for t in 1:capT
        # get today's indexes
        yi, Bi = y_sim_indices[t], B_sim_indices[t]
        defstat = default_status[t]

        # if you are not in default
        if !defstat
            default_today = ae.vc[Bi, yi] < ae.vd[yi]

            if default_today
                # default values
                default_status[t] = true
                default_status[t + 1] = true
                y_sim_val[t] = ae.ydefgrid[y_sim_indices[t]]
                B_sim_indices[t + 1] = zero_index
                B_sim_val[t+1] = 0.
                q_sim_val[t] = ae.q[zero_index, y_sim_indices[t]]
            else
                default_status[t] = false
                y_sim_val[t] = ae.ygrid[y_sim_indices[t]]
                B_sim_indices[t + 1] = ae.policy[Bi, yi]
                B_sim_val[t + 1] = ae.Bgrid[B_sim_indices[t + 1]]
```

```
                q_sim_val[t] = ae.q[B_sim_indices[t + 1], y_sim_indices[t]]
            end

        # if you are in default
        else
            B_sim_indices[t + 1] = zero_index
            B_sim_val[t+1] = 0.
            y_sim_val[t] = ae.ydefgrid[y_sim_indices[t]]
            q_sim_val[t] = ae.q[zero_index, y_sim_indices[t]]

            # with probability θ exit default status
            default_status[t + 1] = rand() ≥ ae.θ
        end
    end

    return (y_sim_val[1:capT], B_sim_val[1:capT], q_sim_val[1:capT],
            default_status[1:capT])
end
```

52.6 Results

Let's start by trying to replicate the results obtained in [5].

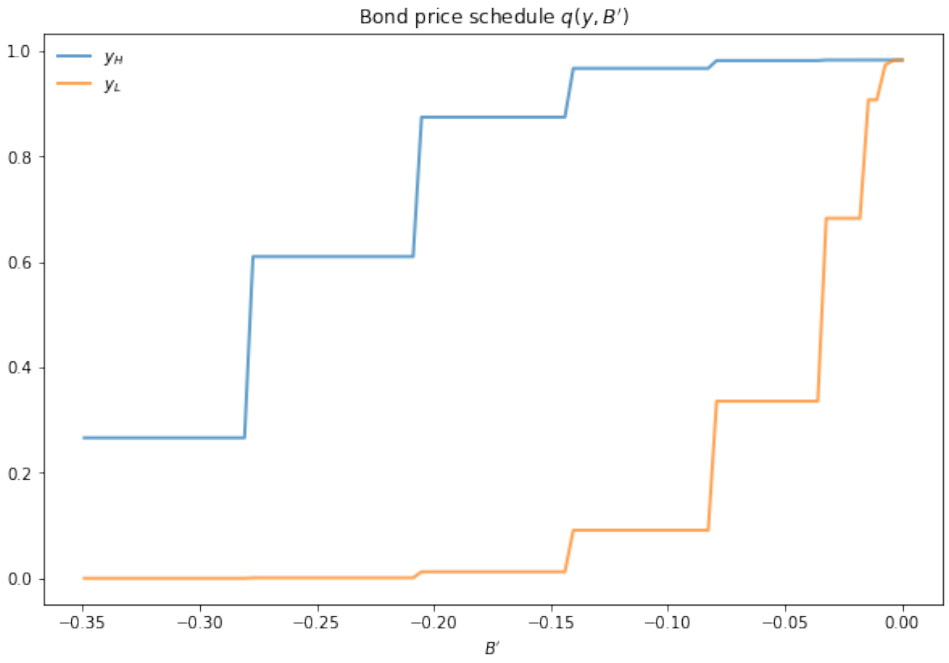
In what follows, all results are computed using Arellano's parameter values.

The values can be seen in the function ArellanoEconomy shown above.

- For example, r=0.017 matches the average quarterly rate on a 5 year US treasury over the period 1983–2001.

Details on how to compute the figures are reported as solutions to the exercises.

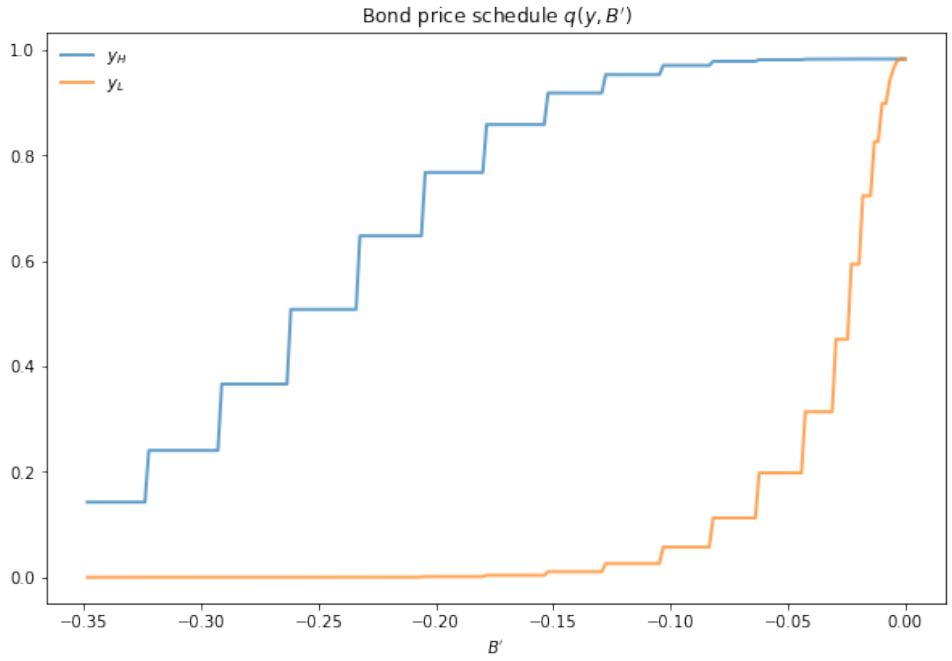
The first figure shows the bond price schedule and replicates Figure 3 of Arellano, where y_L and Y_H are particular below average and above average values of output y



- y_L is 5% below the mean of the y grid values
- y_H is 5% above the mean of the y grid values

The grid used to compute this figure was relatively coarse (ny, nB = 21, 251) in order to match Arrelano's findings.

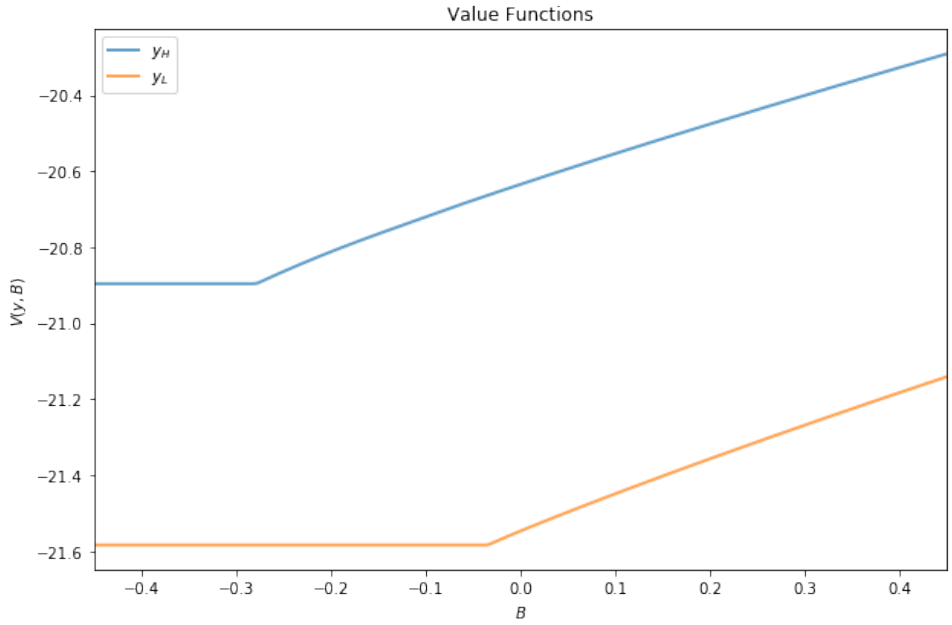
Here's the same relationships computed on a finer grid (ny, nB = 51, 551)



In either case, the figure shows that

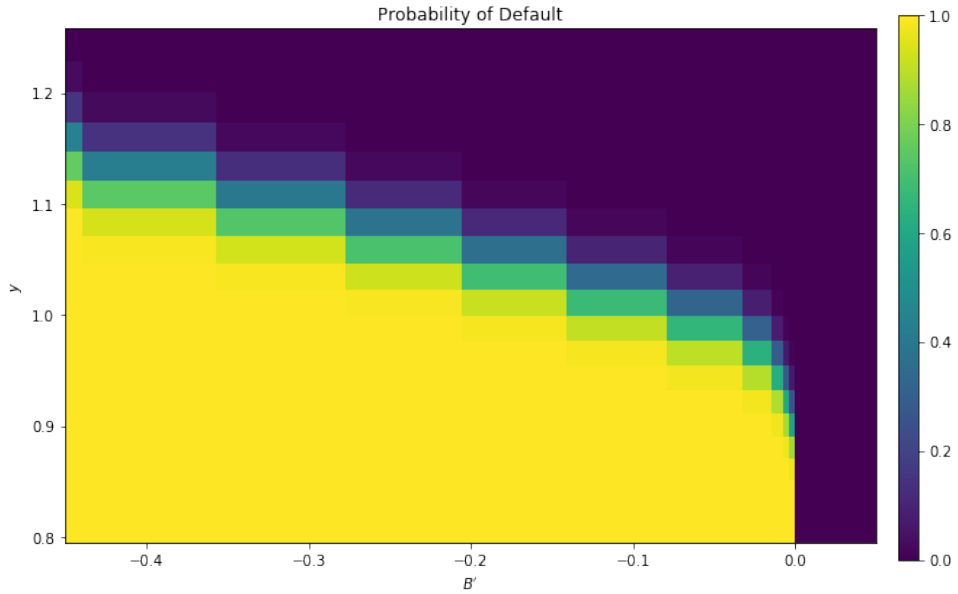
- Higher levels of debt (larger $-B'$) induce larger discounts on the face value, which correspond to higher interest rates.
- Lower income also causes more discounting, as foreign creditors anticipate greater likelihood of default.

The next figure plots value functions and replicates the right hand panel of Figure 4 of [5]



We can use the results of the computation to study the default probability $\delta(B', y)$ defined in (4).

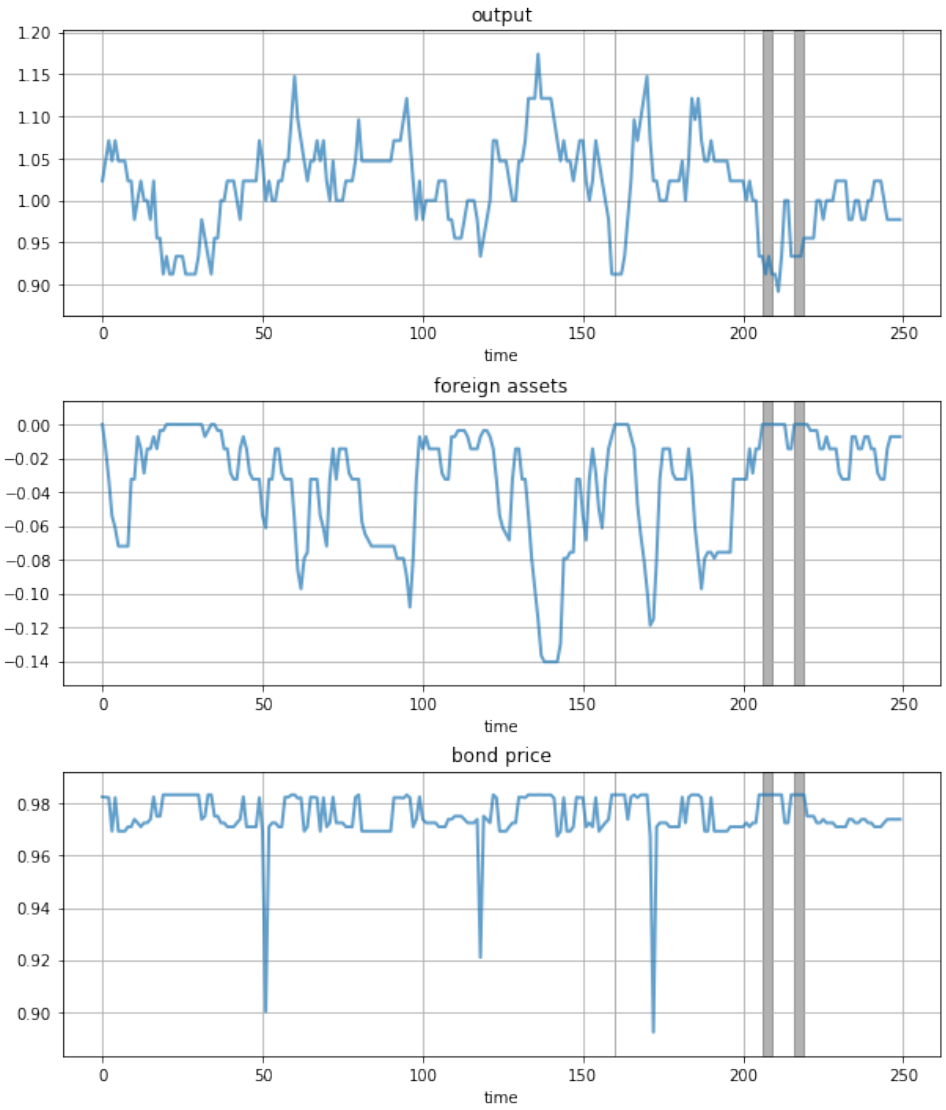
The next plot shows these default probabilities over (B', y) as a heat map



As anticipated, the probability that the government chooses to default in the following period increases with indebtedness and falls with income.

Next let's run a time series simulation of $\{y_t\}$, $\{B_t\}$ and $q(B_{t+1}, y_t)$.

The grey vertical bars correspond to periods when the economy is excluded from financial markets because of a past default



One notable feature of the simulated data is the nonlinear response of interest rates.

Periods of relative stability are followed by sharp spikes in the discount rate on government debt.

52.7 Exercises

52.7.1 Exercise 1

To the extent that you can, replicate the figures shown above

- Use the parameter values listed as defaults in the function ArellanoEconomy.
- The time series will of course vary depending on the shock draws.

52.8 Solutions

```
In [4]: using DataFrames, Plots
        gr(fmt=:png);
```

Compute the value function, policy and equilibrium prices

```
In [5]: ae = ArellanoEconomy(β = .953,      # time discount rate
                            γ = 2.,       # risk aversion
                            r = 0.017,    # international interest rate
                            ρ = .945,     # persistence in output
                            η = 0.025,    # st dev of output shock
                            θ = 0.282,    # prob of regaining access
                            ny = 21,      # number of points in y grid
                            nB = 251)     # number of points in B grid

        # now solve the model on the grid.
        vfi!(ae)
```

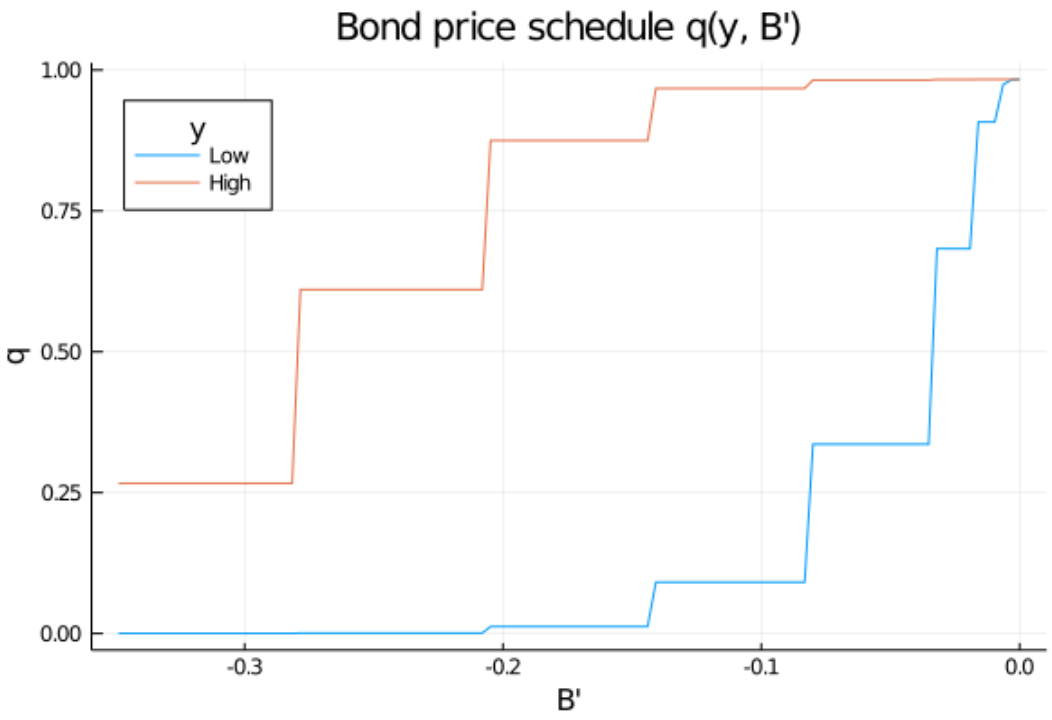
```
   Finished iteration 25 with dist of 0.3424484168091375
Finished iteration 50 with dist of 0.09820394074288075
Finished iteration 75 with dist of 0.02915866229151476
Finished iteration 100 with dist of 0.008729266837651295
Finished iteration 125 with dist of 0.002618400938121823
Finished iteration 150 with dist of 0.0007857709211727126
Finished iteration 175 with dist of 0.00023583246008485048
Finished iteration 200 with dist of 7.078195654131036e-5
Finished iteration 225 with dist of 2.1244388765495614e-5
Finished iteration 250 with dist of 6.376267926100354e-6
Finished iteration 275 with dist of 1.913766855210497e-6
Finished iteration 300 with dist of 5.743961786208729e-7
Finished iteration 325 with dist of 1.723987352875156e-7
Finished iteration 350 with dist of 5.174360495630026e-8
Finished iteration 375 with dist of 1.5530289942944364e-8
```

Compute the bond price schedule as seen in figure 3 of Arellano (2008)

```
In [6]: # create "Y High" and "Y Low" values as 5% devs from mean
        high, low = 1.05 * mean(ae.ygrid), 0.95 * mean(ae.ygrid)
        iy_high, iy_low = map(x -> searchsortedfirst(ae.ygrid, x), (high, low))

        # extract a suitable plot grid
        x = zeros(0)
        q_low = zeros(0)
        q_high = zeros(0)
        for i in 1:ae.nB
            b = ae.Bgrid[i]
            if -0.35 ≤ b ≤ 0  # to match fig 3 of Arellano
                push!(x, b)
                push!(q_low, ae.q[i, iy_low])
                push!(q_high, ae.q[i, iy_high])
            end
        end

        # generate plot
```

```
plot(x, q_low, label = "Low")
plot!(x, q_high, label = "High")
plot!(title = "Bond price schedule q(y, B')",
      xlabel = "B'", ylabel = "q", legend_title = "y", legend = :topleft)
```

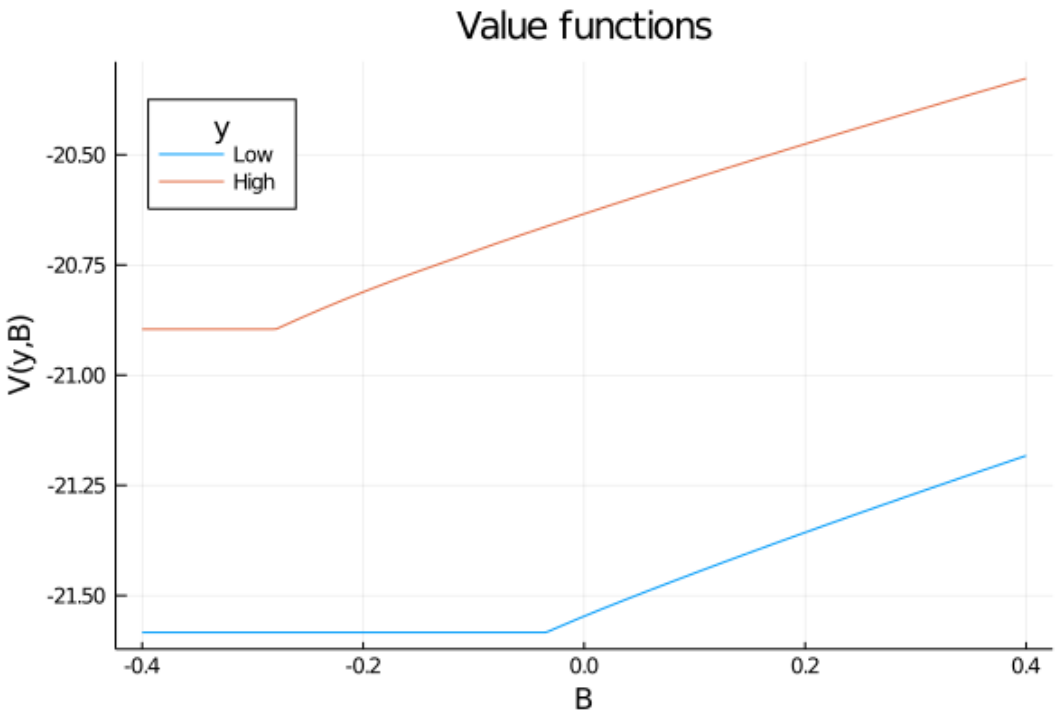
Out[6]:



Draw a plot of the value functions

In [7]:
```
plot(ae.Bgrid, ae.vf[:, iy_low], label = "Low")
plot!(ae.Bgrid, ae.vf[:, iy_high], label = "High")
plot!(xlabel = "B", ylabel = "V(y,B)", title = "Value functions",
      legend_title="y", legend = :topleft)
```

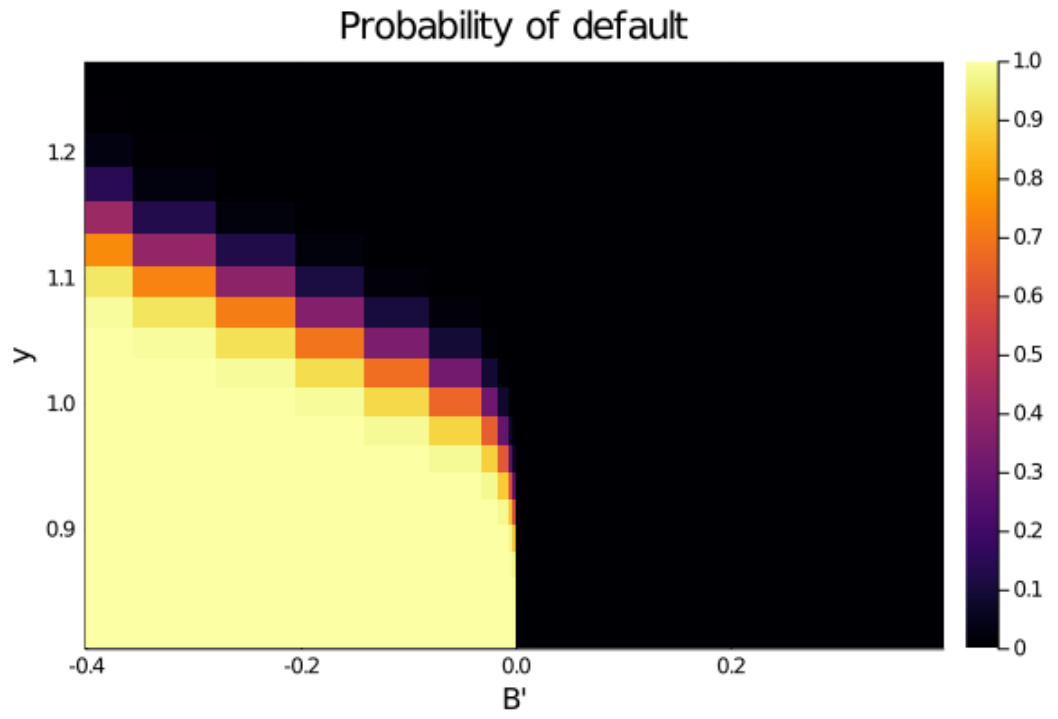
Out[7]:



Draw a heat map for default probability

```
In [8]: heatmap(ae.Bgrid[1:end-1],
            ae.ygrid[2:end],
            reshape(clamp.(vec(ae.defprob[1:end - 1, 1:end - 1]), 0, 1), 250, 20)')
        plot!(xlabel = "B'", ylabel = "y", title = "Probability of default",
            legend = :topleft)
```

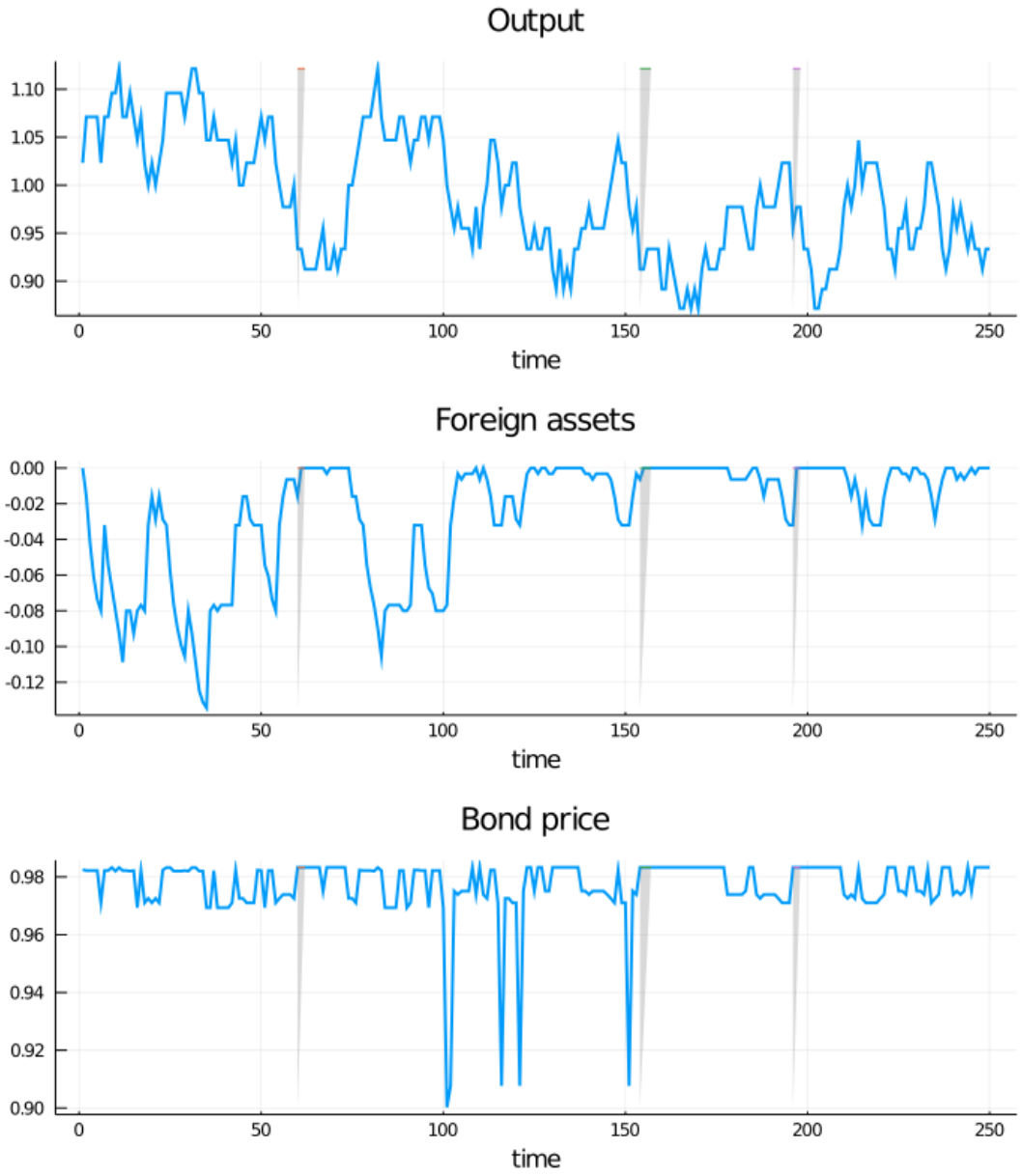
Out[8]:



Plot a time series of major variables simulated from the model

In [9]:
```
using Random
# set random seed for consistent result
Random.seed!(348938)

# simulate
T = 250
y_vec, B_vec, q_vec, default_vec = simulate(ae, T)

# find starting and ending periods of recessions
defs = findall(default_vec)
def_breaks = diff(defs) .> 1
def_start = defs[[true; def_breaks]]
def_end = defs[[def_breaks; true]]

y_vals = [y_vec, B_vec, q_vec]
titles = ["Output", "Foreign assets", "Bond price"]

plots = plot(layout = (3, 1), size = (700, 800))

# Plot the three variables, and for each each variable shading the
↪period(s) of default
# in grey
for i in 1:3
    plot!(plots[i], 1:T, y_vals[i], title = titles[i], xlabel = "time",
↪label = "", lw =
2)
    for j in 1:length(def_start)
        plot!(plots[i], [def_start[j], def_end[j]],
↪fill(maximum(y_vals[i]), 2),
              fillrange = [extrema(y_vals[i])...], fcolor = :grey, falpha =
↪0.3, label =
"")
    end
end

plot(plots)
```

Out[9]:


Output
1.10
1.05
1.00
0.95
0.90
0
50
100
150
200
250
time
Foreign assets
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
0
50
100
150
200
250
time
Bond price
0.98
0.96
0.94
0.92
0.90
0
50
100
150
200
250
time

Chapter 53

Globalization and Cycles

53.1 Contents

Co-authored with Chase Coleman

53.2 Overview

In this lecture, we review the paper Globalization and Synchronization of Innovation Cycles by Kiminori Matsuyama, Laura Gardini and Iryna Sushko.

This model helps us understand several interesting stylized facts about the world economy.

One of these is synchronized business cycles across different countries.

Most existing models that generate synchronized business cycles do so by assumption, since they tie output in each country to a common shock.

They also fail to explain certain features of the data, such as the fact that the degree of synchronization tends to increase with trade ties.

By contrast, in the model we consider in this lecture, synchronization is both endogenous and increasing with the extent of trade integration.

In particular, as trade costs fall and international competition increases, innovation incentives become aligned and countries synchronize their innovation cycles.

53.2.1 Background

The model builds on work by Judd [60], Deneckner and Judd [23] and Helpman and Krugman [52] by developing a two country model with trade and innovation.

On the technical side, the paper introduces the concept of coupled oscillators to economic

modeling.

As we will see, coupled oscillators arise endogenously within the model.

Below we review the model and replicate some of the results on synchronization of innovation across countries.

53.3 Key Ideas

It is helpful to begin with an overview of the mechanism.

53.3.1 Innovation Cycles

As discussed above, two countries produce and trade with each other.

In each country, firms innovate, producing new varieties of goods and, in doing so, receiving temporary monopoly power.

Imitators follow and, after one period of monopoly, what had previously been new varieties now enter competitive production.

Firms have incentives to innovate and produce new goods when the mass of varieties of goods currently in production is relatively low.

In addition, there are strategic complementarities in the timing of innovation.

Firms have incentives to innovate in the same period, so as to avoid competing with substitutes that are competitively produced.

This leads to temporal clustering in innovations in each country.

After a burst of innovation, the mass of goods currently in production increases.

However, goods also become obsolete, so that not all survive from period to period.

This mechanism generates a cycle, where the mass of varieties increases through simultaneous innovation and then falls through obsolescence.

53.3.2 Synchronization

In the absence of trade, the timing of innovation cycles in each country is decoupled.

This will be the case when trade costs are prohibitively high.

If trade costs fall, then goods produced in each country penetrate each other's markets.

As illustrated below, this leads to synchonization of business cycles across the two countries.

53.4 Model

Let's write down the model more formally.

(The treatment is relatively terse since full details can be found in the original paper)

Time is discrete with $t = 0, 1, ...$

There are two countries indexed by j or k.

In each country, a representative household inelastically supplies L_j units of labor at wage rate $w_{j,t}$.

Without loss of generality, it is assumed that $L_1 \geq L_2$.

Households consume a single nontradeable final good which is produced competitively.

Its production involves combining two types of tradeable intermediate inputs via

$$Y_{k,t} = C_{k,t} = \left(\frac{X^o_{k,t}}{1-\alpha}\right)^{1-\alpha} \left(\frac{X_{k,t}}{\alpha}\right)^{\alpha}$$

Here $X^o_{k,t}$ is a homogeneous input which can be produced from labor using a linear, one-for-one technology.

It is freely tradeable, competitively supplied, and homogeneous across countries.

By choosing the price of this good as numeraire and assuming both countries find it optimal to always produce the homogeneous good, we can set $w_{1,t} = w_{2,t} = 1$.

The good $X_{k,t}$ is a composite, built from many differentiated goods via

$$X_{k,t}^{1-\frac{1}{\sigma}} = \int_{\Omega_t} \left[x_{k,t}(\nu)\right]^{1-\frac{1}{\sigma}} d\nu$$

Here $x_{k,t}(\nu)$ is the total amount of a differentiated good $\nu \in \Omega_t$ that is produced.

The parameter $\sigma > 1$ is the direct partial elasticity of substitution between a pair of varieties and Ω_t is the set of varieties available in period t.

We can split the varieties into those which are supplied competitively and those supplied monopolistically; that is, $\Omega_t = \Omega^c_t + \Omega^m_t$.

53.4.1 Prices

Demand for differentiated inputs is

$$x_{k,t}(\nu) = \left(\frac{p_{k,t}(\nu)}{P_{k,t}}\right)^{-\sigma} \frac{\alpha L_k}{P_{k,t}}$$

Here

- $p_{k,t}(\nu)$ is the price of the variety ν and
- $P_{k,t}$ is the price index for differentiated inputs in k, defined by

$$\left[P_{k,t}\right]^{1-\sigma} = \int_{\Omega_t} [p_{k,t}(\nu)]^{1-\sigma} d\nu$$

The price of a variety also depends on the origin, j, and destination, k, of the goods because shipping varieties between countries incurs an iceberg trade cost $\tau_{j,k}$.

Thus the effective price in country k of a variety ν produced in country j becomes $p_{k,t}(\nu) = \tau_{j,k}\, p_{j,t}(\nu)$.

Using these expressions, we can derive the total demand for each variety, which is

$$D_{j,t}(\nu) = \sum_k \tau_{j,k} x_{k,t}(\nu) = \alpha A_{j,t} (p_{j,t}(\nu))^{-\sigma}$$

where

$$A_{j,t} := \sum_k \frac{\rho_{j,k} L_k}{(P_{k,t})^{1-\sigma}} \quad \text{and} \quad \rho_{j,k} = (\tau_{j,k})^{1-\sigma} \leq 1$$

It is assumed that $\tau_{1,1} = \tau_{2,2} = 1$ and $\tau_{1,2} = \tau_{2,1} = \tau$ for some $\tau > 1$, so that

$$\rho_{1,2} = \rho_{2,1} = \rho := \tau^{1-\sigma} < 1$$

The value $\rho \in [0, 1)$ is a proxy for the degree of globalization.

Producing one unit of each differentiated variety requires ψ units of labor, so the marginal cost is equal to ψ for $\nu \in \Omega_{j,t}$.

Additionally, all competitive varieties will have the same price (because of equal marginal cost), which means that, for all $\nu \in \Omega^c$,

$$p_{j,t}(\nu) = p^c_{j,t} := \psi \quad \text{and} \quad D_{j,t} = y^c_{j,t} := \alpha A_{j,t} (p^c_{j,t})^{-\sigma}$$

Monopolists will have the same marked-up price, so, for all $\nu \in \Omega^m$,

$$p_{j,t}(\nu) = p^m_{j,t} := \frac{\psi}{1 - \frac{1}{\sigma}} \quad \text{and} \quad D_{j,t} = y^m_{j,t} := \alpha A_{j,t} (p^m_{j,t})^{-\sigma}$$

Define

$$\theta := \frac{p^c_{j,t}}{p^m_{j,t}} \frac{y^c_{j,t}}{y^m_{j,t}} = \left(1 - \frac{1}{\sigma}\right)^{1-\sigma}$$

Using the preceding definitions and some algebra, the price indices can now be rewritten as

$$\left(\frac{P_{k,t}}{\psi}\right)^{1-\sigma} = M_{k,t} + \rho M_{j,t} \quad \text{where} \quad M_{j,t} := N^c_{j,t} + \frac{N^m_{j,t}}{\theta}$$

The symbols $N^c_{j,t}$ and $N^m_{j,t}$ will denote the measures of Ω^c and Ω^m respectively.

53.4.2 New Varieties

To introduce a new variety, a firm must hire f units of labor per variety in each country.

Monopolist profits must be less than or equal to zero in expectation, so

$$N^m_{j,t} \geq 0, \quad \pi^m_{j,t} := (p^m_{j,t} - \psi) y^m_{j,t} - f \leq 0 \quad \text{and} \quad \pi^m_{j,t} N^m_{j,t} = 0$$

With further manipulations, this becomes

$$N^m_{j,t} = \theta(M_{j,t} - N^c_{j,t}) \geq 0, \quad \frac{1}{\sigma}\left[\frac{\alpha L_j}{\theta(M_{j,t} + \rho M_{k,t})} + \frac{\alpha L_k}{\theta(M_{j,t} + M_{k,t}/\rho)}\right] \leq f$$

53.4.3 Law of Motion

With δ as the exogenous probability of a variety becoming obsolete, the dynamic equation for the measure of firms becomes

$$N^c_{j,t+1} = \delta(N^c_{j,t} + N^m_{j,t}) = \delta(N^c_{j,t} + \theta(M_{j,t} - N^c_{j,t}))$$

We will work with a normalized measure of varieties

$$n_{j,t} := \frac{\theta\sigma f N^c_{j,t}}{\alpha(L_1 + L_2)}, \quad i_{j,t} := \frac{\theta\sigma f N^m_{j,t}}{\alpha(L_1 + L_2)}, \quad m_{j,t} := \frac{\theta\sigma f M_{j,t}}{\alpha(L_1 + L_2)} = n_{j,t} + \frac{i_{j,t}}{\theta}$$

We also use $s_j := \frac{L_j}{L_1 + L_2}$ to be the share of labor employed in country j.

We can use these definitions and the preceding expressions to obtain a law of motion for $n_t := (n_{1,t}, n_{2,t})$.

In particular, given an initial condition, $n_0 = (n_{1,0}, n_{2,0}) \in \mathbb{R}^2_+$, the equilibrium trajectory, $\{n_t\}_{t=0}^{\infty} = \{(n_{1,t}, n_{2,t})\}_{t=0}^{\infty}$, is obtained by iterating on $n_{t+1} = F(n_t)$ where $F : \mathbb{R}^2_+ \to \mathbb{R}^2_+$ is given by

$$F(n_t) = \begin{cases} (\delta(\theta s_1(\rho) + (1-\theta)n_{1,t}), \delta(\theta s_2(\rho) + (1-\theta)n_{2,t})) & \text{for } n_t \in D_{LL} \\ (\delta n_{1,t}, \delta n_{2,t}) & \text{for } n_t \in D_{HH} \\ (\delta n_{1,t}, \delta(\theta h_2(n_{1,t}) + (1-\theta)n_{2,t})) & \text{for } n_t \in D_{HL} \\ (\delta(\theta h_1(n_{2,t}) + (1-\theta)n_{1,t}, \delta n_{2,t})) & \text{for } n_t \in D_{LH} \end{cases}$$

Here

$$\begin{aligned} D_{LL} &:= \{(n_1, n_2) \in \mathbb{R}^2_+ | n_j \leq s_j(\rho)\} \\ D_{HH} &:= \{(n_1, n_2) \in \mathbb{R}^2_+ | n_j \geq h_j(\rho)\} \\ D_{HL} &:= \{(n_1, n_2) \in \mathbb{R}^2_+ | n_1 \geq s_1(\rho) \text{ and } n_2 \leq h_2(n_1)\} \\ D_{LH} &:= \{(n_1, n_2) \in \mathbb{R}^2_+ | n_1 \leq h_1(n_2) \text{ and } n_2 \geq s_2(\rho)\} \end{aligned}$$

while

$$s_1(\rho) = 1 - s_2(\rho) = \min\left\{\frac{s_1 - \rho s_2}{1 - \rho}, 1\right\}$$

and $h_j(n_k)$ is defined implicitly by the equation

$$1 = \frac{s_j}{h_j(n_k) + \rho n_k} + \frac{s_k}{h_j(n_k) + n_k/\rho}$$

Rewriting the equation above gives us a quadratic equation in terms of $h_j(n_k)$.

Since we know $h_j(n_k) > 0$ then we can just solve the quadratic equation and return the positive root.

This gives us

$$h_j(n_k)^2 + \left((\rho + \frac{1}{\rho})n_k - s_j - s_k\right) h_j(n_k) + (n_k^2 - \frac{s_j n_k}{\rho} - s_k n_k \rho) = 0$$

53.5 Simulation

Let's try simulating some of these trajectories.

We will focus in particular on whether or not innovation cycles synchronize across the two countries.

As we will see, this depends on initial conditions.

For some parameterizations, synchronization will occur for "most" initial conditions, while for others synchronization will be rare.

Here's the main body of code.

53.5.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Plots, Parameters
        gr(fmt = :png);
```

```
In [3]: function h_j(j, nk, s1, s2, θ, δ, ρ)
            # Find out who's h we are evaluating
            if j == 1
                sj = s1
                sk = s2
            else
                sj = s2
                sk = s1
            end

            # Coefficients on the quadratic a x^2 + b x + c = 0
            a = 1.0
            b = ((ρ + 1 / ρ) * nk - sj - sk)
            c = (nk * nk - (sj * nk) / ρ - sk * ρ * nk)

            # Positive solution of quadratic form
            root = (-b + sqrt(b * b - 4 * a * c)) / (2 * a)

            return root
        end

        DLL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ) =
```

```
    (n1 ≤ s1_ρ) && (n2 ≤ s2_ρ)

DHH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ) =
    (n1 ≥ h_j(1, n2, s1, s2, θ, δ, ρ)) && (n2 ≥ h_j(2, n1, s1, s2, θ, δ, ρ))

DHL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ) =
    (n1 ≥ s1_ρ) && (n2 ≤ h_j(2, n1, s1, s2, θ, δ, ρ))

DLH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ) =
    (n1 ≤ h_j(1, n2, s1, s2, θ, δ, ρ)) && (n2 ≥ s2_ρ)

function one_step(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
    # Depending on where we are, evaluate the right branch
    if DLL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
        n1_tp1 = δ * (θ * s1_ρ + (1 - θ) * n1)
        n2_tp1 = δ * (θ * s2_ρ + (1 - θ) * n2)
    elseif DHH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
        n1_tp1 = δ * n1
        n2_tp1 = δ * n2
    elseif DHL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
        n1_tp1 = δ * n1
        n2_tp1 = δ * (θ * h_j(2, n1, s1, s2, θ, δ, ρ) + (1 - θ) * n2)
    elseif DLH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
        n1_tp1 = δ * (θ * h_j(1, n2, s1, s2, θ, δ, ρ) + (1 - θ) * n1)
        n2_tp1 = δ * n2
    end

    return n1_tp1, n2_tp1
end

new_n1n2(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ) =
    one_step(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)

function pers_till_sync(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ,
                        maxiter, npers)

    # Initialize the status of synchronization
    synchronized = false
    pers_2_sync = maxiter
    iters = 0

    nsync = 0

    while (~synchronized) && (iters < maxiter)
        # Increment the number of iterations and get next values
        iters += 1

        n1_t, n2_t = new_n1n2(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)

        # Check whether same in this period
        if abs(n1_t - n2_t) < 1e-8
            nsync += 1
        # If not, then reset the nsync counter
        else
            nsync = 0
        end

        # If we have been in sync for npers then stop and countries
```

```
        # became synchronized nsync periods ago
        if nsync > npers
            synchronized = true
            pers_2_sync = iters - nsync
        end
        n1_0, n2_0 = n1_t, n2_t
    end
    return synchronized, pers_2_sync
end

function create_attraction_basis(s1_ρ, s2_ρ, s1, s2, θ, δ, ρ,
                                 maxiter, npers, npts)
    # Create unit range with npts
    synchronized, pers_2_sync = false, 0
    unit_range = range(0.0,  1.0, length = npts)

    # Allocate space to store time to sync
    time_2_sync = zeros(npts, npts)
    # Iterate over initial conditions
    for (i, n1_0) in enumerate(unit_range)
        for (j, n2_0) in enumerate(unit_range)
          synchronized, pers_2_sync = pers_till_sync(n1_0, n2_0, s1_ρ, s2_ρ,
                                                     s1, s2, θ, δ, ρ,
                                                     maxiter, npers)
            time_2_sync[i, j] = pers_2_sync
        end
    end
    return time_2_sync
end

# model
function MSGSync(s1 = 0.5, θ = 2.5, δ = 0.7, ρ = 0.2)
    # Store other cutoffs and parameters we use
    s2 = 1 - s1
    s1_ρ = min((s1 - ρ * s2) / (1 - ρ), 1)
    s2_ρ = 1 - s1_ρ

    return (s1 = s1, s2 = s2, s1_ρ = s1_ρ, s2_ρ = s2_ρ, θ = θ, δ = δ, ρ = ρ)
end

function simulate_n(model, n1_0, n2_0, T)
    # Unpack parameters
    @unpack s1, s2, θ, δ, ρ, s1_ρ, s2_ρ = model

    # Allocate space
    n1 = zeros(T)
    n2 = zeros(T)

    # Simulate for T periods
    for t in 1:T
        # Get next values
        n1[t], n2[t] = n1_0, n2_0
        n1_0, n2_0 = new_n1n2(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
    end

    return n1, n2
end
```

```
function pers_till_sync(model, n1_0, n2_0,
                        maxiter = 500, npers = 3)
    # Unpack parameters
    @unpack s1, s2, θ, δ, ρ, s1_ρ, s2_ρ = model

    return pers_till_sync(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2,
                        θ, δ, ρ, maxiter, npers)
end

function create_attraction_basis(model;
                                 maxiter = 250,
                                 npers = 3,
                                 npts = 50)
    # Unpack parameters
    @unpack s1, s2, θ, δ, ρ, s1_ρ, s2_ρ = model

    ab = create_attraction_basis(s1_ρ, s2_ρ, s1, s2, θ, δ,
                                 ρ, maxiter, npers, npts)
    return ab
end
```

```
Out[3]: create_attraction_basis (generic function with 2 methods)
```

53.5.2 Time Series of Firm Measures

We write a short function below that exploits the preceding code and plots two time series.

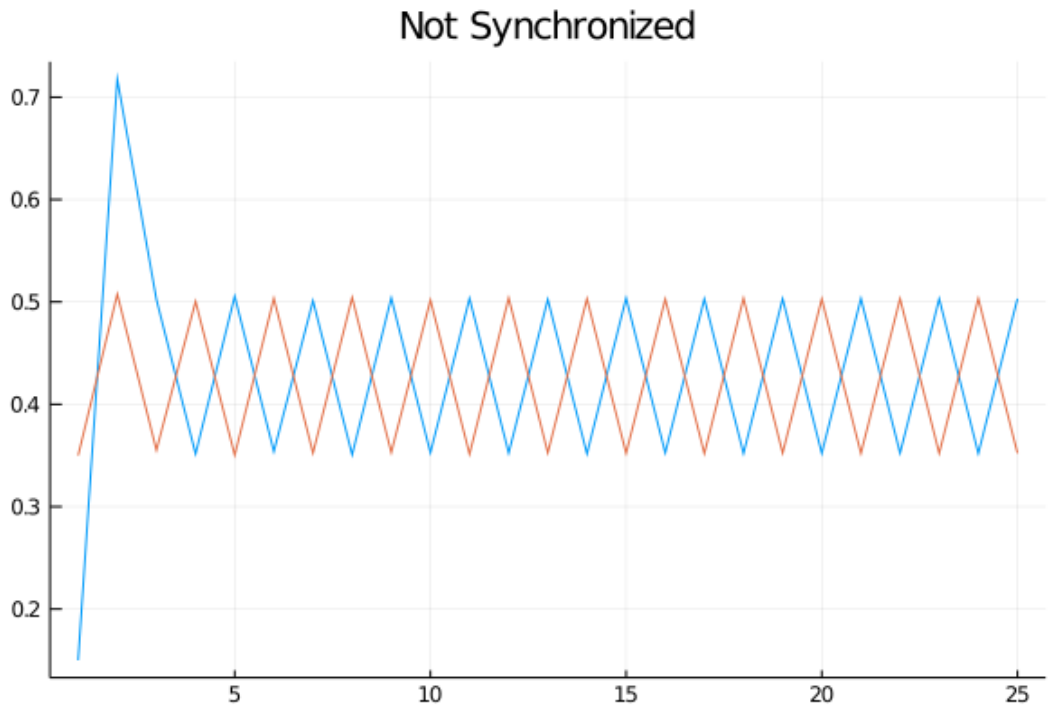
Each time series gives the dynamics for the two countries.

The time series share parameters but differ in their initial condition.

Here's the function

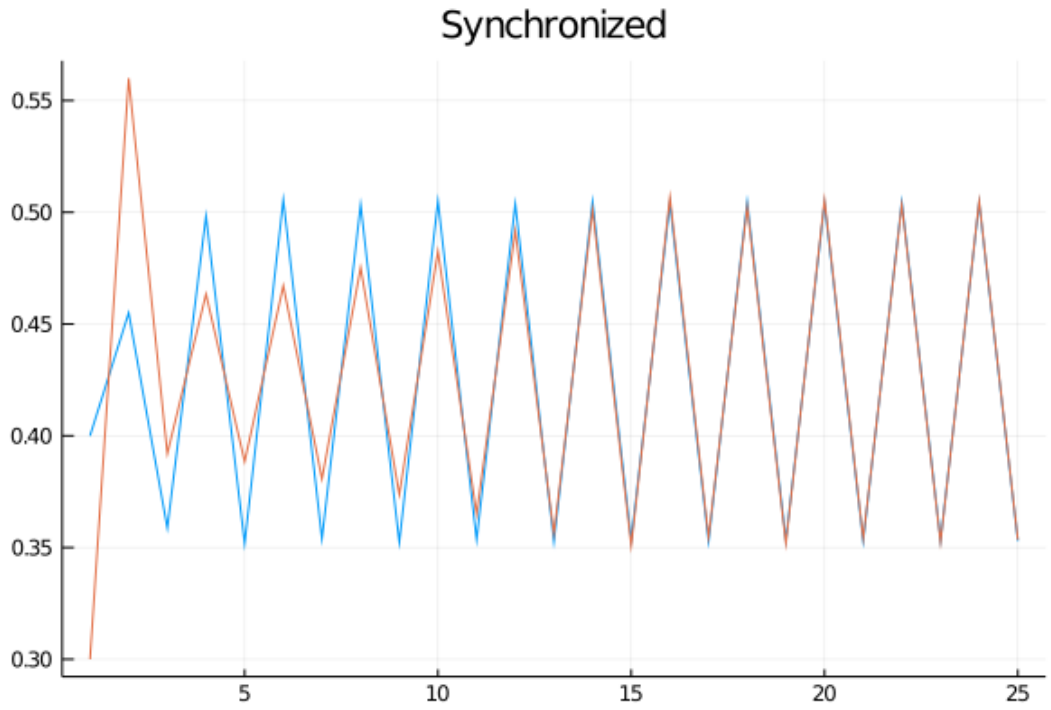
```
In [4]: function plot_timeseries(n1_0, n2_0, s1 = 0.5, θ = 2.5, δ = 0.7, ρ = 0.2)
            model = MSGSync(s1, θ, δ, ρ)
            n1, n2 = simulate_n(model, n1_0, n2_0, 25)
            return [n1 n2]
        end

        # Create figures
        data_ns = plot_timeseries(0.15, 0.35)
        data_s = plot_timeseries(0.4, 0.3)

        plot(data_ns, title = "Not Synchronized", legend = false)
```

```
Out[4]:
```




```
In [5]: plot(data_s, title = "Synchronized", legend = false)
```

Out[5]:



In the first case, innovation in the two countries does not synchronize.

In the second case different initial conditions are chosen, and the cycles become synchronized.

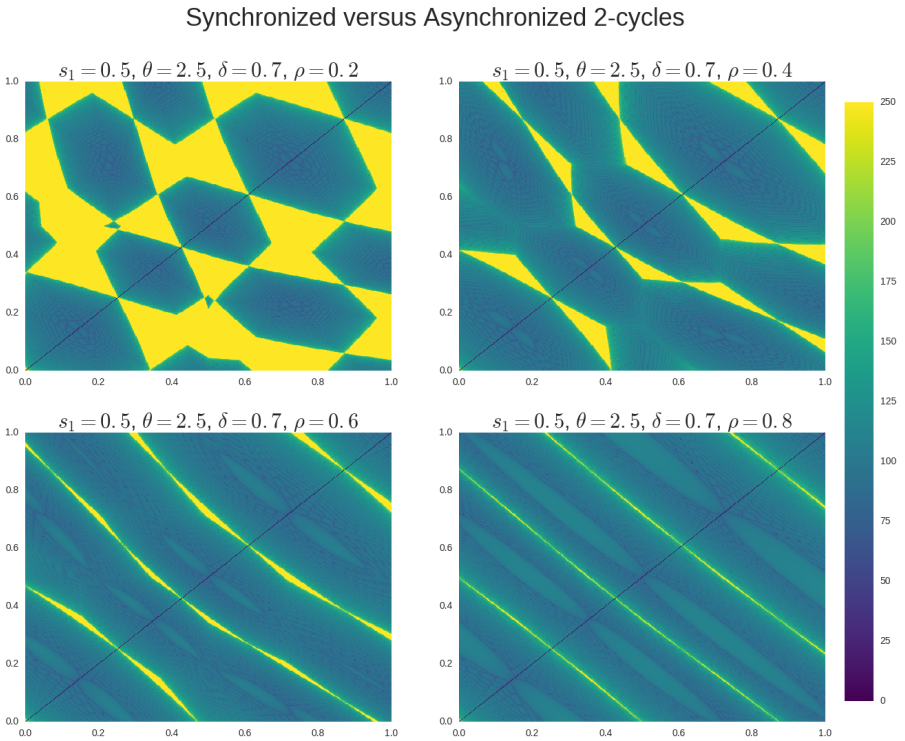
53.5.3 Basin of Attraction

Next let's study the initial conditions that lead to synchronized cycles more systematically.

We generate time series from a large collection of different initial conditions and mark those conditions with different colors according to whether synchronization occurs or not.

The next display shows exactly this for four different parameterizations (one for each subfigure).

Dark colors indicate synchronization, while light colors indicate failure to synchronize.



As you can see, larger values of ρ translate to more synchronization.

You are asked to replicate this figure in the exercises.

53.6 Exercises

53.6.1 Exercise 1

Replicate the figure shown above by coloring initial conditions according to whether or not synchronization occurs from those conditions.

53.7 Solutions

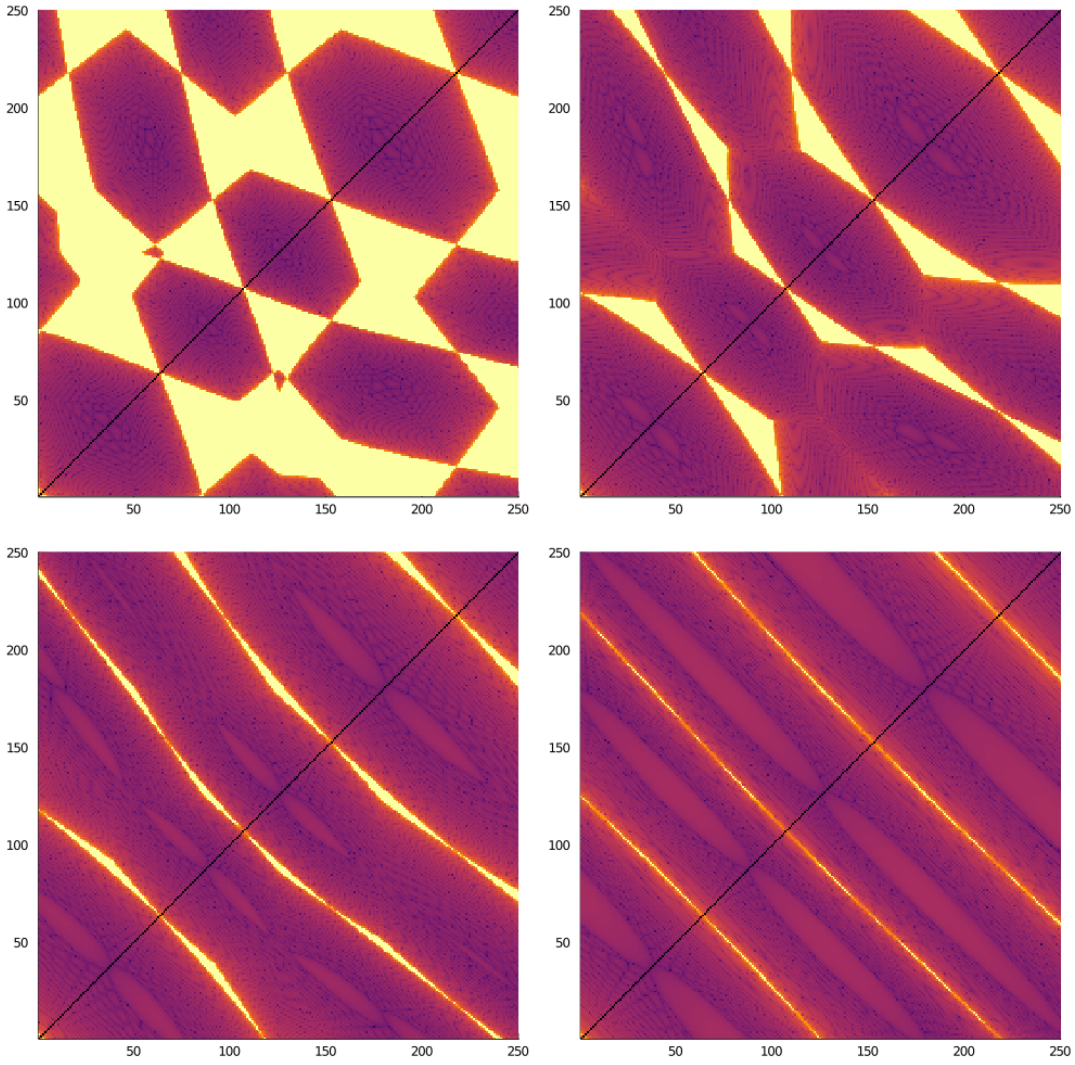
53.7.1 Exercise 1

In [6]:
```
function plot_attraction_basis(s1 = 0.5, θ = 2.5, δ = 0.7, ρ = 0.2; npts =
↪250)
    # Create attraction basis
    unitrange = range(0,  1, length = npts)
    model = MSGSync(s1, θ, δ, ρ)
    ab = create_attraction_basis(model,npts=npts)
    plt = Plots.heatmap(ab, legend = false)
end
```

Out[6]:
```
plot_attraction_basis (generic function with 5 methods)
```

In [7]:
```
params = [[0.5, 2.5, 0.7, 0.2],
          [0.5, 2.5, 0.7, 0.4],
          [0.5, 2.5, 0.7, 0.6],
          [0.5, 2.5, 0.7, 0.8]]

plots = (plot_attraction_basis(p...) for p in params)
plot(plots..., size = (1000, 1000))
```

Out[7]:


250
200
150
100
50
50
100
150
200
250

Part VII

Time Series Models

Chapter 54

Covariance Stationary Processes

54.1 Contents

54.2 Overview

In this lecture we study covariance stationary linear stochastic processes, a class of models routinely used to study economic and financial time series.

This class has the advantage of being

1. simple enough to be described by an elegant and comprehensive theory
2. relatively broad in terms of the kinds of dynamics it can represent

We consider these models in both the time and frequency domain.

54.2.1 ARMA Processes

We will focus much of our attention on linear covariance stationary models with a finite number of parameters.

In particular, we will study stationary ARMA processes, which form a cornerstone of the standard theory of time series analysis.

Every ARMA processes can be represented in linear state space form.

However, ARMA have some important structure that makes it valuable to study them separately.

54.2.2 Spectral Analysis

Analysis in the frequency domain is also called spectral analysis.

In essence, spectral analysis provides an alternative representation of the autocovariance function of a covariance stationary process.

Having a second representation of this important object

- shines light on the dynamics of the process in question
- allows for a simpler, more tractable representation in some important cases

The famous *Fourier transform* and its inverse are used to map between the two representations.

54.2.3 Other Reading

For supplementary reading, see.

- [68], chapter 2
- [94], chapter 11
- John Cochrane's notes on time series analysis, chapter 8
- [98], chapter 6
- [18], all

54.2.4 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

54.3 Introduction

Consider a sequence of random variables $\{X_t\}$ indexed by $t \in \mathbb{Z}$ and taking values in $\mathbb{R}$.

Thus, $\{X_t\}$ begins in the infinite past and extends to the infinite future — a convenient and standard assumption.

As in other fields, successful economic modeling typically assumes the existence of features that are constant over time.

If these assumptions are correct, then each new observation $X_t, X_{t+1}, \ldots$ can provide additional information about the time-invariant features, allowing us to learn from as data arrive.

For this reason, we will focus in what follows on processes that are *stationary* — or become so after a transformation (see for example this lecture and this lecture).

54.3.1 Definitions

A real-valued stochastic process $\{X_t\}$ is called *covariance stationary* if

1. Its mean $\mu := \mathbb{E}X_t$ does not depend on t.

2. For all k in $\mathbb{Z}$, the k-th autocovariance $\gamma(k) := \mathbb{E}(X_t - \mu)(X_{t+k} - \mu)$ is finite and depends only on k.

The function $\gamma \colon \mathbb{Z} \to \mathbb{R}$ is called the *autocovariance function* of the process.

Throughout this lecture, we will work exclusively with zero-mean (i.e., $\mu = 0$) covariance stationary processes.

The zero-mean assumption costs nothing in terms of generality, since working with non-zero-mean processes involves no more than adding a constant.

54.3.2 Example 1: White Noise

Perhaps the simplest class of covariance stationary processes is the white noise processes.

A process $\{\epsilon_t\}$ is called a *white noise process* if

1. $\mathbb{E}\epsilon_t = 0$
2. $\gamma(k) = \sigma^2 \mathbf{1}\{k = 0\}$ for some $\sigma > 0$

(Here $\mathbf{1}\{k = 0\}$ is defined to be 1 if $k = 0$ and zero otherwise)

White noise processes play the role of **building blocks** for processes with more complicated dynamics.

54.3.3 Example 2: General Linear Processes

From the simple building block provided by white noise, we can construct a very flexible family of covariance stationary processes — the *general linear processes*

$$X_t = \sum_{j=0}^{\infty} \psi_j \epsilon_{t-j}, \qquad t \in \mathbb{Z} \tag{1}$$

where

- $\{\epsilon_t\}$ is white noise
- $\{\psi_t\}$ is a square summable sequence in $\mathbb{R}$ (that is, $\sum_{t=0}^{\infty} \psi_t^2 < \infty$)

The sequence $\{\psi_t\}$ is often called a *linear filter*.

Equation (1) is said to present a **moving average** process or a moving average representation.

With some manipulations it is possible to confirm that the autocovariance function for (1) is

$$\gamma(k) = \sigma^2 \sum_{j=0}^{\infty} \psi_j \psi_{j+k} \tag{2}$$

By the Cauchy-Schwartz inequality one can show that $\gamma(k)$ satisfies equation (2).

Evidently, $\gamma(k)$ does not depend on t.

54.3.4 Wold's Decomposition

Remarkably, the class of general linear processes goes a long way towards describing the entire class of zero-mean covariance stationary processes.

In particular, Wold's decomposition theorem states that every zero-mean covariance stationary process $\{X_t\}$ can be written as

$$X_t = \sum_{j=0}^{\infty} \psi_j \epsilon_{t-j} + \eta_t$$

where

- $\{\epsilon_t\}$ is white noise
- $\{\psi_t\}$ is square summable
- η_t can be expressed as a linear function of $X_{t-1}, X_{t-2}, \ldots$ and is perfectly predictable over arbitrarily long horizons

For intuition and further discussion, see [94], p. 286.

54.3.5 AR and MA

General linear processes are a very broad class of processes.

It often pays to specialize to those for which there exists a representation having only finitely many parameters.

(Experience and theory combine to indicate that models with a relatively small number of parameters typically perform better than larger models, especially for forecasting)

One very simple example of such a model is the first-order autoregressive or AR(1) process

$$X_t = \phi X_{t-1} + \epsilon_t \quad \text{where} \quad |\phi| < 1 \quad \text{and } \{\epsilon_t\} \text{ is white noise} \tag{3}$$

By direct substitution, it is easy to verify that $X_t = \sum_{j=0}^{\infty} \phi^j \epsilon_{t-j}$.

Hence $\{X_t\}$ is a general linear process.

Applying (2) to the previous expression for X_t, we get the AR(1) autocovariance function

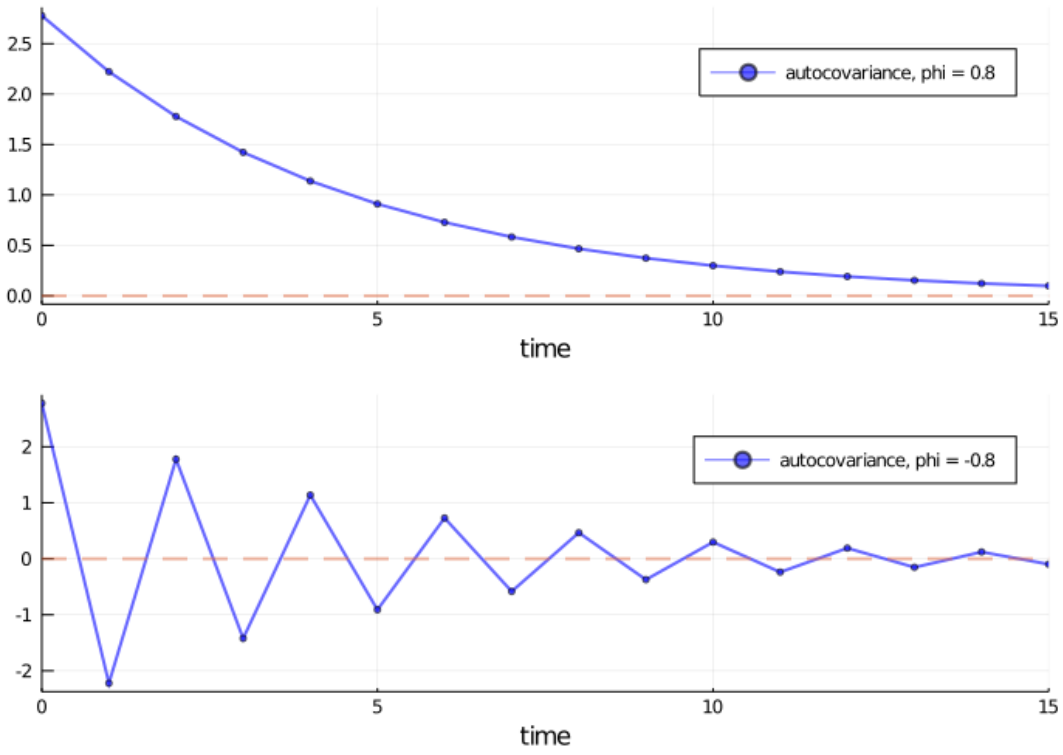
$$\gamma(k) = \phi^k \frac{\sigma^2}{1 - \phi^2}, \qquad k = 0, 1, \ldots \tag{4}$$

The next figure plots an example of this function for $\phi = 0.8$ and $\phi = -0.8$ with $\sigma = 1$

```
In [3]: using Plots
        gr(fmt=:png);

        plt_1=plot()
        plt_2=plot()
        plots = [plt_1, plt_2]

        for (i, ϕ) in enumerate((0.8, -0.8))
            times = 0:16
            acov = [ϕ.^k ./ (1 - ϕ.^2) for k in times]
```

```
        label = "autocovariance, phi = $ϕ"
        plot!(plots[i], times, acov, color=:blue, lw=2, marker=:circle,
↪markersize=3,
              alpha=0.6, label=label)
        plot!(plots[i], legend=:topright, xlabel="time", xlim=(0,15))
        plot!(plots[i], seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
↪lw=2, label="")
    end
    plot(plots[1], plots[2], layout=(2,1), size=(700,500))
```

Out[3]:



Another very simple process is the MA(1) process (here MA means "moving average")

$$X_t = \epsilon_t + \theta \epsilon_{t-1}$$

You will be able to verify that

$$\gamma(0) = \sigma^2(1+\theta^2), \quad \gamma(1) = \sigma^2\theta, \quad \text{and} \quad \gamma(k) = 0 \quad \forall\, k > 1$$

The AR(1) can be generalized to an AR(p) and likewise for the MA(1).

Putting all of this together, we get the

54.3.6 ARMA Processes

A stochastic process $\{X_t\}$ is called an *autoregressive moving average process*, or ARMA(p, q), if it can be written as

$$X_t = \phi_1 X_{t-1} + \cdots + \phi_p X_{t-p} + \epsilon_t + \theta_1 \epsilon_{t-1} + \cdots + \theta_q \epsilon_{t-q} \tag{5}$$

where $\{\epsilon_t\}$ is white noise.

An alternative notation for ARMA processes uses the *lag operator* L.

Def. Given arbitrary variable Y_t, let $L^k Y_t := Y_{t-k}$.

It turns out that

- lag operators facilitate succinct representations for linear stochastic processes
- algebraic manipulations that treat the lag operator as an ordinary scalar are legitimate

Using L, we can rewrite (5) as

$$L^0 X_t - \phi_1 L^1 X_t - \cdots - \phi_p L^p X_t = L^0 \epsilon_t + \theta_1 L^1 \epsilon_t + \cdots + \theta_q L^q \epsilon_t \tag{6}$$

If we let $\phi(z)$ and $\theta(z)$ be the polynomials

$$\phi(z) := 1 - \phi_1 z - \cdots - \phi_p z^p \quad \text{and} \quad \theta(z) := 1 + \theta_1 z + \cdots + \theta_q z^q \tag{7}$$

then (6) becomes

$$\phi(L) X_t = \theta(L) \epsilon_t \tag{8}$$

In what follows we **always assume** that the roots of the polynomial $\phi(z)$ lie outside the unit circle in the complex plane.

This condition is sufficient to guarantee that the ARMA(p, q) process is convariance stationary.

In fact it implies that the process falls within the class of general linear processes described above.

That is, given an ARMA(p, q) process $\{X_t\}$ satisfying the unit circle condition, there exists a square summable sequence $\{\psi_t\}$ with $X_t = \sum_{j=0}^{\infty} \psi_j \epsilon_{t-j}$ for all t.

The sequence $\{\psi_t\}$ can be obtained by a recursive procedure outlined on page 79 of [18].

The function $t \mapsto \psi_t$ is often called the *impulse response function*.

54.4 Spectral Analysis

Autocovariance functions provide a great deal of information about covariance stationary processes.

In fact, for zero-mean Gaussian processes, the autocovariance function characterizes the entire joint distribution.

Even for non-Gaussian processes, it provides a significant amount of information.

It turns out that there is an alternative representation of the autocovariance function of a covariance stationary process, called the *spectral density*.

At times, the spectral density is easier to derive, easier to manipulate, and provides additional intuition.

54.4.1 Complex Numbers

Before discussing the spectral density, we invite you to recall the main properties of complex numbers (or skip to the next section).

It can be helpful to remember that, in a formal sense, complex numbers are just points $(x, y) \in \mathbb{R}^2$ endowed with a specific notion of multiplication.

When (x, y) is regarded as a complex number, x is called the *real part* and y is called the *imaginary part*.

The *modulus* or *absolute value* of a complex number $z = (x, y)$ is just its Euclidean norm in $\mathbb{R}^2$, but is usually written as $|z|$ instead of $\|z\|$.

The product of two complex numbers (x, y) and (u, v) is defined to be $(xu - vy, xv + yu)$, while addition is standard pointwise vector addition.

When endowed with these notions of multiplication and addition, the set of complex numbers forms a field — addition and multiplication play well together, just as they do in $\mathbb{R}$.

The complex number (x, y) is often written as $x + iy$, where i is called the *imaginary unit*, and is understood to obey $i^2 = -1$.

The $x + iy$ notation provides an easy way to remember the definition of multiplication given above, because, proceeding naively,

$$(x + iy)(u + iv) = xu - yv + i(xv + yu)$$

Converted back to our first notation, this becomes $(xu - vy, xv + yu)$ as promised.

Complex numbers can be represented in the polar form $re^{i\omega}$ where

$$re^{i\omega} := r(\cos(\omega) + i \sin(\omega)) = x + iy$$

where $x = r\cos(\omega), y = r\sin(\omega)$, and $\omega = \arctan(y/z)$ or $\tan(\omega) = y/x$.

54.4.2 Spectral Densities

Let $\{X_t\}$ be a covariance stationary process with autocovariance function γ satisfying $\sum_k \gamma(k)^2 < \infty$.

The *spectral density* f of $\{X_t\}$ is defined as the discrete time Fourier transform of its autocovariance function γ

$$f(\omega) := \sum_{k \in \mathbb{Z}} \gamma(k) e^{-i\omega k}, \qquad \omega \in \mathbb{R}$$

(Some authors normalize the expression on the right by constants such as $1/\pi$ — the convention chosen makes little difference provided you are consistent)

Using the fact that γ is *even*, in the sense that $\gamma(t) = \gamma(-t)$ for all t, we can show that

$$f(\omega) = \gamma(0) + 2 \sum_{k \geq 1} \gamma(k) \cos(\omega k) \tag{9}$$

It is not difficult to confirm that f is

- real-valued
- even ($f(\omega) = f(-\omega)$), and
- 2π-periodic, in the sense that $f(2\pi + \omega) = f(\omega)$ for all ω

It follows that the values of f on $[0, \pi]$ determine the values of f on all of $\mathbb{R}$ — the proof is an exercise.

For this reason it is standard to plot the spectral density only on the interval $[0, \pi]$.

54.4.3 Example 1: White Noise

Consider a white noise process $\{\epsilon_t\}$ with standard deviation σ.

It is easy to check that in this case $f(\omega) = \sigma^2$. So f is a constant function.

As we will see, this can be interpreted as meaning that "all frequencies are equally present".

(White light has this property when frequency refers to the visible spectrum, a connection that provides the origins of the term "white noise")

54.4.4 Example 2: AR and MA and ARMA

It is an exercise to show that the MA(1) process $X_t = \theta\epsilon_{t-1} + \epsilon_t$ has spectral density

$$f(\omega) = \sigma^2(1 + 2\theta\cos(\omega) + \theta^2) \tag{10}$$

With a bit more effort, it is possible to show (see, e.g., p. 261 of [94]) that the spectral density of the AR(1) process $X_t = \phi X_{t-1} + \epsilon_t$ is

$$f(\omega) = \frac{\sigma^2}{1 - 2\phi\cos(\omega) + \phi^2} \tag{11}$$

More generally, it can be shown that the spectral density of the ARMA process (5) is

$$f(\omega) = \left|\frac{\theta(e^{i\omega})}{\phi(e^{i\omega})}\right|^2 \sigma^2 \tag{12}$$

where

- σ is the standard deviation of the white noise process $\{\epsilon_t\}$
- the polynomials $\phi(\cdot)$ and $\theta(\cdot)$ are as defined in (7)

The derivation of (12) uses the fact that convolutions become products under Fourier transformations.

The proof is elegant and can be found in many places — see, for example, [94], chapter 11, section 4.

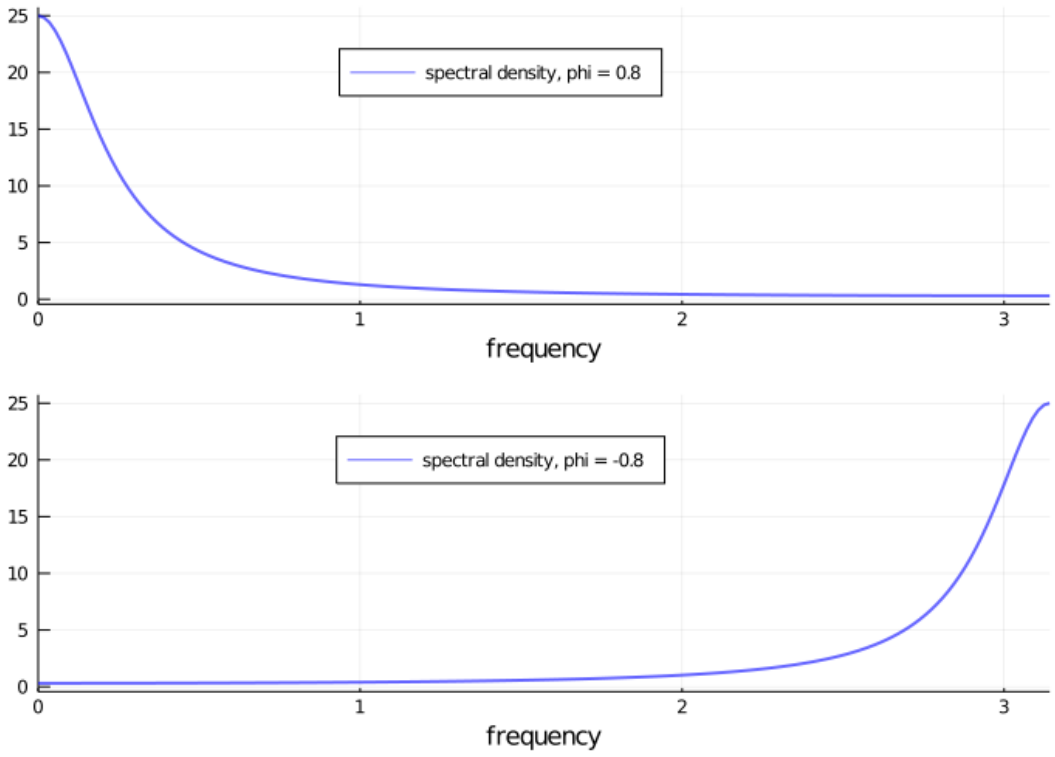
It is a nice exercise to verify that (10) and (11) are indeed special cases of (12).

54.4.5 Interpreting the Spectral Density

Plotting (11) reveals the shape of the spectral density for the AR(1) model when ϕ takes the values 0.8 and -0.8 respectively

In [4]:
```
ar1_sd(ϕ, ω) = 1 ./ (1 .- 2 * ϕ * cos.(ω) .+ ϕ.^2)

ω_s = range(0, π, length = 180)

plt_1=plot()
plt_2=plot()
plots=[plt_1, plt_2]

for (i, ϕ) in enumerate((0.8, -0.8))
    sd = ar1_sd(ϕ, ω_s)
    label = "spectral density, phi = $ϕ"
    plot!(plots[i], ω_s, sd, color=:blue, alpha=0.6, lw=2, label=label)
    plot!(plots[i], legend=:top, xlabel="frequency", xlim=(0,π))
end
plot(plots[1], plots[2], layout=(2,1), size=(700,500))
```

Out[4]:



These spectral densities correspond to the autocovariance functions for the AR(1) process shown above.

Informally, we think of the spectral density as being large at those $\omega \in [0, \pi]$ at which the autocovariance function seems approximately to exhibit big damped cycles.

To see the idea, let's consider why, in the lower panel of the preceding figure, the spectral density for the case $\phi = -0.8$ is large at $\omega = \pi$.

Recall that the spectral density can be expressed as

$$f(\omega) = \gamma(0) + 2 \sum_{k \geq 1} \gamma(k) \cos(\omega k) = \gamma(0) + 2 \sum_{k \geq 1} (-0.8)^k \cos(\omega k) \tag{13}$$

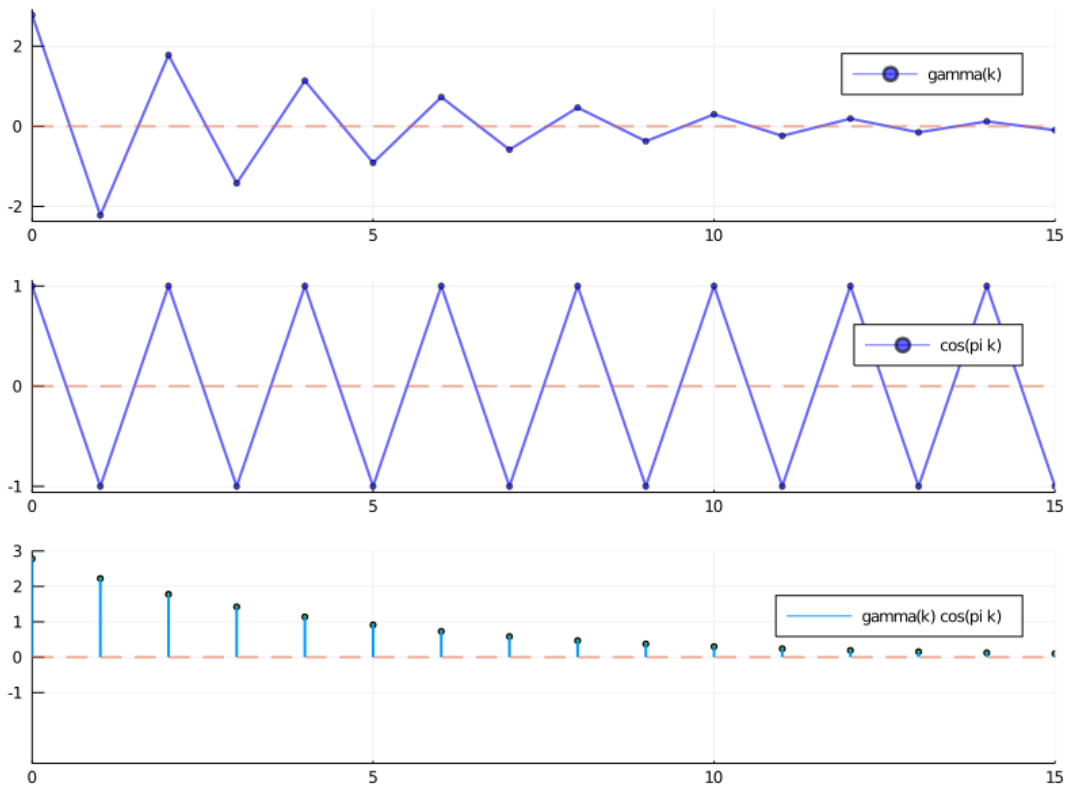
When we evaluate this at $\omega = \pi$, we get a large number because $\cos(\pi k)$ is large and positive when $(-0.8)^k$ is positive, and large in absolute value and negative when $(-0.8)^k$ is negative.

Hence the product is always large and positive, and hence the sum of the products on the right-hand side of (13) is large.

These ideas are illustrated in the next figure, which has k on the horizontal axis

In [5]:
```
ϕ = -0.8
times = 0:16
y1 = [ϕ.^k ./ (1 - ϕ.^2) for k in times]
y2 = [cos.(π * k) for k in times]
y3 = [a * b for (a, b) in zip(y1, y2)]

# Autocovariance when ☒ = -0.8
plt_1 = plot(times, y1, color=:blue, lw=2, marker=:circle, markersize=3,
             alpha=0.6, label="gamma(k)")
plot!(plt_1, seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
      lw=2, label="")
plot!(plt_1, legend=:topright, xlim=(0,15), yticks=[-2, 0, 2])

# Cycles at frequence 𝝅
plt_2 = plot(times, y2, color=:blue, lw=2, marker=:circle, markersize=3,
             alpha=0.6, label="cos(pi k)")
plot!(plt_2, seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
      lw=2, label="")
plot!(plt_2, legend=:topright, xlim=(0,15), yticks=[-1, 0, 1])

# Product
plt_3 = plot(times, y3, seriestype=:sticks, marker=:circle, markersize=3,
             lw=2, label="gamma(k) cos(pi k)")
plot!(plt_3, seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
      lw=2, label="")
plot!(plt_3, legend=:topright, xlim=(0,15), ylim=(-3,3), yticks=[-1, 0, 1,
↪2, 3])

plot(plt_1, plt_2, plt_3, layout=(3,1), size=(800,600))
```

Out[5]:

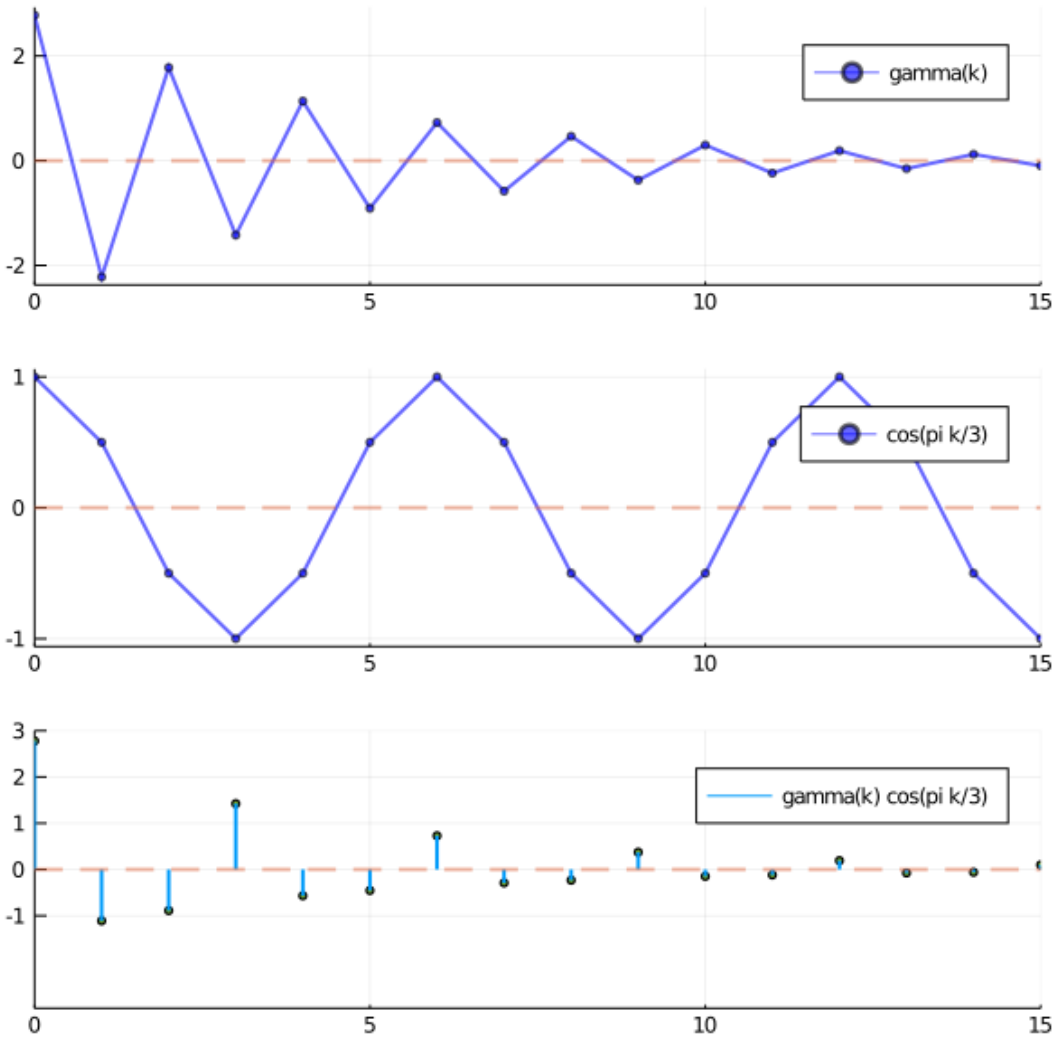


On the other hand, if we evaluate $f(\omega)$ at $\omega = \pi/3$, then the cycles are not matched, the sequence $\gamma(k)\cos(\omega k)$ contains both positive and negative terms, and hence the sum of these terms is much smaller

In [6]:
```
ϕ = -0.8
times = 0:16
y1 = [ϕ.^k ./ (1 - ϕ.^2) for k in times]
y2 = [cos.(π * k/3) for k in times]
y3 = [a * b for (a, b) in zip(y1, y2)]

# Autocovariance when ☒ = -0.8
plt_1 = plot(times, y1, color=:blue, lw=2, marker=:circle, markersize=3,
             alpha=0.6, label="gamma(k)")
plot!(plt_1, seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
      lw=2, label="")
plot!(plt_1, legend=:topright, xlim=(0,15), yticks=[-2, 0, 2])

# Cycles at frequence π
plt_2 = plot(times, y2, color=:blue, lw=2, marker=:circle, markersize=3,
             alpha=0.6, label="cos(pi k/3)")
plot!(plt_2, seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
      lw=2, label="")
plot!(plt_2, legend=:topright, xlim=(0,15), yticks=[-1, 0, 1])

# Product
plt_3 = plot(times, y3, seriestype=:sticks, marker=:circle, markersize=3,
             lw=2, label="gamma(k) cos(pi k/3)")
plot!(plt_3, seriestype=:hline, [0], linestyle=:dash, alpha=0.5,
      lw=2, label="")
plot!(plt_3, legend=:topright, xlim=(0,15), ylim=(-3,3), yticks=[-1, 0, 1,
↪2, 3])
```

```
plot(plt_1, plt_2, plt_3, layout=(3,1), size=(600,600))
```

Out[6]:



In summary, the spectral density is large at frequencies ω where the autocovariance function exhibits damped cycles.

54.4.6 Inverting the Transformation

We have just seen that the spectral density is useful in the sense that it provides a frequency-based perspective on the autocovariance structure of a covariance stationary process.

Another reason that the spectral density is useful is that it can be "inverted" to recover the autocovariance function via the *inverse Fourier transform*.

In particular, for all $k \in \mathbb{Z}$, we have

$$\gamma(k) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(\omega) e^{i\omega k} d\omega \tag{14}$$

This is convenient in situations where the spectral density is easier to calculate and manipulate than the autocovariance function.

(For example, the expression (12) for the ARMA spectral density is much easier to work with than the expression for the ARMA autocovariance)

54.4.7 Mathematical Theory

This section is loosely based on [94], p. 249-253, and included for those who

- would like a bit more insight into spectral densities
- and have at least some background in Hilbert space theory

Others should feel free to skip to the next section — none of this material is necessary to progress to computation.

Recall that every separable Hilbert space H has a countable orthonormal basis $\{h_k\}$.

The nice thing about such a basis is that every $f \in H$ satisfies

$$f = \sum_k \alpha_k h_k \quad \text{where} \quad \alpha_k := \langle f, h_k \rangle \tag{15}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in H.

Thus, f can be represented to any degree of precision by linearly combining basis vectors.

The scalar sequence $\alpha = \{\alpha_k\}$ is called the *Fourier coefficients* of f, and satisfies $\sum_k |\alpha_k|^2 < \infty$.

In other words, α is in ℓ_2, the set of square summable sequences.

Consider an operator T that maps $\alpha \in \ell_2$ into its expansion $\sum_k \alpha_k h_k \in H$.

The Fourier coefficients of $T\alpha$ are just $\alpha = \{\alpha_k\}$, as you can verify by confirming that $\langle T\alpha, h_k \rangle = \alpha_k$.

Using elementary results from Hilbert space theory, it can be shown that

- T is one-to-one — if α and β are distinct in ℓ_2, then so are their expansions in H
- T is onto — if $f \in H$ then its preimage in ℓ_2 is the sequence α given by $\alpha_k = \langle f, h_k \rangle$
- T is a linear isometry — in particular $\langle \alpha, \beta \rangle = \langle T\alpha, T\beta \rangle$

Summarizing these results, we say that any separable Hilbert space is isometrically isomorphic to ℓ_2.

In essence, this says that each separable Hilbert space we consider is just a different way of looking at the fundamental space ℓ_2.

With this in mind, let's specialize to a setting where

- $\gamma \in \ell_2$ is the autocovariance function of a covariance stationary process, and f is the spectral density
- $H = L_2$, where L_2 is the set of square summable functions on the interval $[-\pi, \pi]$, with inner product $\langle g, h \rangle = \int_{-\pi}^{\pi} g(\omega) h(\omega) d\omega$
- $\{h_k\}$ = the orthonormal basis for L_2 given by the set of trigonometric functions

$$h_k(\omega) = \frac{e^{i\omega k}}{\sqrt{2\pi}}, \quad k \in \mathbb{Z}, \quad \omega \in [-\pi, \pi]$$

Using the definition of T from above and the fact that f is even, we now have

$$T\gamma = \sum_{k \in \mathbb{Z}} \gamma(k) \frac{e^{i\omega k}}{\sqrt{2\pi}} = \frac{1}{\sqrt{2\pi}} f(\omega) \tag{16}$$

In other words, apart from a scalar multiple, the spectral density is just an transformation of $\gamma \in \ell_2$ under a certain linear isometry — a different way to view γ.

In particular, it is an expansion of the autocovariance function with respect to the trigonometric basis functions in L_2.

As discussed above, the Fourier coefficients of $T\gamma$ are given by the sequence γ, and, in particular, $\gamma(k) = \langle T\gamma, h_k \rangle$.

Transforming this inner product into its integral expression and using (16) gives (14), justifying our earlier expression for the inverse transform.

54.5 Implementation

Most code for working with covariance stationary models deals with ARMA models.

Julia code for studying ARMA models can be found in the `DSP.jl` package.

Since this code doesn't quite cover our needs — particularly vis-a-vis spectral analysis — we've put together the module arma.jl, which is part of QuantEcon.jl package.

The module provides functions for mapping ARMA(p, q) models into their

1. impulse response function
2. simulated time series
3. autocovariance function
4. spectral density

54.5.1 Application

Let's use this code to replicate the plots on pages 68–69 of [68].

Here are some functions to generate the plots

In [7]:
```
using QuantEcon, Random

# plot functions
function plot_spectral_density(arma, plt)
    (w, spect) = spectral_density(arma, two_pi=false)
    plot!(plt, w, spect, lw=2, alpha=0.7,label="")
    plot!(plt, title="Spectral density", xlim=(0,π),
          xlabel="frequency", ylabel="spectrum", yscale=:log)
    return plt
end

function plot_spectral_density(arma)
    plt = plot()
```

```
        plot_spectral_density(arma, plt=plt)
        return plt
    end

    function plot_autocovariance(arma, plt)
        acov = autocovariance(arma)
        n = length(acov)
        plot!(plt, 0:(n-1), acov, seriestype=:sticks, marker=:circle,
              markersize=2,label="")
        plot!(plt, seriestype=:hline, [0], color=:red, label="")
        plot!(plt, title="Autocovariance", xlim=(-0.5, n-0.5),
              xlabel="time", ylabel="autocovariance")
        return plt
    end

    function plot_autocovariance(arma)
        plt = plot()
        plot_spectral_density(arma, plt=plt)
        return plt
    end

    function plot_impulse_response(arma, plt)
        psi = impulse_response(arma)
        n = length(psi)
        plot!(plt, 0:(n-1), psi, seriestype=:sticks, marker=:circle,
              markersize=2, label="")
        plot!(plt, seriestype=:hline, [0], color=:red, label="")
        plot!(plt, title="Impluse response", xlim=(-0.5,n-0.5),
              xlabel="time", ylabel="response")
        return plt
    end

    function plot_impulse_response(arma)
        plt = plot()
        plot_spectral_density(arma, plt=plt)
        return plt
    end

    function plot_simulation(arma, plt)
        X = simulation(arma)
        n = length(X)
        plot!(plt, 0:(n-1), X, lw=2, alpha=0.7, label="")
        plot!(plt, title="Sample path", xlim=(0,0,n), xlabel="time",
↪ylabel="state space")
        return plt
    end

    function plot_simulation(arma)
        plt = plot()
        plot_spectral_density(arma, plt=plt)
        return plt
    end

    function quad_plot(arma)
        plt_1 = plot()
        plt_2 = plot()
        plt_3 = plot()
        plt_4 = plot()
```

```
        plots = [plt_1, plt_2, plt_3, plt_4]

        plot_functions = [plot_spectral_density,
                          plot_impulse_response,
                          plot_autocovariance,
                          plot_simulation]
        for (i, plt, plot_func) in zip(1:1:4, plots, plot_functions)
            plots[i] = plot_func(arma, plt)
        end
        return plot(plots[1], plots[2], plots[3], plots[4], layout=(2,2),
↪size=(800,800))

    end
```

```
Out[7]: quad_plot (generic function with 1 method)
```

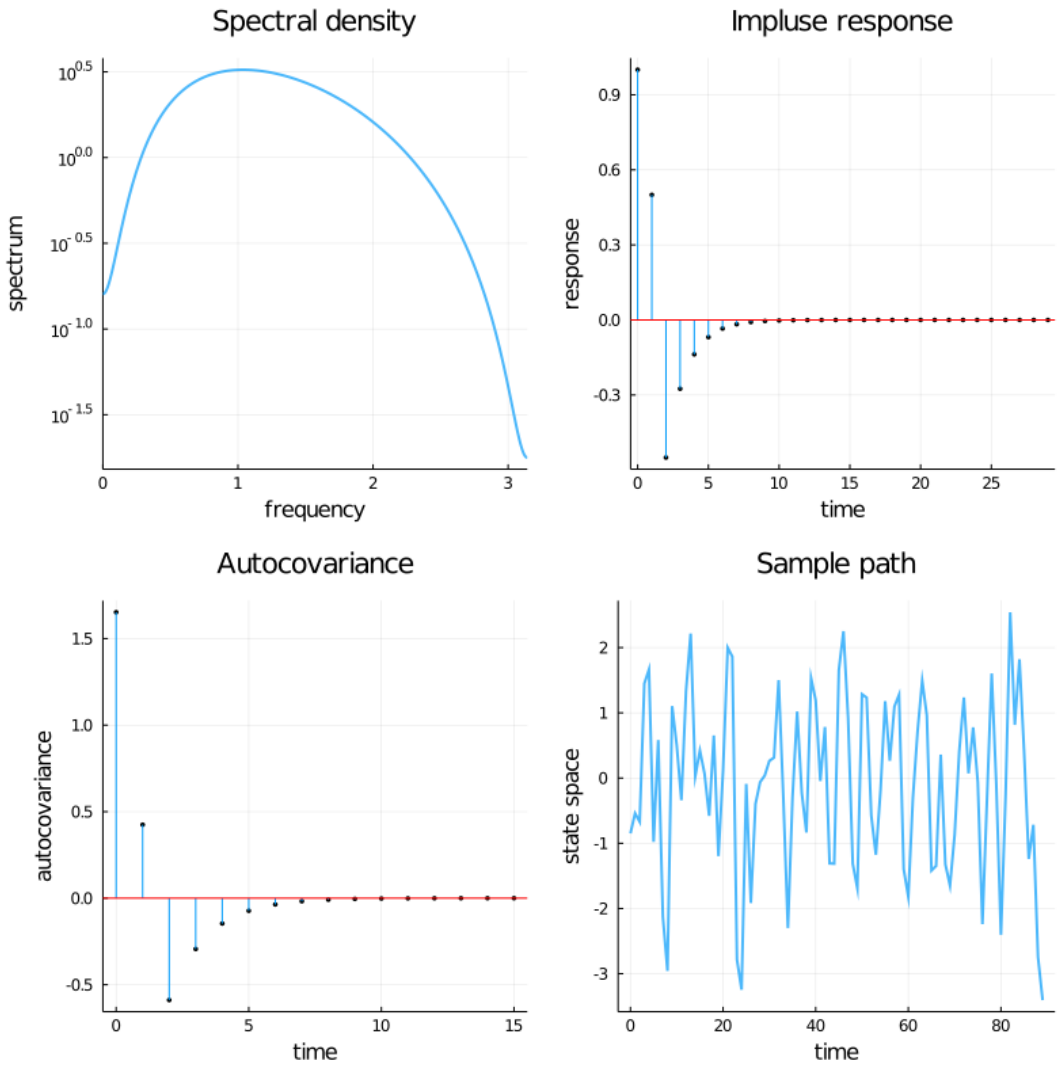
Now let's call these functions to generate the plots.

We'll use the model $X_t = 0.5X_{t-1} + \epsilon_t - 0.8\epsilon_{t-2}$

```
In [8]: Random.seed!(42) # For reproducible results.
        ϕ = 0.5;
        θ = [0, -0.8];
        arma = ARMA(ϕ, θ, 1.0)
        quad_plot(arma)
```



```
Out[8]:
```



54.5.2 Explanation

The call

```
arma = ARMA(ϕ, θ, σ)
```

creates an instance `arma` that represents the ARMA(p, q) model

$$X_t = \phi_1 X_{t-1} + ... + \phi_p X_{t-p} + \epsilon_t + \theta_1 \epsilon_{t-1} + ... + \theta_q \epsilon_{t-q}$$

If ϕ and θ are arrays or sequences, then the interpretation will be

- ϕ holds the vector of parameters $(\phi_1, \phi_2, ..., \phi_p)$
- θ holds the vector of parameters $(\theta_1, \theta_2, ..., \theta_q)$

The parameter σ is always a scalar, the standard deviation of the white noise.

We also permit ϕ and θ to be scalars, in which case the model will be interpreted as

$$X_t = \phi X_{t-1} + \epsilon_t + \theta \epsilon_{t-1}$$

The two numerical packages most useful for working with ARMA models are `DSP.jl` and the `fft` routine in Julia.

54.5.3 Computing the Autocovariance Function

As discussed above, for ARMA processes the spectral density has a simple representation that is relatively easy to calculate.

Given this fact, the easiest way to obtain the autocovariance function is to recover it from the spectral density via the inverse Fourier transform.

Here we use Julia's Fourier transform routine fft, which wraps a standard C-based package called FFTW.

A look at the fft documentation shows that the inverse transform ifft takes a given sequence $A_0, A_1, \ldots, A_{n-1}$ and returns the sequence $a_0, a_1, \ldots, a_{n-1}$ defined by

$$a_k = \frac{1}{n} \sum_{t=0}^{n-1} A_t e^{ik2\pi t/n}$$

Thus, if we set $A_t = f(\omega_t)$, where f is the spectral density and $\omega_t := 2\pi t/n$, then

$$a_k = \frac{1}{n} \sum_{t=0}^{n-1} f(\omega_t) e^{i\omega_t k} = \frac{1}{2\pi} \frac{2\pi}{n} \sum_{t=0}^{n-1} f(\omega_t) e^{i\omega_t k}, \qquad \omega_t := 2\pi t/n$$

For n sufficiently large, we then have

$$a_k \approx \frac{1}{2\pi} \int_0^{2\pi} f(\omega) e^{i\omega k} d\omega = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(\omega) e^{i\omega k} d\omega$$

(You can check the last equality)

In view of (14) we have now shown that, for n sufficiently large, $a_k \approx \gamma(k)$ — which is exactly what we want to compute.

Chapter 55

Estimation of Spectra

55.1 Contents

55.2 Overview

In a previous lecture we covered some fundamental properties of covariance stationary linear stochastic processes.

One objective for that lecture was to introduce spectral densities — a standard and very useful technique for analyzing such processes.

In this lecture we turn to the problem of estimating spectral densities and other related quantities from data.

Estimates of the spectral density are computed using what is known as a periodogram — which in turn is computed via the famous fast Fourier transform.

Once the basic technique has been explained, we will apply it to the analysis of several key macroeconomic time series.

For supplementary reading, see [94] or [18].

55.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

55.3 Periodograms

Recall that the spectral density f of a covariance stationary process with autocorrelation function γ can be written

$$f(\omega) = \gamma(0) + 2\sum_{k\geq 1}\gamma(k)\cos(\omega k), \qquad \omega \in \mathbb{R}$$

Now consider the problem of estimating the spectral density of a given time series, when γ is unknown.

In particular, let $X_0, \ldots, X_{n-1}$ be n consecutive observations of a single time series that is assumed to be covariance stationary.

The most common estimator of the spectral density of this process is the *periodogram* of $X_0, \ldots, X_{n-1}$, which is defined as

$$I(\omega) := \frac{1}{n}\left|\sum_{t=0}^{n-1} X_t e^{it\omega}\right|^2, \qquad \omega \in \mathbb{R} \tag{1}$$

(Recall that $|z|$ denotes the modulus of complex number z)

Alternatively, $I(\omega)$ can be expressed as

$$I(\omega) = \frac{1}{n}\left\{\left[\sum_{t=0}^{n-1} X_t\cos(\omega t)\right]^2 + \left[\sum_{t=0}^{n-1} X_t\sin(\omega t)\right]^2\right\}$$

It is straightforward to show that the function I is even and 2π-periodic (i.e., $I(\omega) = I(-\omega)$ and $I(\omega + 2\pi) = I(\omega)$ for all $\omega \in \mathbb{R}$).

From these two results, you will be able to verify that the values of I on $[0, \pi]$ determine the values of I on all of $\mathbb{R}$.

The next section helps to explain the connection between the periodogram and the spectral density.

55.3.1 Interpretation

To interpret the periodogram, it is convenient to focus on its values at the *Fourier frequencies*

$$\omega_j := \frac{2\pi j}{n}, \quad j = 0, \ldots, n-1$$

In what sense is $I(\omega_j)$ an estimate of $f(\omega_j)$?

The answer is straightforward, although it does involve some algebra.

With a bit of effort one can show that, for any integer $j > 0$,

$$\sum_{t=0}^{n-1} e^{it\omega_j} = \sum_{t=0}^{n-1}\exp\left\{i2\pi j\frac{t}{n}\right\} = 0$$

Letting $\bar{X}$ denote the sample mean $n^{-1}\sum_{t=0}^{n-1} X_t$, we then have

$$nI(\omega_j) = \left| \sum_{t=0}^{n-1} (X_t - \bar{X}) e^{it\omega_j} \right|^2 = \sum_{t=0}^{n-1} (X_t - \bar{X}) e^{it\omega_j} \sum_{r=0}^{n-1} (X_r - \bar{X}) e^{-ir\omega_j}$$

By carefully working through the sums, one can transform this to

$$nI(\omega_j) = \sum_{t=0}^{n-1} (X_t - \bar{X})^2 + 2 \sum_{k=1}^{n-1} \sum_{t=k}^{n-1} (X_t - \bar{X})(X_{t-k} - \bar{X}) \cos(\omega_j k)$$

Now let

$$\hat{\gamma}(k) := \frac{1}{n} \sum_{t=k}^{n-1} (X_t - \bar{X})(X_{t-k} - \bar{X}), \qquad k = 0, 1, \ldots, n-1$$

This is the sample autocovariance function, the natural "plug-in estimator" of the autocovariance function γ.

("Plug-in estimator" is an informal term for an estimator found by replacing expectations with sample means)

With this notation, we can now write

$$I(\omega_j) = \hat{\gamma}(0) + 2 \sum_{k=1}^{n-1} \hat{\gamma}(k) \cos(\omega_j k)$$

Recalling our expression for f given above, we see that $I(\omega_j)$ is just a sample analog of $f(\omega_j)$.

55.3.2 Calculation

Let's now consider how to compute the periodogram as defined in (1).

There are already functions available that will do this for us — an example is `periodogram` in the `DSP.jl` package.

However, it is very simple to replicate their results, and this will give us a platform to make useful extensions.

The most common way to calculate the periodogram is via the discrete Fourier transform, which in turn is implemented through the fast Fourier transform algorithm.

In general, given a sequence $a_0, \ldots, a_{n-1}$, the discrete Fourier transform computes the sequence

$$A_j := \sum_{t=0}^{n-1} a_t \exp\left\{ i 2\pi \frac{tj}{n} \right\}, \qquad j = 0, \ldots, n-1$$

With $a_0, \ldots, a_{n-1}$ stored in Julia array `a`, the function call `fft(a)` returns the values $A_0, \ldots, A_{n-1}$ as a Julia array.

It follows that, when the data $X_0, \ldots, X_{n-1}$ are stored in array `X`, the values $I(\omega_j)$ at the Fourier frequencies, which are given by

$$\frac{1}{n}\left|\sum_{t=0}^{n-1} X_t \exp\left\{i2\pi\frac{tj}{n}\right\}\right|^2, \qquad j = 0, \dots, n-1$$

can be computed by `abs(fft(X)).^2 / length(X)`.

Note: The Julia function `abs` acts elementwise, and correctly handles complex numbers (by computing their modulus, which is exactly what we need).

A function called `periodogram` that puts all this together can be found here.

Let's generate some data for this function using the `ARMA` type from QuantEcon.jl (see the lecture on linear processes for more details).

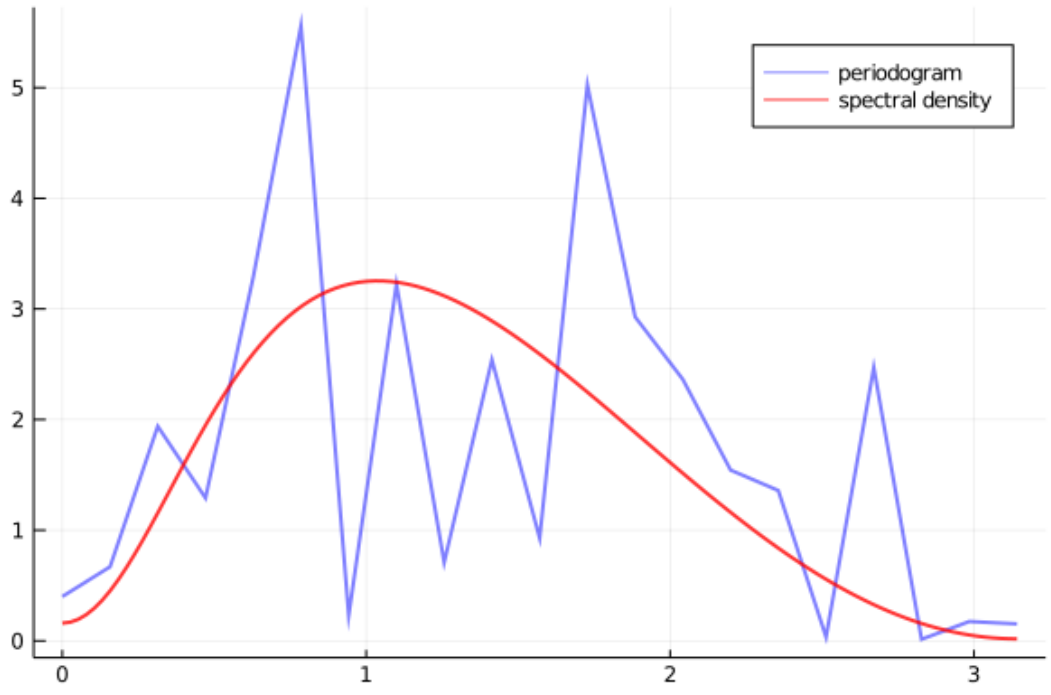
Here's a code snippet that, once the preceding code has been run, generates data from the process

$$X_t = 0.5X_{t-1} + \epsilon_t - 0.8\epsilon_{t-2} \tag{2}$$

where $\{\epsilon_t\}$ is white noise with unit variance, and compares the periodogram to the actual spectral density

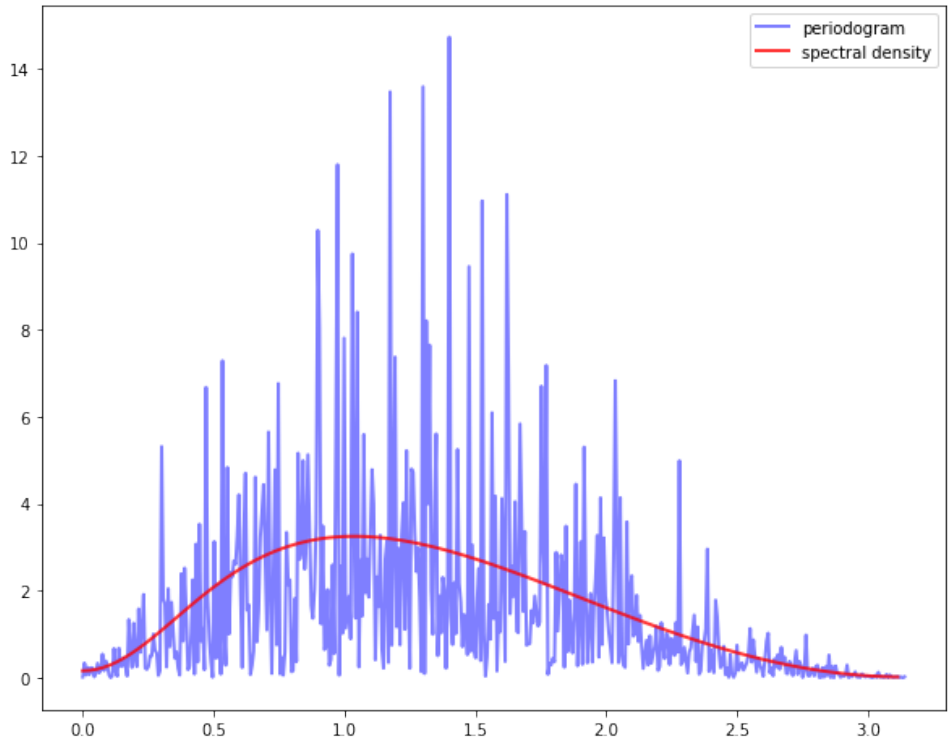
In [3]:
```
using QuantEcon, Plots, Random
gr(fmt = :png);
Random.seed!(42) # For reproducible results.

n = 40               # Data size
ϕ = 0.5              # AR parameter
θ = [0, -0.8]        # MA parameter
σ = 1.0
lp = ARMA(ϕ, θ, σ)
X = simulation(lp, ts_length = n)

x, y = periodogram(X)
x_sd, y_sd = spectral_density(lp, two_pi=false, res=120)

plot(x, y,linecolor="blue", linewidth=2, linealpha=0.5, lab="periodogram")
plot!(x_sd, y_sd, linecolor="red", linewidth=2, linealpha=0.8,
↪lab="spectral density")
```

Out[3]:



This estimate looks rather disappointing, but the data size is only 40, so perhaps it's not surprising that the estimate is poor.

However, if we try again with `n = 1200` the outcome is not much better



The periodogram is far too irregular relative to the underlying spectral density.

This brings us to our next topic.

55.4 Smoothing

There are two related issues here.

One is that, given the way the fast Fourier transform is implemented, the number of points ω at which $I(\omega)$ is estimated increases in line with the amount of data.

In other words, although we have more data, we are also using it to estimate more values.

A second issue is that densities of all types are fundamentally hard to estimate without parametric assumptions.

Typically, nonparametric estimation of densities requires some degree of smoothing.

The standard way that smoothing is applied to periodograms is by taking local averages.

In other words, the value $I(\omega_j)$ is replaced with a weighted average of the adjacent values

$$I(\omega_{j-p}), I(\omega_{j-p+1}), \ldots, I(\omega_j), \ldots, I(\omega_{j+p})$$

This weighted average can be written as

$$I_S(\omega_j) := \sum_{\ell=-p}^{p} w(\ell) I(\omega_{j+\ell}) \tag{3}$$

where the weights $w(-p), \ldots, w(p)$ are a sequence of $2p+1$ nonnegative values summing to one.

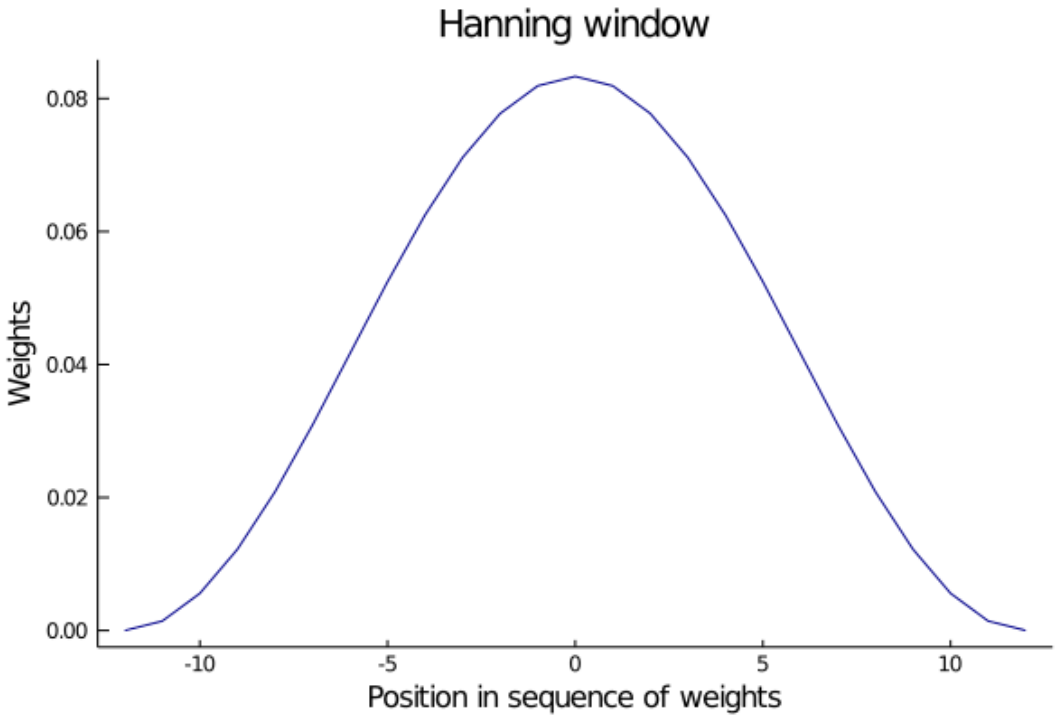
In generally, larger values of p indicate more smoothing — more on this below.

The next figure shows the kind of sequence typically used.

Note the smaller weights towards the edges and larger weights in the center, so that more distant values from $I(\omega_j)$ have less weight than closer ones in the sum (3)

In [4]:
```
function hanning_window(M)
    w = [0.5 - 0.5 * cos(2 * pi * n / (M - 1)) for n = 0:(M-1)]
    return w
end

window = hanning_window(25) / sum(hanning_window(25))
x = range(-12, 12, length = 25)
plot(x, window, color="darkblue", title="Hanning window", ylabel="Weights",
    xlabel="Position in sequence of weights", legend=false, grid=false)
```

Out[4]:



55.4.1 Estimation with Smoothing

Our next step is to provide code that will not only estimate the periodogram but also provide smoothing as required.

Such functions have been written in estspec.jl and are available once you've installed QuantEcon.jl.

The GitHub listing displays three functions, `smooth()`, `periodogram()`, `ar_periodogram()`. We will discuss the first two here and the third one below.

The `periodogram()` function returns a periodogram, optionally smoothed via the `smooth()` function.

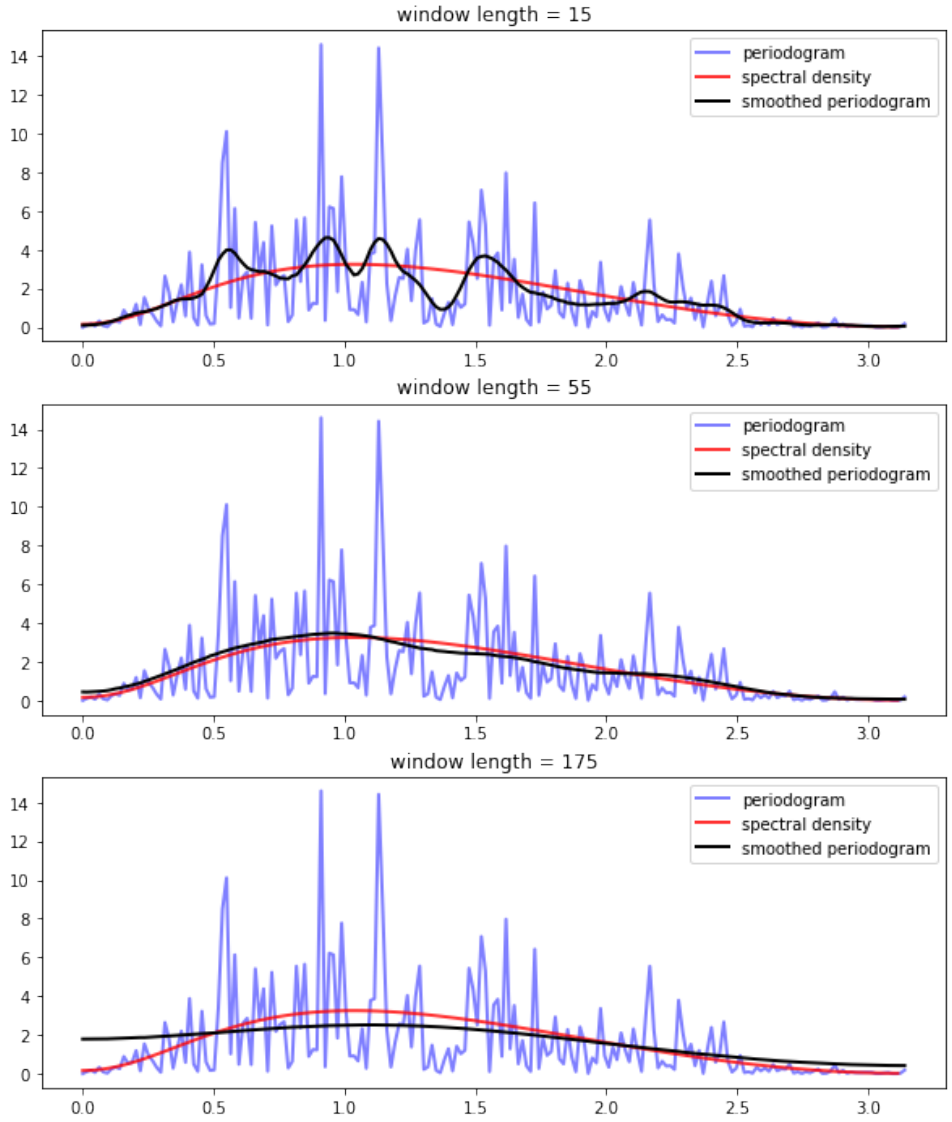
Regarding the `smooth()` function, since smoothing adds a nontrivial amount of computation, we have applied a fairly terse array-centric method based around `conv`.

Readers are left either to explore or simply to use this code according to their interests.

The next three figures each show smoothed and unsmoothed periodograms, as well as the population or "true" spectral density.

(The model is the same as before — see equation (2) — and there are 400 observations)

From top figure to bottom, the window length is varied from small to large.



In looking at the figure, we can see that for this model and data size, the window length chosen in the middle figure provides the best fit.

Relative to this value, the first window length provides insufficient smoothing, while the third gives too much smoothing.

Of course in real estimation problems the true spectral density is not visible and the choice of appropriate smoothing will have to be made based on judgement/priors or some other theory.

55.4.2 Pre-Filtering and Smoothing

In the code listing we showed three functions from the file `estspec.jl`.

The third function in the file (`ar_periodogram()`) adds a pre-processing step to periodogram smoothing.

First we describe the basic idea, and after that we give the code.

The essential idea is to

1. Transform the data in order to make estimation of the spectral density more efficient.
2. Compute the periodogram associated with the transformed data.
3. Reverse the effect of the transformation on the periodogram, so that it now estimates the spectral density of the original process.

Step 1 is called *pre-filtering* or *pre-whitening*, while step 3 is called *recoloring*.

The first step is called pre-whitening because the transformation is usually designed to turn the data into something closer to white noise.

Why would this be desirable in terms of spectral density estimation?

The reason is that we are smoothing our estimated periodogram based on estimated values at nearby points — recall (3).

The underlying assumption that makes this a good idea is that the true spectral density is relatively regular — the value of $I(\omega)$ is close to that of $I(\omega')$ when ω is close to ω'.

This will not be true in all cases, but it is certainly true for white noise.

For white noise, I is as regular as possible — it is a constant function.

In this case, values of $I(\omega')$ at points ω' near to ω provided the maximum possible amount of information about the value $I(\omega)$.

Another way to put this is that if I is relatively constant, then we can use a large amount of smoothing without introducing too much bias.

55.4.3 The AR(1) Setting

Let's examine this idea more carefully in a particular setting — where the data are assumed to be generated by an AR(1) process.

(More general ARMA settings can be handled using similar techniques to those described below)

Suppose in particular that $\{X_t\}$ is covariance stationary and AR(1), with

$$X_{t+1} = \mu + \phi X_t + \epsilon_{t+1} \tag{4}$$

where μ and $\phi \in (-1, 1)$ are unknown parameters and $\{\epsilon_t\}$ is white noise.

It follows that if we regress X_{t+1} on X_t and an intercept, the residuals will approximate white noise.

Let

- g be the spectral density of $\{\epsilon_t\}$ — a constant function, as discussed above
- I_0 be the periodogram estimated from the residuals — an estimate of g
- f be the spectral density of $\{X_t\}$ — the object we are trying to estimate

In view of an earlier result we obtained while discussing ARMA processes, f and g are related by

$$f(\omega) = \left| \frac{1}{1 - \phi e^{i\omega}} \right|^2 g(\omega) \tag{5}$$

This suggests that the recoloring step, which constructs an estimate I of f from I_0, should set

$$I(\omega) = \left| \frac{1}{1 - \hat{\phi} e^{i\omega}} \right|^2 I_0(\omega)$$

where $\hat{\phi}$ is the OLS estimate of ϕ.

The code for `ar_periodogram()` — the third function in `estspec.jl` — does exactly this. (See the code here).

The next figure shows realizations of the two kinds of smoothed periodograms

1. "standard smoothed periodogram", the ordinary smoothed periodogram, and

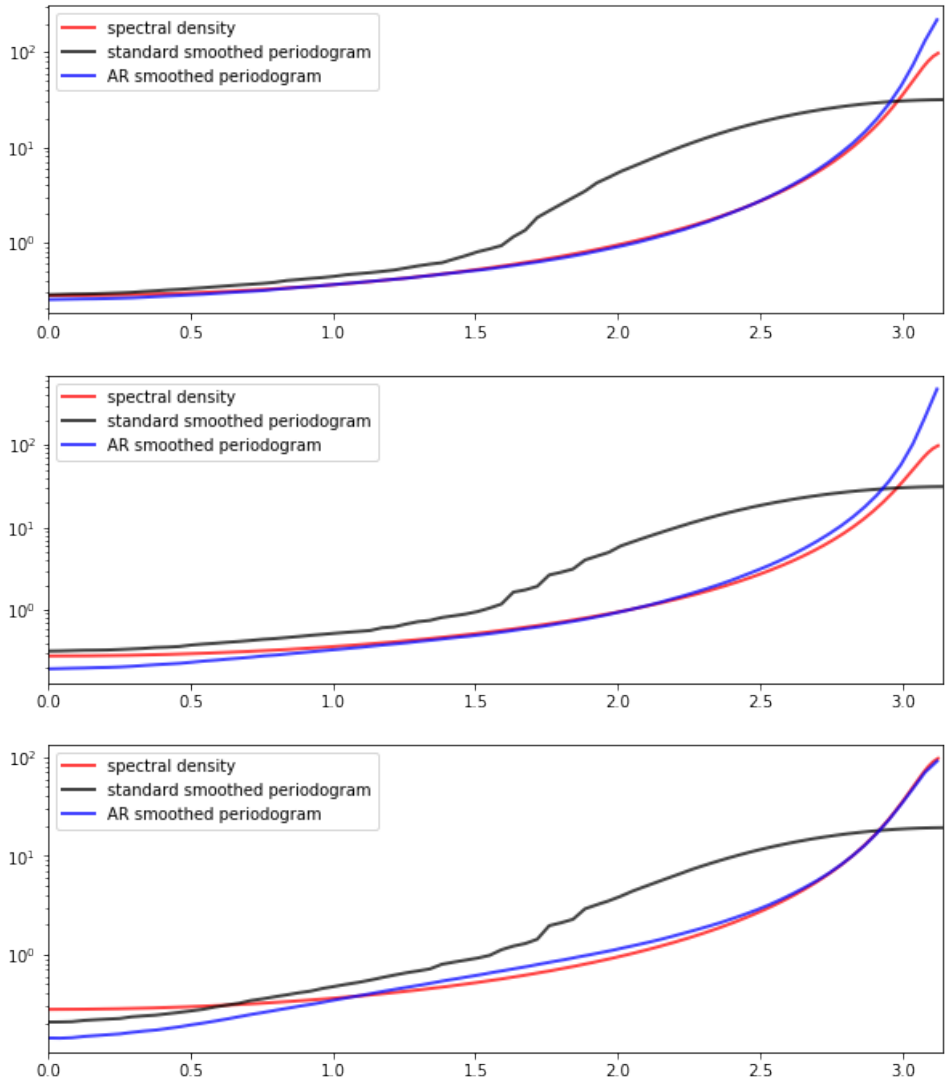
2. "AR smoothed periodogram", the pre-whitened and recolored one generated by `ar_periodogram()`

The periodograms are calculated from time series drawn from (4) with $\mu = 0$ and $\phi = -0.9$.

Each time series is of length 150.

The difference between the three subfigures is just randomness — each one uses a different

draw of the time series.



In all cases, periodograms are fit with the "hamming" window and window length of 65.

Overall, the fit of the AR smoothed periodogram is much better, in the sense of being closer to the true spectral density.

55.5 Exercises

55.5.1 Exercise 1

Replicate this figure (modulo randomness).

The model is as in equation (2) and there are 400 observations.

For the smoothed periodogram, the window type is "hamming".

55.5.2 Exercise 2

Replicate this figure (modulo randomness).

The model is as in equation (4), with $\mu = 0$, $\phi = -0.9$ and 150 observations in each time series.

All periodograms are fit with the "hamming" window and window length of 65.

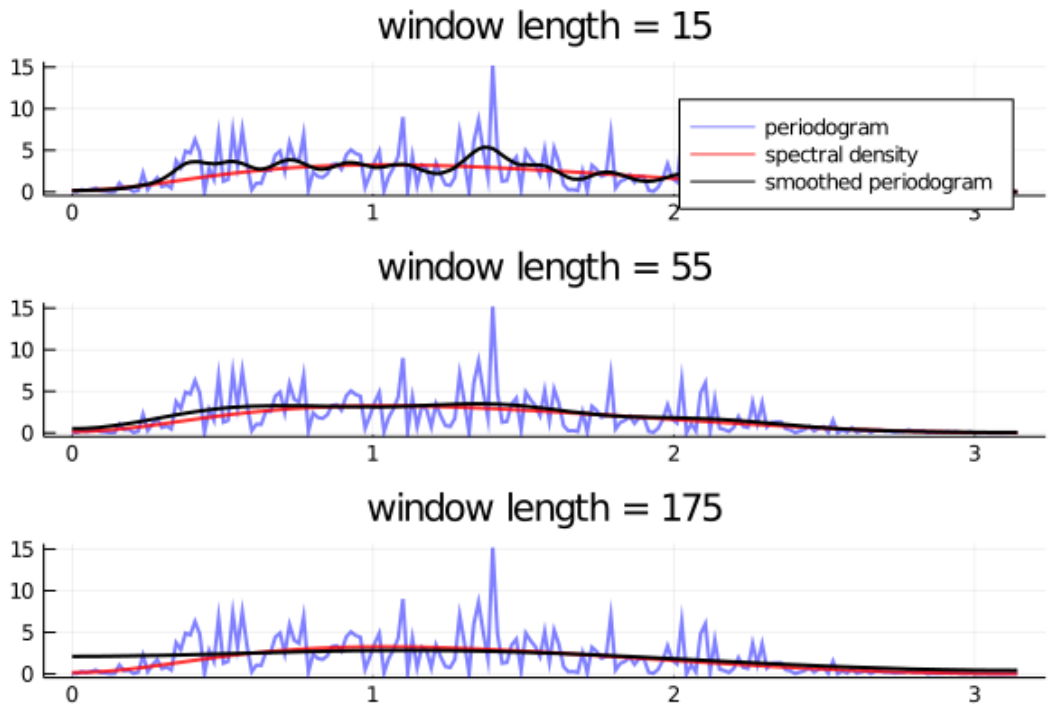
55.6 Solutions

55.6.1 Exercise 1

In [5]:
```
n = 400
ϕ = 0.5
θ = [0, -0.8]
σ = 1.0
lp = ARMA(ϕ, θ, 1.0)
X = simulation(lp, ts_length = n)

xs = []
x_sds = []
x_sms = []
ys = []
y_sds = []
y_sms = []
titles = []

for (i, wl) in enumerate([15, 55, 175])  # window lengths
    x, y = periodogram(X)
    push!(xs, x)
    push!(ys, y)

    x_sd, y_sd = spectral_density(lp, two_pi=false, res=120)
    push!(x_sds, x_sd)
    push!(y_sds, y_sd)

    x, y_smoothed = periodogram(X, "hamming", wl)
    push!(x_sms, x)
    push!(y_sms, y_smoothed)

    t = "window length = $wl"
    push!(titles, t)
end
```

In [6]:
```
plot(xs, ys, layout=(3,1), color=:blue, alpha=0.5,
    linewidth=2, label=["periodogram" "" ""])
plot!(x_sds, y_sds, layout=(3,1), color=:red, alpha=0.8,
    linewidth=2, label=["spectral density" "" ""])
plot!(x_sms, y_sms, layout=(3,1), color=:black,
    linewidth=2, label=["smoothed periodogram" "" ""])
plot!(title=reshape(titles,1,length(titles)))
```

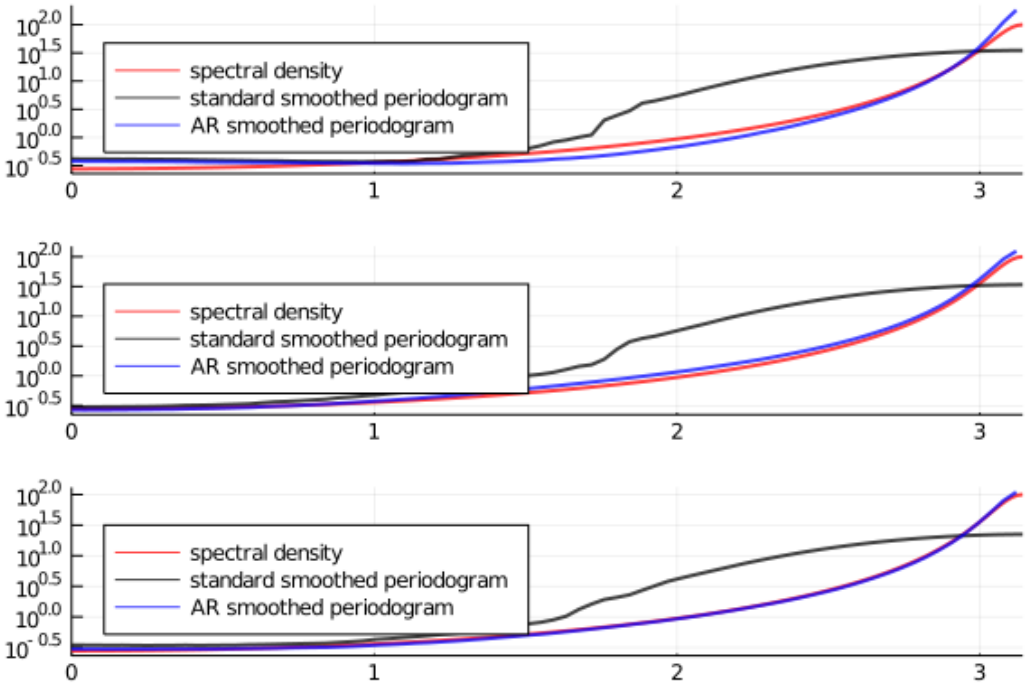
Out[6]:



55.6.2 Exercise 2

In [7]:
```
lp2 = ARMA(-0.9, 0.0, 1.0)
wl = 65
p = plot(layout=(3,1))

for i in 1:3
    X = simulation(lp2,ts_length=150)
    plot!(p[i],xlims = (0,pi))

    x_sd, y_sd = spectral_density(lp2,two_pi=false, res=180)
    plot!(p[i],x_sd, y_sd, linecolor=:red, linestyle=:solid,
        yscale=:log10, linewidth=2, linealpha=0.75,
        label="spectral density",legend=:topleft)

    x, y_smoothed = periodogram(X, "hamming", wl)
    plot!(p[i],x, y_smoothed, linecolor=:black, linestyle=:solid,
        yscale=:log10, linewidth=2, linealpha=0.75,
        label="standard smoothed periodogram",legend=:topleft)

    x, y_ar = ar_periodogram(X, "hamming", wl)
    plot!(p[i],x, y_ar, linecolor=:blue, linestyle=:solid,
        yscale=:log10, linewidth=2, linealpha=0.75,
        label="AR smoothed periodogram",legend=:topleft)
end
p
```

Out[7]:


spectral density
standard smoothed periodogram
AR smoothed periodogram
spectral density
standard smoothed periodogram
AR smoothed periodogram
spectral density
standard smoothed periodogram
AR smoothed periodogram

Chapter 56

Additive Functionals

56.1 Contents

Co-authored with Chase Coleman and Balint Szoke

56.2 Overview

Some time series are nonstationary.

For example, output, prices, and dividends are typically nonstationary, due to irregular but persistent growth.

Which kinds of models are useful for studying such time series?

Hansen and Scheinkman [47] analyze two classes of time series models that accommodate growth.

They are:

1. **additive functionals** that display random "arithmetic growth"
2. **multiplicative functionals** that display random "geometric growth"

These two classes of processes are closely connected.

For example, if a process $\{y_t\}$ is an additive functional and $\phi_t = \exp(y_t)$, then $\{\phi_t\}$ is a multiplicative functional.

Hansen and Sargent [46] (chs. 5 and 6) describe discrete time versions of additive and multiplicative functionals.

In this lecture we discuss the former (i.e., additive functionals).

In the next lecture we discuss multiplicative functionals.

We also consider fruitful decompositions of additive and multiplicative processes, a more in depth discussion of which can be found in Hansen and Sargent [46].

56.3 A Particular Additive Functional

This lecture focuses on a particular type of additive functional: a scalar process $\{y_t\}_{t=0}^{\infty}$ whose increments are driven by a Gaussian vector autoregression.

It is simple to construct, simulate, and analyze.

This additive functional consists of two components, the first of which is a **first-order vector autoregression** (VAR)

$$x_{t+1} = Ax_t + Bz_{t+1} \tag{1}$$

Here

- x_t is an $n \times 1$ vector,
- A is an $n \times n$ stable matrix (all eigenvalues lie within the open unit circle),
- $z_{t+1} \sim N(0, I)$ is an $m \times 1$ i.i.d. shock,
- B is an $n \times m$ matrix, and
- $x_0 \sim N(\mu_0, \Sigma_0)$ is a random initial condition for x

The second component is an equation that expresses increments of $\{y_t\}_{t=0}^{\infty}$ as linear functions of

- a scalar constant ν,
- the vector x_t, and
- the same Gaussian vector z_{t+1} that appears in the VAR (1)

In particular,

$$y_{t+1} - y_t = \nu + Dx_t + Fz_{t+1} \tag{2}$$

Here $y_0 \sim N(\mu_{y0}, \Sigma_{y0})$ is a random initial condition.

The nonstationary random process $\{y_t\}_{t=0}^{\infty}$ displays systematic but random *arithmetic growth*.

56.3.1 A linear state space representation

One way to represent the overall dynamics is to use a linear state space system.

To do this, we set up state and observation vectors

$$\hat{x}_t = \begin{bmatrix} 1 \\ x_t \\ y_t \end{bmatrix} \quad \text{and} \quad \hat{y}_t = \begin{bmatrix} x_t \\ y_t \end{bmatrix}$$

Now we construct the state space system

$$\begin{bmatrix} 1 \\ x_{t+1} \\ y_{t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & A & 0 \\ \nu & D' & 1 \end{bmatrix} \begin{bmatrix} 1 \\ x_t \\ y_t \end{bmatrix} + \begin{bmatrix} 0 \\ B \\ F' \end{bmatrix} z_{t+1}$$

$$\begin{bmatrix} x_t \\ y_t \end{bmatrix} = \begin{bmatrix} 0 & I & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ x_t \\ y_t \end{bmatrix}$$

This can be written as

$$\hat{x}_{t+1} = \hat{A}\hat{x}_t + \hat{B}z_{t+1}$$
$$\hat{y}_t = \hat{D}\hat{x}_t$$

which is a standard linear state space system.

To study it, we could map it into an instance of LSS from QuantEcon.jl.

We will in fact use a different set of code for simulation, for reasons described below.

56.4 Dynamics

Let's run some simulations to build intuition.

In doing so we'll assume that z_{t+1} is scalar and that $\tilde{x}_t$ follows a 4th-order scalar autoregression

$$\tilde{x}_{t+1} = \phi_1\tilde{x}_t + \phi_2\tilde{x}_{t-1} + \phi_3\tilde{x}_{t-2} + \phi_4\tilde{x}_{t-3} + \sigma z_{t+1} \tag{3}$$

Let the increment in $\{y_t\}$ obey

$$y_{t+1} - y_t = \nu + \tilde{x}_t + \sigma z_{t+1}$$

with an initial condition for y_0.

While (3) is not a first order system like (1), we know that it can be mapped into a first order system

- for an example of such a mapping, see this example

In fact this whole model can be mapped into the additive functional system definition in (1) – (2) by appropriate selection of the matrices A, B, D, F.

You can try writing these matrices down now as an exercise — the correct expressions will appear in the code below.

56.4.1 Simulation

When simulating we embed our variables into a bigger system.

This system also constructs the components of the decompositions of y_t and of $\exp(y_t)$ proposed by Hansen and Scheinkman [47].

All of these objects are computed using the code below.

56.4.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

In [2]:
```
using LinearAlgebra, Statistics
```

In [3]:
```
using Distributions, Parameters, Plots, QuantEcon
gr(fmt = :png);
```

In [4]:
```
function AMF_LSS_VAR(A, B, D, F = nothing; ν = nothing)

    if B isa AbstractVector
        B = reshape(B, length(B), 1)
    end
    # unpack required elements
    nx, nk = size(B)

    # checking the dimension of D (extended from the scalar case)
    if ndims(D) > 1
        nm = size(D, 1)
        if D isa Union{Adjoint, Transpose}
            D = convert(Matrix, D)
        end
    else
        nm = 1
        D = reshape(D, 1, length(D))
    end

    # set F
    if isnothing(F)
        F = zeros(nk, 1)
    elseif ndims(F) == 1
        F = reshape(F, length(F), 1)
    end

    # set ν
    if isnothing(ν)
        ν = zeros(nm, 1)
    elseif ndims(ν) == 1
        ν = reshape(ν, length(ν), 1)
    else
        throw(ArgumentError("ν must be column vector!"))
    end

    if size(ν, 1) != size(D, 1)
        error("The size of ν is inconsistent with D!")
    end

    # construct BIG state space representation
    lss = construct_ss(A, B, D, F, ν, nx, nk, nm)

    return (A = A, B = B, D = D, F = F, ν = ν, nx = nx, nk = nk, nm = nm,
↪lss = lss)
end

AMF_LSS_VAR(A, B, D) =
    AMF_LSS_VAR(A, B, D, nothing, ν=nothing)
AMF_LSS_VAR(A, B, D, F, ν) =
    AMF_LSS_VAR(A, B, D, [F], ν=[ν])

function construct_ss(A, B, D, F,
```

```
                    ν, nx, nk, nm)

        H, g = additive_decomp(A, B, D, F, nx)

        # auxiliary blocks with 0's and 1's to fill out the lss matrices
        nx0c = zeros(nx, 1)
        nx0r = zeros(1, nx)
        nx1 = ones(1, nx)
        nk0 = zeros(1, nk)
        ny0c = zeros(nm, 1)
        ny0r = zeros(1, nm)
        ny1m = I + zeros(nm, nm)
        ny0m = zeros(nm, nm)
        nyx0m = similar(D)

        # build A matrix for LSS
        # order of states is: [1, t, xt, yt, mt]
        A1 = hcat(1, 0, nx0r, ny0r, ny0r)          # transition for 1
        A2 = hcat(1, 1, nx0r, ny0r, ny0r)          # transition for t
        A3 = hcat(nx0c, nx0c, A, nyx0m', nyx0m')   # transition for x_{t+1}
        A4 = hcat(ν, ny0c, D, ny1m, ny0m)          # transition for y_{t+1}
        A5 = hcat(ny0c, ny0c, nyx0m, ny0m, ny1m)   # transition for m_{t+1}
        Abar = vcat(A1, A2, A3, A4, A5)

        # build B matrix for LSS
        Bbar = vcat(nk0, nk0, B, F, H)

        # build G matrix for LSS
        # order of observation is: [xt, yt, mt, st, tt]
        G1 = hcat(nx0c, nx0c, I, nyx0m', nyx0m')          # selector for x_{t}
        G2 = hcat(ny0c, ny0c, nyx0m, ny1m, ny0m)          # selector for y_{t}
        G3 = hcat(ny0c, ny0c, nyx0m, ny0m, ny1m)          # selector for
↪martingale
        G4 = hcat(ny0c, ny0c, -g, ny0m, ny0m)             # selector for
↪stationary
        G5 = hcat(ny0c, ν, nyx0m, ny0m, ny0m)             # selector for trend
        Gbar = vcat(G1, G2, G3, G4, G5)

        # build LSS type
        x0 = hcat(1, 0, nx0r, ny0r, ny0r)
        S0 = zeros(length(x0), length(x0))
        lss = LSS(Abar, Bbar, Gbar, zeros(nx+4nm, 1), x0, S0)

        return lss
    end

    function additive_decomp(A, B, D, F, nx)
        A_res = \(I - A, I)
        g = D * A_res
        H = F .+ D * A_res * B

        return H, g
    end

    function multiplicative_decomp(A, B, D, F, ν, nx)
        H, g = additive_decomp(A, B, D, F, nx)
        ν_tilde = ν .+ 0.5 * diag(H * H')
```

```
        return H, g, ν_tilde
    end

    function loglikelihood_path(amf, x, y)
        @unpack A, B, D, F = amf
        k, T = size(y)
        FF = F * F'
        FFinv = inv(FF)
        temp = y[:, 2:end]-y[:, 1:end-1] - D*x[:, 1:end-1]
        obs =  temp .* FFinv .* temp
        obssum = cumsum(obs)
        scalar = (logdet(FF) + k * log(2π)) * (1:T)

        return -(obssum + scalar) / 2
    end

    function loglikelihood(amf, x, y)
        llh = loglikelihood_path(amf, x, y)

        return llh[end]
    end

    function plot_additive(amf, T; npaths = 25, show_trend = true)

        # pull out right sizes so we know how to increment
        @unpack nx, nk, nm = amf

        # allocate space (nm is the number of additive functionals - we want
↪npaths for
    each)
        mpath = zeros(nm*npaths, T)
        mbounds = zeros(2nm, T)
        spath = zeros(nm*npaths, T)
        sbounds = zeros(2nm, T)
        tpath = zeros(nm*npaths, T)
        ypath = zeros(nm*npaths, T)

        # simulate for as long as we wanted
        moment_generator = moment_sequence(amf.lss)

        # pull out population moments
        for (t, x) in enumerate(moment_generator)
            ymeans = x[2]
            yvar = x[4]

            # lower and upper bounds - for each additive functional
            for ii in 1:nm
                li, ui = 2(ii - 1) + 1, 2ii
                if sqrt(yvar[nx + nm + ii, nx + nm + ii]) != 0.0
                    madd_dist = Normal(ymeans[nx + nm + ii], sqrt(yvar[nx + nm
↪+ ii, nx + nm
    + ii]))
                    mbounds[li, t] = quantile(madd_dist, 0.01)
                    mbounds[ui, t] = quantile(madd_dist, 0.99)
                elseif sqrt(yvar[nx + nm + ii, nx + nm + ii]) == 0.0
                    mbounds[li, t] = ymeans[nx + nm + ii]
                    mbounds[ui, t] = ymeans[nx + nm + ii]
                else
```

```
                    error("standard error is negative")
                end

                if sqrt(yvar[nx + 2nm + ii, nx + 2nm + ii]) != 0.0
                    sadd_dist = Normal(ymeans[nx + 2nm + ii], sqrt(yvar[nx +
↪2nm + ii, nx +
    2nm + ii]))
                    sbounds[li, t] = quantile(sadd_dist, 0.01)
                    sbounds[ui, t] = quantile(sadd_dist, 0.99)
                elseif sqrt(yvar[nx + 2nm + ii, nx + 2nm + ii]) == 0.0
                    sbounds[li, t] = ymeans[nx + 2nm + ii]
                    sbounds[ui, t] = ymeans[nx + 2nm + ii]
                else
                    error("standard error is negative")
                end
            end
            t == T && break
        end

        # pull out paths
        for n in 1:npaths
            x, y = simulate(amf.lss,T)
            for ii in 0:nm - 1
                ypath[npaths * ii + n, :] = y[nx + ii + 1, :]
                mpath[npaths * ii + n, :] = y[nx + nm + ii + 1, :]
                spath[npaths * ii + n, :] = y[nx + 2nm + ii + 1, :]
                tpath[npaths * ii + n, :] = y[nx + 3nm + ii + 1, :]
            end
        end

        add_figs = []

        for ii in 0:nm-1
            li, ui = npaths*(ii), npaths*(ii + 1)
            LI, UI = 2ii, 2(ii + 1)
            push!(add_figs,
                plot_given_paths(T, ypath[li + 1:ui, :], mpath[li + 1:ui, :],
↪spath[li +
    1:ui, :],
                                 tpath[li + 1:ui, :], mbounds[LI + 1:UI, :],
↪sbounds[LI +
    1:UI, :],
                                 show_trend = show_trend))
        end
        return add_figs
    end

    function plot_multiplicative(amf, T, npaths = 25, show_trend = true)
        # pull out right sizes so we know how to increment
        @unpack nx, nk, nm = amf
        # matrices for the multiplicative decomposition
        H, g, ν_tilde = multiplicative_decomp(A, B, D, F, ν, nx)

        # allocate space (nm is the number of functionals - we want npaths for
↪each)
        mpath_mult = zeros(nm * npaths, T)
        mbounds_mult = zeros(2nm, T)
        spath_mult = zeros(nm * npaths, T)
```

```
        sbounds_mult = zeros(2nm, T)
        tpath_mult = zeros(nm * npaths, T)
        ypath_mult = zeros(nm * npaths, T)

        # simulate for as long as we wanted
        moment_generator = moment_sequence(amf.lss)

        # pull out population moments
        for (t, x) in enumerate(moment_generator)
            ymeans = x[2]
            yvar = x[4]

            # lower and upper bounds - for each multiplicative functional
            for ii in 1:nm
                li, ui = 2(ii - 1)+1, 2ii
                if yvar[nx + nm + ii, nx + nm + ii] != 0.0
                    Mdist = LogNormal(ymeans[nx + nm + ii]- 0.5t * diag(H *
↪H')[ii],
                                      sqrt(yvar[nx + nm + ii, nx + nm + ii]))
                    mbounds_mult[li, t] = quantile(Mdist, 0.01)
                    mbounds_mult[ui, t] = quantile(Mdist, 0.99)
                elseif yvar[nx + nm + ii, nx + nm + ii] == 0.0
                    mbounds_mult[li, t] = exp.(ymeans[nx + nm + ii] - 0.5t *
↪diag(H *
      H')[ii])
                    mbounds_mult[ui, t] = exp.(ymeans[nx + nm + ii] - 0.5t *
↪diag(H *
      H')[ii])
                else
                    error("standard error is negative")
                end
                if yvar[nx + 2nm + ii, nx + 2nm + ii] != 0.0
                    Sdist = LogNormal(-ymeans[nx + 2nm + ii],
                                      sqrt(yvar[nx + 2nm + ii, nx + 2nm + ii]))
                    sbounds_mult[li, t] = quantile(Sdist, 0.01)
                    sbounds_mult[ui, t] = quantile(Sdist, 0.99)
                elseif yvar[nx + 2nm + ii, nx + 2nm + ii] == 0.0
                    sbounds_mult[li, t] = exp.(-ymeans[nx + 2nm + ii])
                    sbounds_mult[ui, t] = exp.(-ymeans[nx + 2nm + ii])
                else
                    error("standard error is negative")
                end
            end
            t == T && break
        end

        # pull out paths
        for n in 1:npaths
            x, y = simulate(amf.lss,T)
            for ii in 0:nm-1
                ypath_mult[npaths * ii + n, :] = exp.(y[nx+ii+1, :])
                mpath_mult[npaths * ii + n, :] =
                  exp.(y[nx+nm + ii+1, :] - collect(1:T)*0.5*diag(H * H')[ii+1])
                spath_mult[npaths * ii + n, :] = 1 ./exp.(-y[nx+2*nm + ii+1, :])
                tpath_mult[npaths * ii + n, :] =
                    exp.(y[nx + 3nm + ii+1, :] + (1:T) * 0.5 * diag(H * H')[ii
↪+ 1])
            end
```

```
        end

        mult_figs = []

        for ii in 0:nm-1
            li, ui = npaths * ii, npaths * (ii + 1)
            LI, UI = 2ii, 2(ii + 1)
            push!(mult_figs,
                plot_given_paths(T, ypath_mult[li+1:ui, :], mpath_mult[li+1:
↪ui, :],
                                 spath_mult[li+1:ui, :], tpath_mult[li+1:ui, :],
                                mbounds_mult[LI+1:UI, :], sbounds_mult[LI+1:UI, :],
                                 horline = 1.0, show_trend=show_trend))
        end

        return mult_figs
    end

    function plot_martingales(amf, T, npaths = 25)

        # pull out right sizes so we know how to increment
        @unpack A, B, D, F, ν, nx, nk, nm = amf
        # matrices for the multiplicative decomposition
        H, g, ν_tilde = multiplicative_decomp(A, B, D, F, ν, nx)

        # allocate space (nm is the number of functionals - we want npaths for
↪each)
        mpath_mult = zeros(nm * npaths, T)
        mbounds_mult = zeros(2nm, T)

        # simulate for as long as we wanted
        moment_generator = moment_sequence(amf.lss)
        # pull out population moments
        for (t, x) in enumerate(moment_generator)
            ymeans = x[2]
            yvar = x[4]

            # lower and upper bounds - for each functional
            for ii in 1:nm
                li, ui = 2(ii - 1) + 1, 2ii
                if yvar[nx + nm + ii, nx + nm + ii] != 0.0
                   Mdist = LogNormal(ymeans[nx + nm + ii] - 0.5^2 * t * diag(H
↪* H')[ii],
                                     sqrt(yvar[nx + nm + ii, nx + nm + ii]))
                    mbounds_mult[li, t] = quantile(Mdist, 0.01)
                    mbounds_mult[ui, t] = quantile(Mdist, 0.99)
                elseif yvar[nx + nm + ii, nx + nm + ii] == 0.0
                    mbounds_mult[li, t] = ymeans[nx + nm + ii] - 0.5^2 * t *
↪diag(H *
    H')[ii]
                   mbounds_mult[ui, t] = ymeans[nx + nm + ii]- 0.5t * diag(H *
↪H')[ii]
                else
                    error("standard error is negative")
                end
            end
            t == T && break
        end
```

```
        # pull out paths
        for n in 1:npaths
            x, y = simulate(amf.lss, T)
            for ii in 0:nm-1
                mpath_mult[npaths * ii + n, :] =
                    exp.(y[nx+nm + ii+1, :] - (1:T) * 0.5 * diag(H * H')[ii+1])
            end
        end

        mart_figs = []

        for ii in 0:nm-1
            li, ui = npaths*(ii), npaths*(ii + 1)
            LI, UI = 2ii, 2(ii + 1)
            push!(mart_figs,
                plot_martingale_paths(T, mpath_mult[li + 1:ui, :],
                                                    mbounds_mult[LI + 1:UI, :
↪], horline
    = 1))
            plot!(mart_figs[ii + 1], title = "Martingale components for many␣
↪paths of y_(ii
    + 1)")
        end

        return mart_figs
    end

    function plot_given_paths(T, ypath, mpath, spath, tpath, mbounds, sbounds;
                              horline = 0.0, show_trend = true)

        # allocate space
        trange = 1:T

        # allocate transpose
        mpath = Matrix(mpath')

        # create figure
        plots=plot(layout = (2, 2), size = (800, 800))

        # plot all paths together

        plot!(plots[1], trange, ypath[1, :], label = "y_t", color = :black)
        plot!(plots[1], trange, mpath[1, :], label = "m_t", color = :magenta)
        plot!(plots[1], trange, spath[1, :], label = "s_t", color = :green)
        if show_trend
            plot!(plots[1], trange, tpath[1, :], label = "t_t", color = :red)
        end
        plot!(plots[1], seriestype = :hline, [horline], color = :black,␣
↪linestyle=:dash,
    label = "")
        plot!(plots[1], title = "One Path of All Variables", legend=:topleft)

        # plot martingale component
        plot!(plots[2], trange, mpath[1, :], color = :magenta, label = "")
        plot!(plots[2], trange, mpath, alpha = 0.45, color = :magenta, label␣
↪= "")
        ub = mbounds[2, :]
```

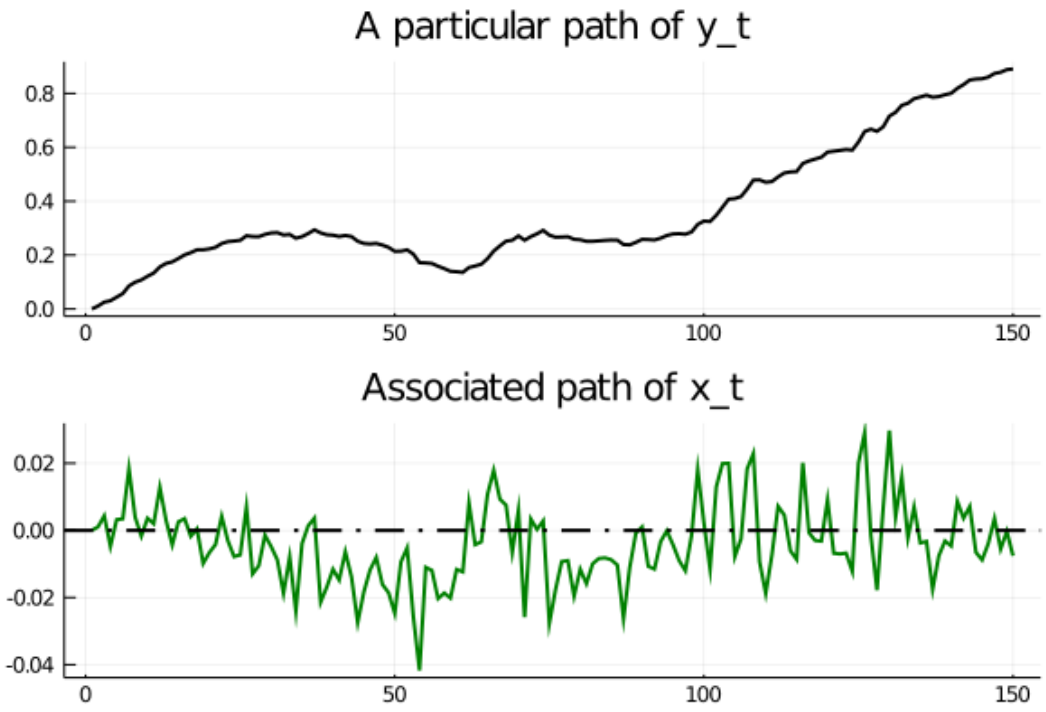
```
            lb = mbounds[1, :]
            plot!(plots[2], ub, fillrange = [lb, ub], alpha = 0.25, color = :
↪magenta, label =
        "")
            plot!(plots[2], seriestype = :hline, [horline], color = :black,
↪linestyle =:dash,
        label = "")
            plot!(plots[2], title = "Martingale Components for Many Paths")

            # plot stationary component
            plot!(plots[3], spath[1, :], color = :green, label = "")
           plot!(plots[3], Matrix(spath'), alpha = 0.25, color = :green, label = "")
            ub = sbounds[2, :]
            lb = sbounds[1, :]
            plot!(plots[3], ub, fillrange = [lb, ub], alpha = 0.25, color = :
↪green, label = "")
            plot!(plots[3], seriestype = :hline, [horline], color = :black,
↪linestyle=:dash,
        label = "")
            plot!(plots[3], title = "Stationary Components for Many Paths")

            # plot trend component
            if show_trend == true
                plot!(plots[4], Matrix(tpath'), color = :red, label = "")
            end
            plot!(plots[4], seriestype = :hline, [horline], color = :black,
↪linestyle =:dash,
        label = "")
            plot!(plots[4], title = "Trend Components for Many Paths")

            return plots
        end

        function plot_martingale_paths(T, mpath, mbounds;
                                       horline = 1, show_trend = false)
            # allocate space
            trange = 1:T

            # create the plot
            plt = plot()

            # plot martingale component
            ub = mbounds[2, :]
            lb = mbounds[1, :]
            plot!(plt, lb, fillrange = [lb, ub], alpha = 0.25, color = :magenta,
↪label = "")
           plot!(plt, seriestype = :hline, [horline], color = :black, linestyle =:
↪dash, label =
        "")
            plot!(plt, trange, Matrix(mpath'), linewidth=0.25, color = :black,
↪label = "")

            return plt
        end
```

```
Out[4]: plot_martingale_paths (generic function with 1 method)
```

For now, we just plot y_t and x_t, postponing until later a description of exactly how we compute them.

In [5]:
```
ϕ_1, ϕ_2, ϕ_3, ϕ_4 = 0.5, -0.2, 0, 0.5
σ = 0.01
ν = 0.01 # growth rate

# A matrix should be n x n
A = [ϕ_1 ϕ_2 ϕ_3 ϕ_4;
       1   0   0   0;
       0   1   0   0;
       0   0   1   0]

# B matrix should be n x k
B = [σ, 0, 0, 0]

D = [1 0 0 0] * A
F = [1, 0, 0, 0] ⊗ vec(B)

amf = AMF_LSS_VAR(A, B, D, F, ν)

T = 150
x, y = simulate(amf.lss, T)

plots = plot(layout = (2, 1))

plot!(plots[1], 1:T, y[amf.nx + 1, :], color = :black, lw = 2, label = "")
plot!(plots[1], title =  "A particular path of y_t")
plot!(plots[2], 1:T, y[1, :], color = :green, lw = 2, label = "")
plot!(plots[2], seriestype = :hline, [0], color = :black, lw = 2,⏎
↪linestyle=:dashdot,
      label = "")
plot!(plots[2], title = "Associated path of x_t")

plot(plots)
```

Out[5]:



Notice the irregular but persistent growth in y_t.

56.4.3 Decomposition

Hansen and Sargent [46] describe how to construct a decomposition of an additive functional into four parts:

- a constant inherited from initial values x_0 and y_0
- a linear trend
- a martingale
- an (asymptotically) stationary component

To attain this decomposition for the particular class of additive functionals defined by (1) and (2), we first construct the matrices

$$
\begin{aligned}
H &:= F + B'(I - A')^{-1} D \\
g &:= D'(I - A)^{-1}
\end{aligned}
$$

Then the Hansen-Scheinkman [47] decomposition is

$$
y_t = \underbrace{t\nu}_{\text{trend component}} + \overbrace{\sum_{j=1}^{t} H z_j}^{\text{Martingale component}} - \underbrace{g x_t}_{\text{stationary component}} + \overbrace{g x_0 + y_0}^{\text{initial conditions}}
$$

At this stage you should pause and verify that $y_{t+1} - y_t$ satisfies (2).

It is convenient for us to introduce the following notation:

- $\tau_t = \nu t$, a linear, deterministic trend
- $m_t = \sum_{j=1}^{t} H z_j$, a martingale with time $t+1$ increment $H z_{t+1}$

- $s_t = g x_t$, an (asymptotically) stationary component

We want to characterize and simulate components τ_t, m_t, s_t of the decomposition.

A convenient way to do this is to construct an appropriate instance of a linear state space system by using LSS from QuantEcon.jl.

This will allow us to use the routines in LSS to study dynamics.

To start, observe that, under the dynamics in (1) and (2) and with the definitions just given,

$$\begin{bmatrix} 1 \\ t+1 \\ x_{t+1} \\ y_{t+1} \\ m_{t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & A & 0 & 0 \\ \nu & 0 & D' & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ t \\ x_t \\ y_t \\ m_t \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ B \\ F' \\ H' \end{bmatrix} z_{t+1}$$

and

$$\begin{bmatrix} x_t \\ y_t \\ \tau_t \\ m_t \\ s_t \end{bmatrix} = \begin{bmatrix} 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & \nu & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -g & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ t \\ x_t \\ y_t \\ m_t \end{bmatrix}$$

With

$$\tilde{x} := \begin{bmatrix} 1 \\ t \\ x_t \\ y_t \\ m_t \end{bmatrix} \quad \text{and} \quad \tilde{y} := \begin{bmatrix} x_t \\ y_t \\ \tau_t \\ m_t \\ s_t \end{bmatrix}$$

we can write this as the linear state space system

$$\begin{aligned} \tilde{x}_{t+1} &= \tilde{A}\tilde{x}_t + \tilde{B} z_{t+1} \\ \tilde{y}_t &= \tilde{D}\tilde{x}_t \end{aligned}$$

By picking out components of $\tilde{y}_t$, we can track all variables of interest.

56.5 Code

The type AMF_LSS_VAR mentioned above does all that we want to study our additive functional.

In fact AMF_LSS_VAR does more, as we shall explain below.

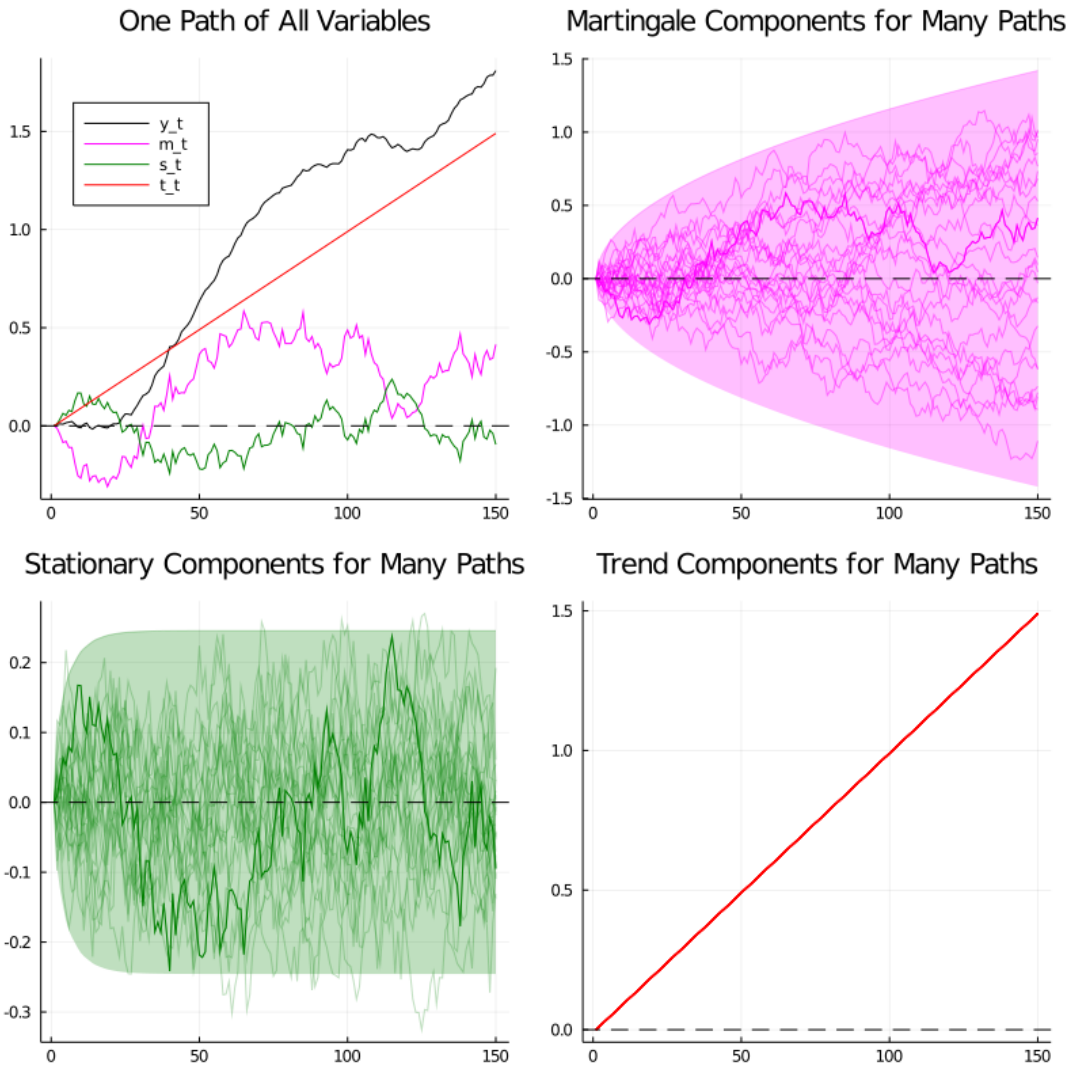
(A hint that it does more is the name of the type – here AMF stands for "additive and multiplicative functional" – the code will do things for multiplicative functionals too)

Let's use this code (embedded above) to explore the example process described above.

If you run the code that first simulated that example again and then the method call you will generate (modulo randomness) the plot

```
In [6]: plt = plot_additive(amf, T)
        plt[1]
```

Out[6]:



When we plot multiple realizations of a component in the 2nd, 3rd, and 4th panels, we also plot population 95% probability coverage sets computed using the LSS type.

We have chosen to simulate many paths, all starting from the *same* nonrandom initial conditions x_0, y_0 (you can tell this from the shape of the 95% probability coverage shaded areas).

Notice tell-tale signs of these probability coverage shaded areas

- the purple one for the martingale component m_t grows with $\sqrt{t}$
- the green one for the stationary component s_t converges to a constant band

56.5.1 An associated multiplicative functional

Where $\{y_t\}$ is our additive functional, let $M_t = \exp(y_t)$.

As mentioned above, the process $\{M_t\}$ is called a **multiplicative functional**.

Corresponding to the additive decomposition described above we have the multiplicative decomposition of the M_t

$$\frac{M_t}{M_0} = \exp(t\nu) \exp\Big(\sum_{j=1}^{t} H \cdot Z_j\Big) \exp\Big(D'(I-A)^{-1}x_0 - D'(I-A)^{-1}x_t\Big)$$

or

$$\frac{M_t}{M_0} = \exp\left(\tilde{\nu} t\right) \left(\frac{\widetilde{M}_t}{\widetilde{M}_0}\right) \left(\frac{\tilde{e}(X_0)}{\tilde{e}(x_t)}\right)$$

where

$$\tilde{\nu} = \nu + \frac{H \cdot H}{2}, \quad \widetilde{M}_t = \exp\left(\sum_{j=1}^{t}\left(H \cdot z_j - \frac{H \cdot H}{2}\right)\right), \quad \widetilde{M}_0 = 1$$

and

$$\tilde{e}(x) = \exp[g(x)] = \exp[D'(I-A)^{-1}x]$$

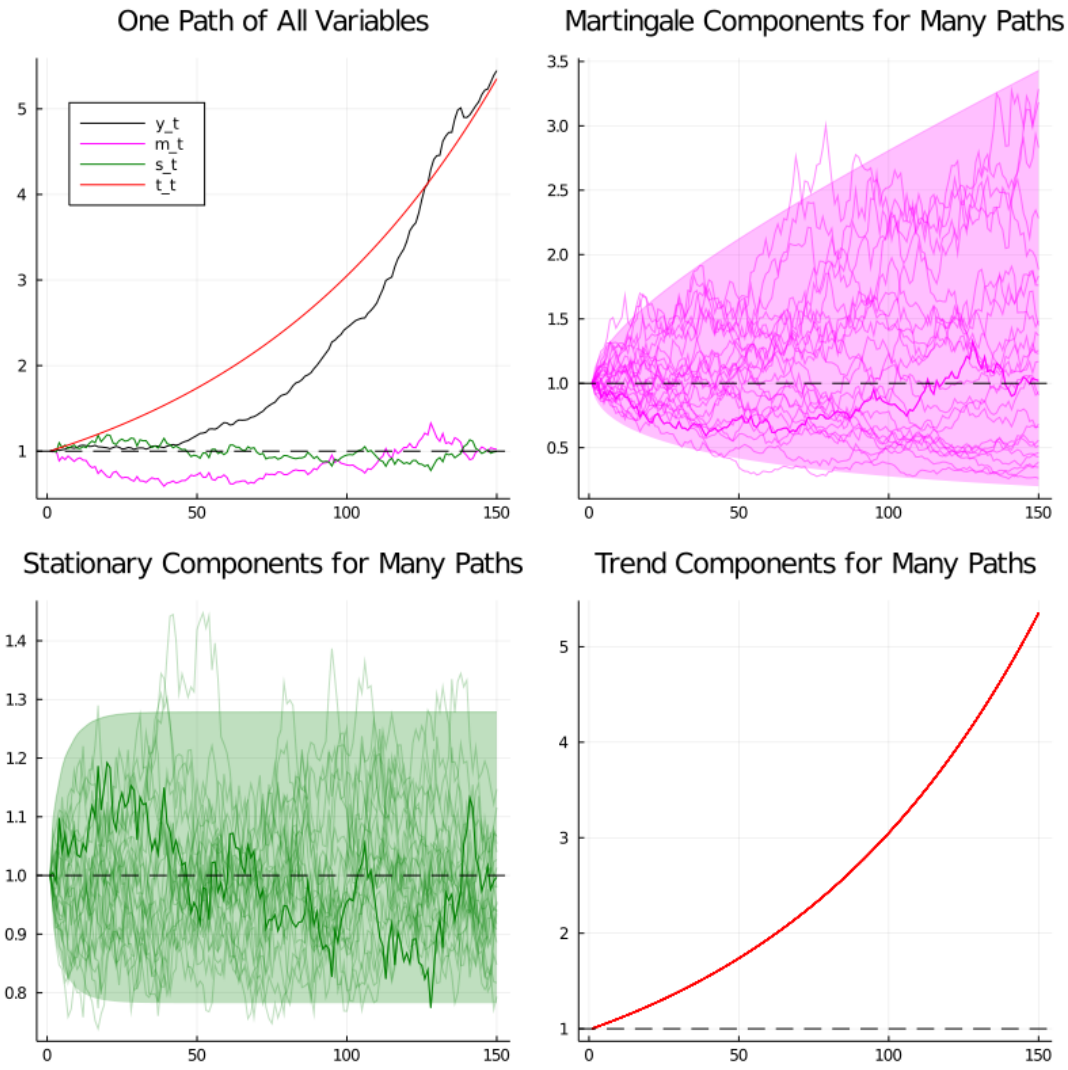
An instance of type AMF_LSS_VAR includes this associated multiplicative functional as an attribute.

Let's plot this multiplicative functional for our example.

If you run the code that first simulated that example again and then the method call

```
In [7]: plt = plot_multiplicative(amf, T)
        plt[1]
```

Out[7]:



As before, when we plotted multiple realizations of a component in the 2nd, 3rd, and 4th panels, we also plotted population 95% confidence bands computed using the LSS type.

Comparing this figure and the last also helps show how geometric growth differs from arithmetic growth.

56.5.2 A peculiar large sample property

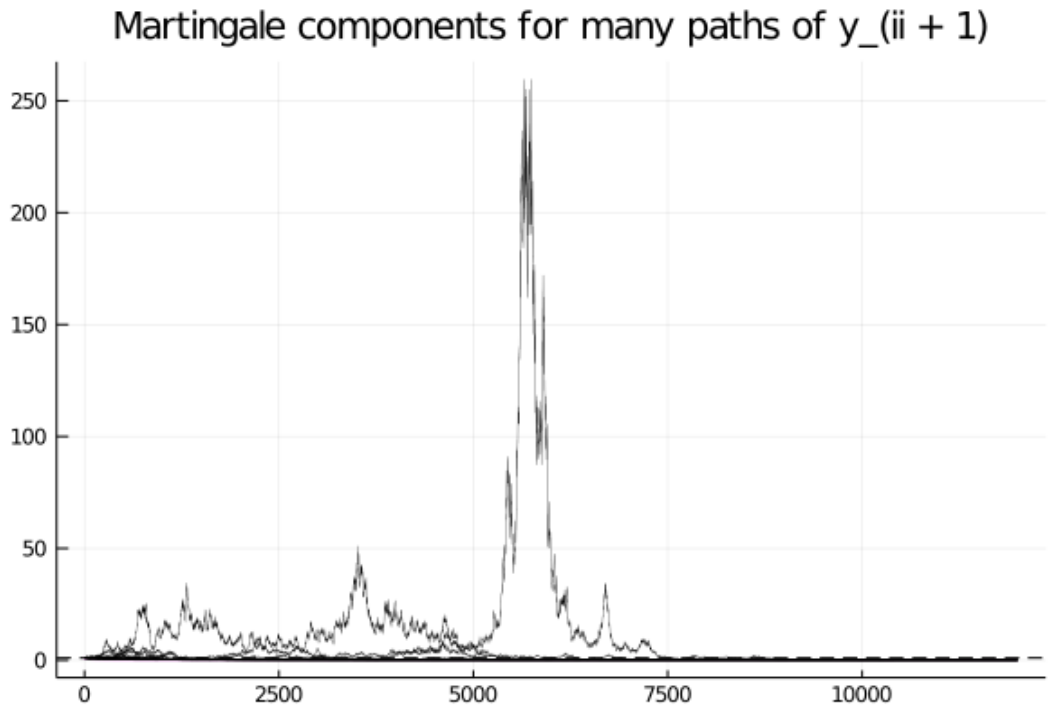
Hansen and Sargent [46] (ch. 6) note that the martingale component $\widetilde{M}_t$ of the multiplicative decomposition has a peculiar property.

- While $E_0 \widetilde{M}_t = 1$ for all $t \geq 0$, nevertheless ....
- As $t \to +\infty$, $\widetilde{M}_t$ converges to zero almost surely.

The following simulation of many paths of $\widetilde{M}_t$ illustrates this property

```
In [8]: plt = plot_martingales(amf, 12000)
        plt[1]
```

```
Out[8]:
```


Martingale components for many paths of y_(ii + 1)
250
200
150
100
50
0
0
2500
5000
7500
10000

Chapter 57

Multiplicative Functionals

57.1 Contents

Co-authored with Chase Coleman and Balint Szoke

57.2 Overview

This lecture is a sequel to the lecture on additive functionals.

That lecture

1. defined a special class of **additive functionals** driven by a first-order vector VAR
2. by taking the exponential of that additive functional, created an associated **multiplicative functional**

This lecture uses this special class to create and analyze two examples

- A **log likelihood process**, an object at the foundation of both frequentist and Bayesian approaches to statistical inference.
- A version of Robert E. Lucas's [70] and Thomas Tallarini's [103] approaches to measuring the benefits of moderating aggregate fluctuations.

57.3 A Log-Likelihood Process

Consider a vector of additive functionals $\{y_t\}_{t=0}^{\infty}$ described by

$$
\begin{aligned}
x_{t+1} &= Ax_t + Bz_{t+1} \\
y_{t+1} - y_t &= Dx_t + Fz_{t+1},
\end{aligned}
$$

where A is a stable matrix, $\{z_{t+1}\}_{t=0}^{\infty}$ is an i.i.d. sequence of $N(0, I)$ random vectors, F is nonsingular, and x_0 and y_0 are vectors of known numbers.

Evidently,

$$x_{t+1} = (A - BF^{-1}D)\, x_t + BF^{-1}\,(y_{t+1} - y_t)\,,$$

so that x_{t+1} can be constructed from observations on $\{y_s\}_{s=0}^{t+1}$ and x_0.

The distribution of $y_{t+1} - y_t$ conditional on x_t is normal with mean Dx_t and nonsingular covariance matrix FF'.

Let θ denote the vector of free parameters of the model.

These parameters pin down the elements of A, B, D, F.

The **log likelihood function** of $\{y_s\}_{s=1}^{t}$ is

$$\begin{aligned}\log L_t(\theta) = &-\frac{1}{2}\sum_{j=1}^{t}(y_j - y_{j-1} - Dx_{j-1})'(FF')^{-1}(y_j - y_{j-1} - Dx_{j-1}) \\ &-\frac{t}{2}\log\det(FF') - \frac{kt}{2}\log(2\pi)\end{aligned}$$

Let's consider the case of a scalar process in which A, B, D, F are scalars and z_{t+1} is a scalar stochastic process.

We let θ_o denote the "true" values of θ, meaning the values that generate the data.

For the purposes of this exercise, set $\theta_o = (A, B, D, F) = (0.8, 1, 0.5, 0.2)$.

Set $x_0 = y_0 = 0$.

57.3.1 Simulating sample paths

Let's write a program to simulate sample paths of $\{x_t, y_t\}_{t=0}^{\infty}$.

We'll do this by formulating the additive functional as a linear state space model and putting the LSS struct to work.

57.3.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using Distributions, Parameters, Plots, QuantEcon
        import Distributions: loglikelihood
        gr(fmt = :png);
```

```
In [3]: AMF_LSS_VAR = @with_kw (A, B, D, F = 0.0, ν = 0.0, lss = construct_ss(A,
        B, D, F, ν))

        function construct_ss(A, B, D, F, ν)
            H, g = additive_decomp(A, B, D, F)
```

```
    # Build A matrix for LSS
    # Order of states is: [1, t, xt, yt, mt]
    A1 = [1 0 0 0 0]       # Transition for 1
    A2 = [1 1 0 0 0]       # Transition for t
    A3 = [0 0 A 0 0]       # Transition for x_{t+1}
    A4 = [ν 0 D 1 0]       # Transition for y_{t+1}
    A5 = [0 0 0 0 1]       # Transition for m_{t+1}
    Abar = vcat(A1, A2, A3, A4, A5)

    # Build B matrix for LSS
    Bbar = [0, 0, B, F, H]

    # Build G matrix for LSS
    # Order of observation is: [xt, yt, mt, st, tt]
    G1 = [0 0 1 0 0]               # Selector for x_{t}
    G2 = [0 0 0 1 0]               # Selector for y_{t}
    G3 = [0 0 0 0 1]               # Selector for martingale
    G4 = [0 0 -g 0 0]              # Selector for stationary
    G5 = [0 ν 0 0 0]               # Selector for trend
    Gbar = vcat(G1, G2, G3, G4, G5)

    # Build LSS struct
    x0 = [0, 0, 0, 0, 0]
    S0 = zeros(5, 5)
    return LSS(Abar, Bbar, Gbar, mu_0 = x0, Sigma_0 = S0)
end

function additive_decomp(A, B, D, F)
    A_res = 1 / (1 - A)
    g = D * A_res
    H = F + D * A_res * B

    return H, g
end

function multiplicative_decomp(A, B, D, F, ν)
    H, g = additive_decomp(A, B, D, F)
    ν_tilde = ν + 0.5 * H^2

    return ν_tilde, H, g
end

function loglikelihood_path(amf, x, y)
    @unpack A, B, D, F = amf
    T = length(y)
    FF = F^2
    FFinv = inv(FF)
    temp = y[2:end] - y[1:end-1] - D*x[1:end-1]
    obs =  temp .* FFinv .* temp
    obssum = cumsum(obs)
    scalar = (log(FF) + log(2pi)) * (1:T-1)
    return -0.5 * (obssum + scalar)
end

function loglikelihood(amf, x, y)
    llh = loglikelihood_path(amf, x, y)
    return llh[end]
end
```

```
Out[3]: loglikelihood (generic function with 4 methods)
```

The heavy lifting is done inside the AMF_LSS_VAR struct.

The following code adds some simple functions that make it straightforward to generate sample paths from an instance of AMF_LSS_VAR

```
In [4]: function simulate_xy(amf, T)
            foo, bar = simulate(amf.lss, T)
            x = bar[1, :]
            y = bar[2, :]
            return x, y
        end

        function simulate_paths(amf, T = 150, I = 5000)
            # Allocate space
            storeX = zeros(I, T)
            storeY = zeros(I, T)

            for i in 1:I
                # Do specific simulation
                x, y = simulate_xy(amf, T)

                # Fill in our storage matrices
                storeX[i, :] = x
                storeY[i, :] = y
            end

            return storeX, storeY
        end

        function population_means(amf, T = 150)
            # Allocate Space
            xmean = zeros(T)
            ymean = zeros(T)

            # Pull out moment generator
            moment_generator = moment_sequence(amf.lss)
            for (tt, x) = enumerate(moment_generator)
                ymeans = x[2]
                xmean[tt] = ymeans[1]
                ymean[tt] = ymeans[2]
                if tt == T
                    break
                end
            end
            return xmean, ymean
        end
```

```
Out[4]: population_means (generic function with 2 methods)
```

Now that we have these functions in our took kit, let's apply them to run some simulations.

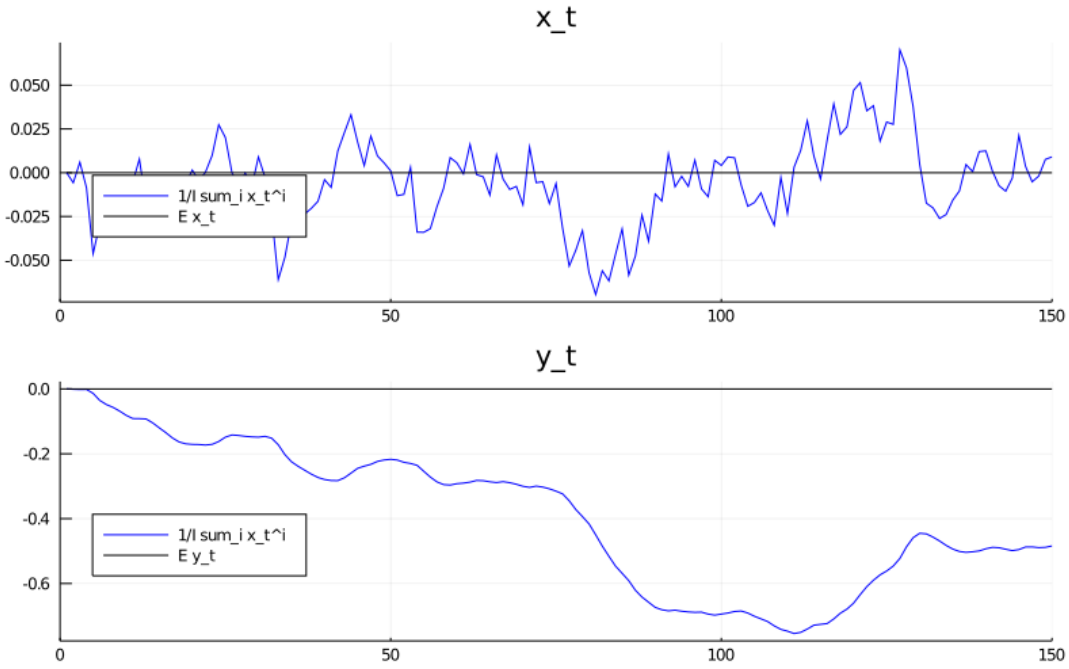
In particular, let's use our program to generate $I = 5000$ sample paths of length $T = 150$, labeled $\{x_t^i, y_t^i\}_{t=0}^{\infty}$ for $i = 1, ..., I$.

Then we compute averages of $\frac{1}{I}\sum_i x_t^i$ and $\frac{1}{I}\sum_i y_t^i$ across the sample paths and compare them with the population means of x_t and y_t.

Here goes

In [5]:
```
F = 0.2
amf = AMF_LSS_VAR(A = 0.8, B = 1.0, D = 0.5, F = F)

T = 150
I = 5000

# Simulate and compute sample means
Xit, Yit = simulate_paths(amf, T, I)
Xmean_t = mean(Xit, dims = 1)
Ymean_t = mean(Yit, dims = 1)

# Compute population means
Xmean_pop, Ymean_pop = population_means(amf, T)

# Plot sample means vs population means
plt_1 = plot(Xmean_t', color = :blue, label = "1/I sum_i x_t^i")
plot!(plt_1, Xmean_pop, color = :black, label = "E x_t")
plot!(plt_1, title = "x_t", xlim = (0, T), legend = :bottomleft)

plt_2 = plot(Ymean_t', color = :blue, label = "1/I sum_i x_t^i")
plot!(plt_2, Ymean_pop, color = :black, label = "E y_t")
plot!(plt_2, title = "y_t", xlim = (0, T), legend = :bottomleft)

plot(plt_1, plt_2, layout = (2, 1), size = (800,500))
```

Out[5]:



57.3.3 Simulating log-likelihoods

Our next aim is to write a program to simulate $\{\log L_t \mid \theta_o\}_{t=1}^T$.

We want as inputs to this program the *same* sample paths $\{x_t^i, y_t^i\}_{t=0}^T$ that we have already computed.

We now want to simulate $I = 5000$ paths of $\{\log L_t^i \mid \theta_o\}_{t=1}^T$.

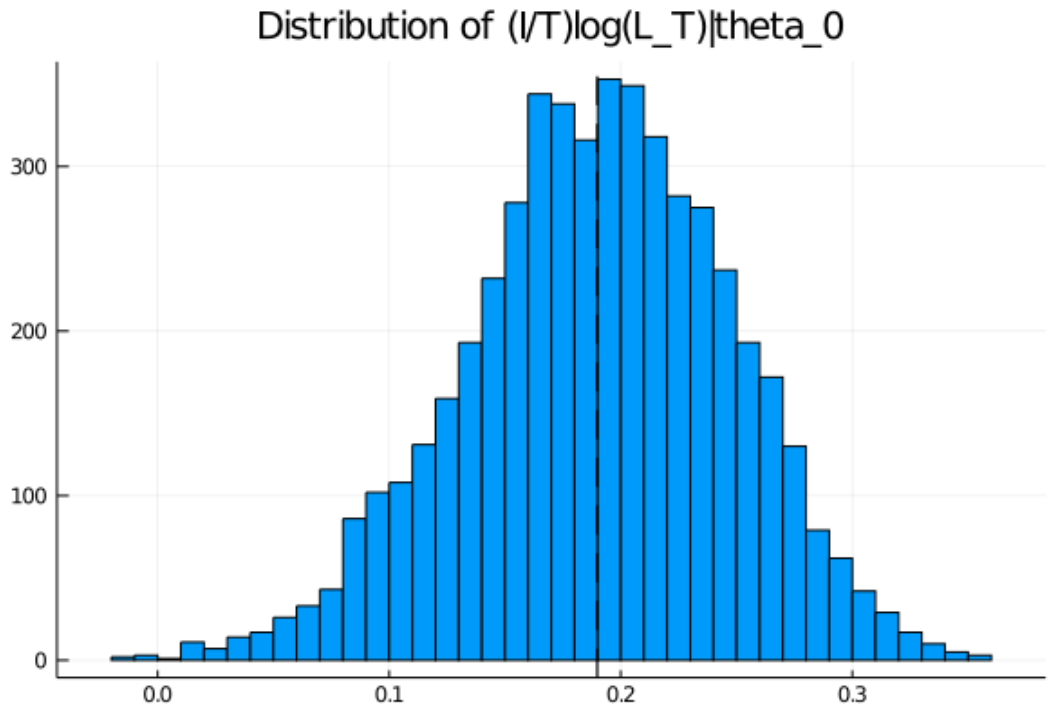
- For each path, we compute $\log L_T^i / T$.
- We also compute $\frac{1}{I}\sum_{i=1}^I \log L_T^i / T$.

Then we to compare these objects.

Below we plot the histogram of $\log L_T^i / T$ for realizations $i = 1, \ldots, 5000$

In [6]:
```
function simulate_likelihood(amf, Xit, Yit)
    # Get size
    I, T = size(Xit)

    # Allocate space
    LLit = zeros(I, T-1)

    for i in 1:I
        LLit[i, :] = loglikelihood_path(amf, Xit[i, :], Yit[i, :])
    end

    return LLit
end

# Get likelihood from each path x^{i}, Y^{i}
LLit = simulate_likelihood(amf, Xit, Yit)

LLT = 1 / T * LLit[:, end]
LLmean_t = mean(LLT)

plot(seriestype = :histogram, LLT, label = "")
plot!(title = "Distribution of (I/T)log(L_T)|theta_0")
vline!([LLmean_t], linestyle = :dash, color = :black, lw = 2, alpha = 0.6,
↪label = "")
```

Out[6]:



Notice that the log likelihood is almost always nonnegative, implying that L_t is typically bigger than 1.

Recall that the likelihood function is a pdf (probability density function) and **not** a probability measure, so it can take values larger than 1.

In the current case, the conditional variance of Δy_{t+1}, which equals $FF^T = 0.04$, is so small that the maximum value of the pdf is 2 (see the figure below).

This implies that approximately 75% of the time (a bit more than one sigma deviation), we should expect the **increment** of the log likelihood to be nonnegative.

Let's see this in a simulation

```
In [7]: normdist = Normal(0, F)
        mult = 1.175
        println("The pdf at +/- $mult sigma takes the value:
↪$(pdf(normdist,mult*F))")
        println("Probability of dL being larger than 1 is approx: "*
                "$(cdf(normdist,mult*F)-cdf(normdist,-mult*F))")

        # Compare this to the sample analogue:
        L_increment = LLit[:,2:end] - LLit[:,1:end-1]
        r,c = size(L_increment)
        frac_nonegative = sum(L_increment.>=0)/(c*r)
        print("Fraction of dlogL being nonnegative in the sample is:
↪$(frac_nonegative)")
```

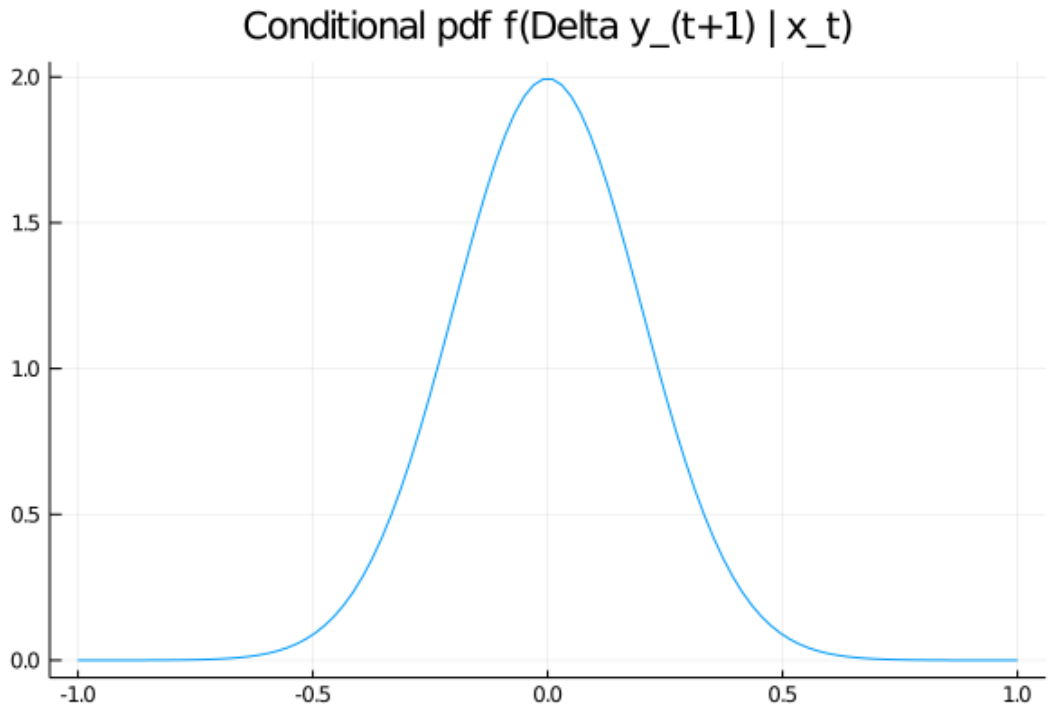
```
    The pdf at +/- 1.175 sigma takes the value: 1.0001868966924388
Probability of dL being larger than 1 is approx: 0.7600052842019751
Fraction of dlogL being nonnegative in the sample is: 0.7601202702702703
```

Let's also plot the conditional pdf of Δy_{t+1}

In [8]:
```
xgrid = range(-1,  1, length = 100)
println("The pdf at +/- one sigma takes the value: $(pdf(normdist, F)) ")
plot(xgrid, pdf.(normdist, xgrid), label = "")
plot!(title = "Conditional pdf f(Delta y_(t+1) | x_t)")
```

```
The pdf at +/- one sigma takes the value: 1.2098536225957168
```

Out[8]:



57.3.4 An alternative parameter vector

Now consider alternative parameter vector $\theta_1 = [A, B, D, F] = [0.9, 1.0, 0.55, 0.25]$.

We want to compute $\{\log L_t \mid \theta_1\}_{t=1}^T$.

The x_t, y_t inputs to this program should be exactly the **same** sample paths $\{x_t^i, y_t^i\}_{t=0}^T$ that we we computed above.

This is because we want to generate data under the θ_o probability model but evaluate the likelihood under the θ_1 model.

So our task is to use our program to simulate $I = 5000$ paths of $\{\log L_t^i \mid \theta_1\}_{t=1}^T$.

- For each path, compute $\frac{1}{T} \log L_T^i$.
- Then compute $\frac{1}{I} \sum_{i=1}^I \frac{1}{T} \log L_T^i$.

We want to compare these objects with each other and with the analogous objects that we computed above.

Then we want to interpret outcomes.

A function that we constructed can handle these tasks.

The only innovation is that we must create an alternative model to feed in.

We will creatively call the new model `amf2`.

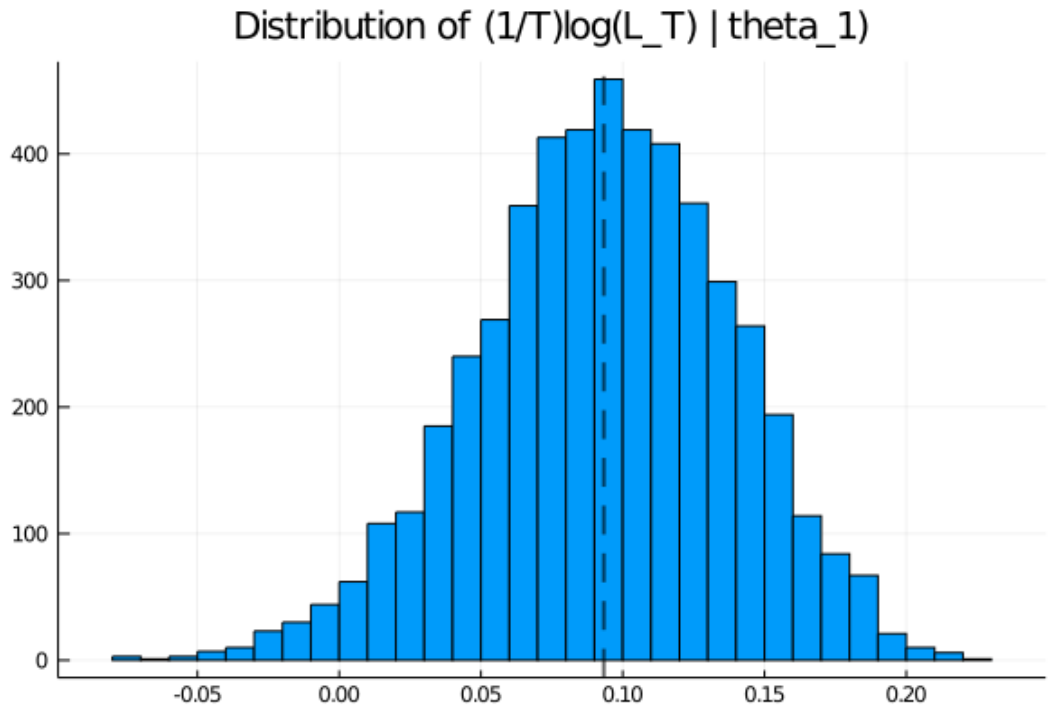
We make three graphs

- the first sets the stage by repeating an earlier graph
- the second contains two histograms of values of log likelihoods of the two models over the period T
- the third compares likelihoods under the true and alternative models

Here's the code

```
In [9]: # Create the second (wrong) alternative model
        amf2 = AMF_LSS_VAR(A = 0.9, B = 1.0, D = 0.55, F = 0.25) # parameters for
 ↪θ_1 closer to
        θ_0

        # Get likelihood from each path x^{i}, y^{i}
        LLit2 = simulate_likelihood(amf2, Xit, Yit)

        LLT2 = 1/(T-1) * LLit2[:, end]
        LLmean_t2 = mean(LLT2)

        plot(seriestype = :histogram, LLT2, label = "")
        vline!([LLmean_t2], color = :black, lw = 2, linestyle = :dash, alpha = 0.
 ↪6, label = "")
        plot!(title = "Distribution of (1/T)log(L_T) | theta_1)")
```

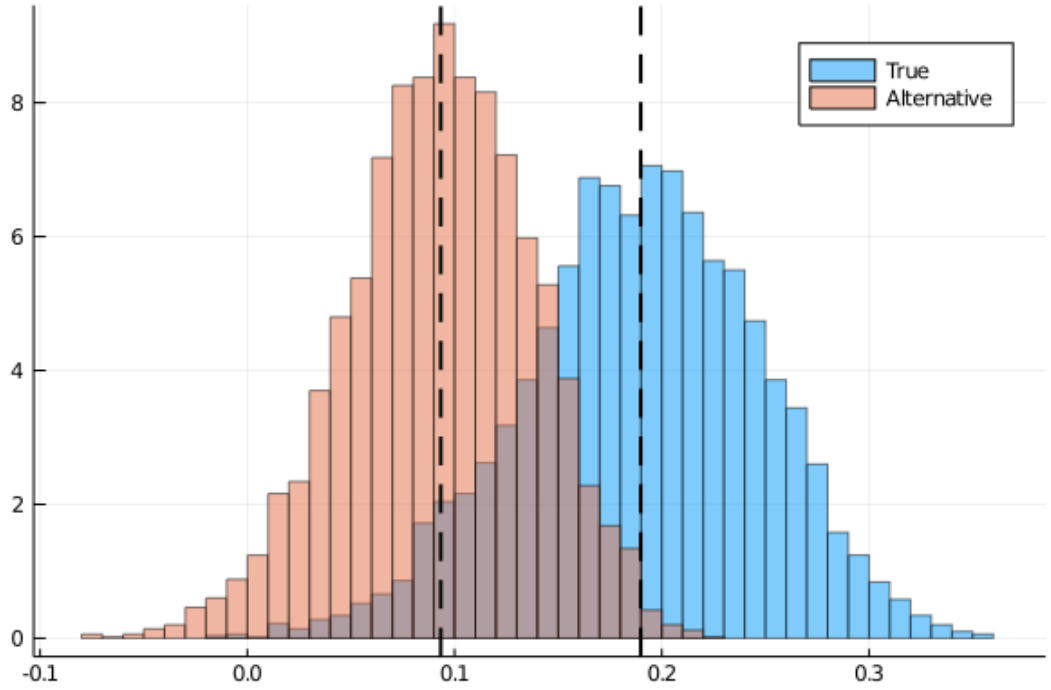
Out[9]:



Let's see a histogram of the log-likelihoods under the true and the alternative model (same sample paths)

```
In [10]: plot(seriestype = :histogram, LLT, bin = 50, alpha = 0.5, label = "True",
  ↪normed = true)
         plot!(seriestype = :histogram, LLT2, bin = 50, alpha = 0.5, label =
  ↪"Alternative",
               normed = true)
         vline!([mean(LLT)], color = :black, lw = 2, linestyle = :dash, label = "")
         vline!([mean(LLT2)], color = :black, lw = 2, linestyle = :dash, label = "")
```

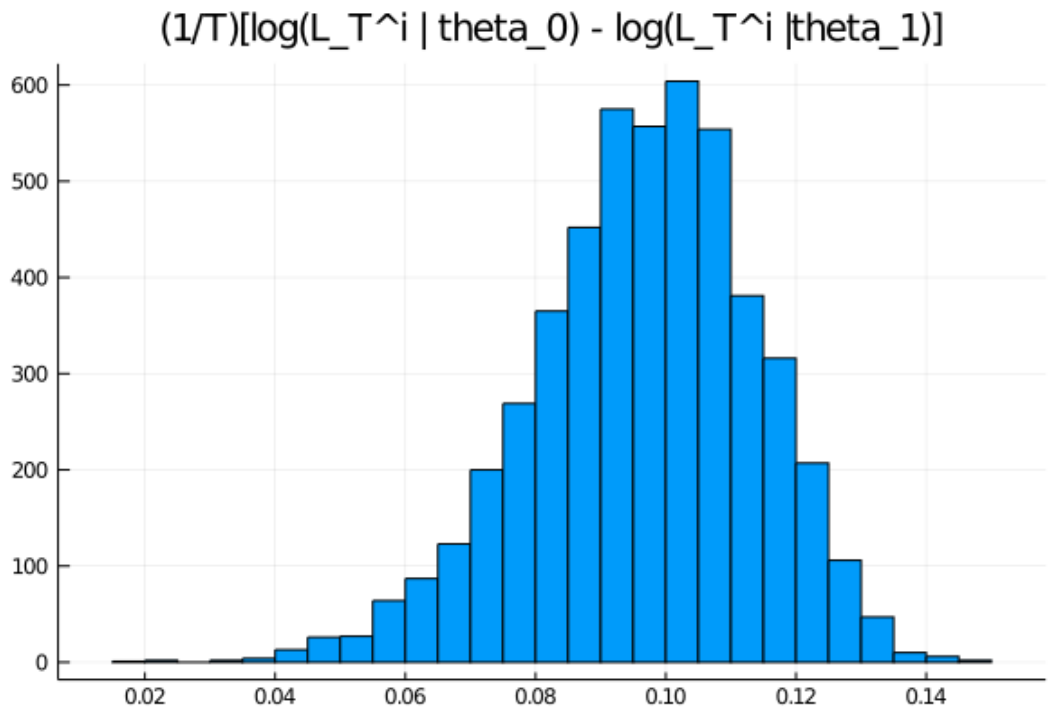
Out[10]:



Now we'll plot the histogram of the difference in log likelihood ratio

```
In [11]: LLT_diff = LLT - LLT2

         plot(seriestype = :histogram, LLT_diff, bin = 50, label = "")
         plot!(title = "(1/T)[log(L_T^i | theta_0) - log(L_T^i |theta_1)]")
```

Out[11]:



57.3.5 Interpretation

These histograms of log likelihood ratios illustrate important features of **likelihood ratio tests** as tools for discriminating between statistical models.

- The loglikeklihood is higher on average under the true model – obviously a very useful property.
- Nevertheless, for a positive fraction of realizations, the log likelihood is higher for the incorrect than for the true model

    - in these instances, a likelihood ratio test mistakenly selects the wrong model

- These mechanics underlie the statistical theory of **mistake probabilities** associated with model selection tests based on likelihood ratio.

(In a subsequent lecture, we'll use some of the code prepared in this lecture to illustrate mistake probabilities)

57.4 Benefits from Reduced Aggregate Fluctuations

Now let's turn to a new example of multiplicative functionals.

This example illustrates ideas in the literatures on

- **long-run risk** in the consumption based asset pricing literature (e.g., [7], [42], [41])
- **benefits of eliminating aggregate fluctuations** in representative agent macro models (e.g., [103], [70])

Let c_t be consumption at date $t \geq 0$.

Suppose that $\{\log c_t\}_{t=0}^{\infty}$ is an additive functional described by

$$\log c_{t+1} - \log c_t = \nu + D \cdot x_t + F \cdot z_{t+1}$$

where

$$x_{t+1} = Ax_t + Bz_{t+1}$$

Here $\{z_{t+1}\}_{t=0}^{\infty}$ is an i.i.d. sequence of $N(0, I)$ random vectors.

A representative household ranks consumption processes $\{c_t\}_{t=0}^{\infty}$ with a utility functional $\{V_t\}_{t=0}^{\infty}$ that satisfies

$$\log V_t - \log c_t = U \cdot x_t + \mathsf{u} \tag{1}$$

where

$$U = \exp(-\delta) \left[I - \exp(-\delta) A'\right]^{-1} D$$

and

$$\mathsf{u} = \frac{\exp(-\delta)}{1 - \exp(-\delta)} \nu + \frac{(1-\gamma)}{2} \frac{\exp(-\delta)}{1 - \exp(-\delta)} \left| D' \left[I - \exp(-\delta) A\right]^{-1} B + F \right|^2,$$

Here $\gamma \geq 1$ is a risk-aversion coefficient and $\delta > 0$ is a rate of time preference.

57.4.1 Consumption as a multiplicative process

We begin by showing that consumption is a **multiplicative functional** with representation

$$\frac{c_t}{c_0} = \exp(\tilde{\nu} t) \left(\frac{\tilde{M}_t}{\tilde{M}_0}\right) \left(\frac{\tilde{e}(x_0)}{\tilde{e}(x_t)}\right) \tag{2}$$

where $\left(\frac{\tilde{M}_t}{\tilde{M}_0}\right)$ is a likelihood ratio process and $\tilde{M}_0 = 1$.

At this point, as an exercise, we ask the reader please to verify the follow formulas for $\tilde{\nu}$ and $\tilde{e}(x_t)$ as functions of A, B, D, F:

$$\tilde{\nu} = \nu + \frac{H \cdot H}{2}$$

and

$$\tilde{e}(x) = \exp[g(x)] = \exp[D'(I - A)^{-1} x]$$

57.4.2 Simulating a likelihood ratio process again

Next, we want a program to simulate the likelihood ratio process $\{\tilde{M}_t\}_{t=0}^{\infty}$.

In particular, we want to simulate 5000 sample paths of length $T = 1000$ for the case in which x is a scalar and $[A, B, D, F] = [0.8, 0.001, 1.0, 0.01]$ and $\nu = 0.005$.

After accomplishing this, we want to display a histogram of $\tilde{M}_T^i$ for $T = 1000$.

Here is code that accomplishes these tasks

```
In [12]: function simulate_martingale_components(amf, T = 1_000, I = 5_000)
             # Get the multiplicative decomposition
             @unpack A, B, D, F, ν, lss = amf
             ν, H, g = multiplicative_decomp(A, B, D, F, ν)

             # Allocate space
             add_mart_comp = zeros(I, T)

             # Simulate and pull out additive martingale component
             for i in 1:I
                 foo, bar = simulate(lss, T)
                 # Martingale component is third component
                 add_mart_comp[i, :] = bar[3, :]
             end

             mul_mart_comp = exp.(add_mart_comp' .- (0:T-1) * H^2 / 2)'

             return add_mart_comp, mul_mart_comp
         end

         # Build model
         amf_2 = AMF_LSS_VAR(A = 0.8, B = 0.001, D = 1.0, F = 0.01, ν = 0.005)

         amc, mmc = simulate_martingale_components(amf_2, 1_000, 5_000)

         amcT = amc[:, end]
         mmcT = mmc[:, end]

         println("The (min, mean, max) of additive Martingale component in period␣
↪T is")
         println("\t ($(minimum(amcT)), $(mean(amcT)), $(maximum(amcT)))")

         println("The (min, mean, max) of multiplicative Martingale component in␣
↪period T is")
         println("\t ($(minimum(mmcT)), $(mean(mmcT)), $(maximum(mmcT)))")
```

```
The (min, mean, max) of additive Martingale component in period T is
     (-1.5976378832036093, 0.011688395462056569, 1.8548306466611928)
The (min, mean, max) of multiplicative Martingale component in period T is
     (0.18086120172214815, 1.0115798917139234, 5.711279885712145)
```

Comments

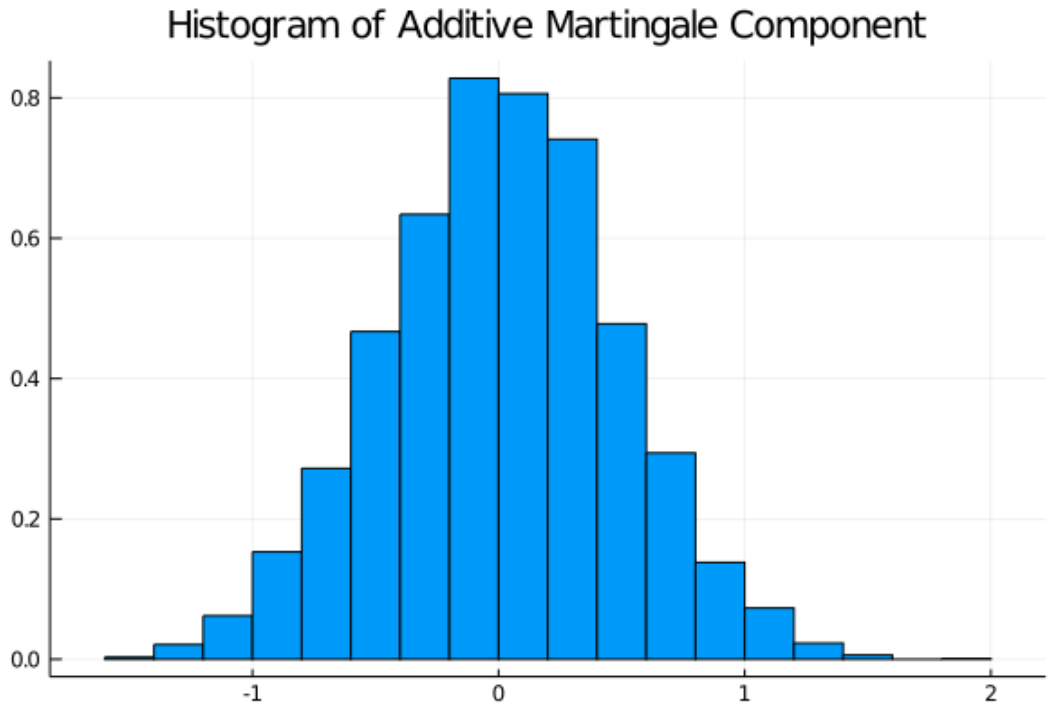
- The preceding min, mean, and max of the cross-section of the date T realizations of the multiplicative martingale component of c_t indicate that the sample mean is close to its population mean of 1.
  - This outcome prevails for all values of the horizon T.
- The cross-section distribution of the multiplicative martingale component of c at date T approximates a log normal distribution well.

- The histogram of the additive martingale component of $\log c_t$ at date T approximates a normal distribution well.

Here's a histogram of the additive martingale component

```
In [13]: plot(seriestype = :histogram, amcT, bin = 25, normed = true, label = "")
         plot!(title = "Histogram of Additive Martingale Component")
```

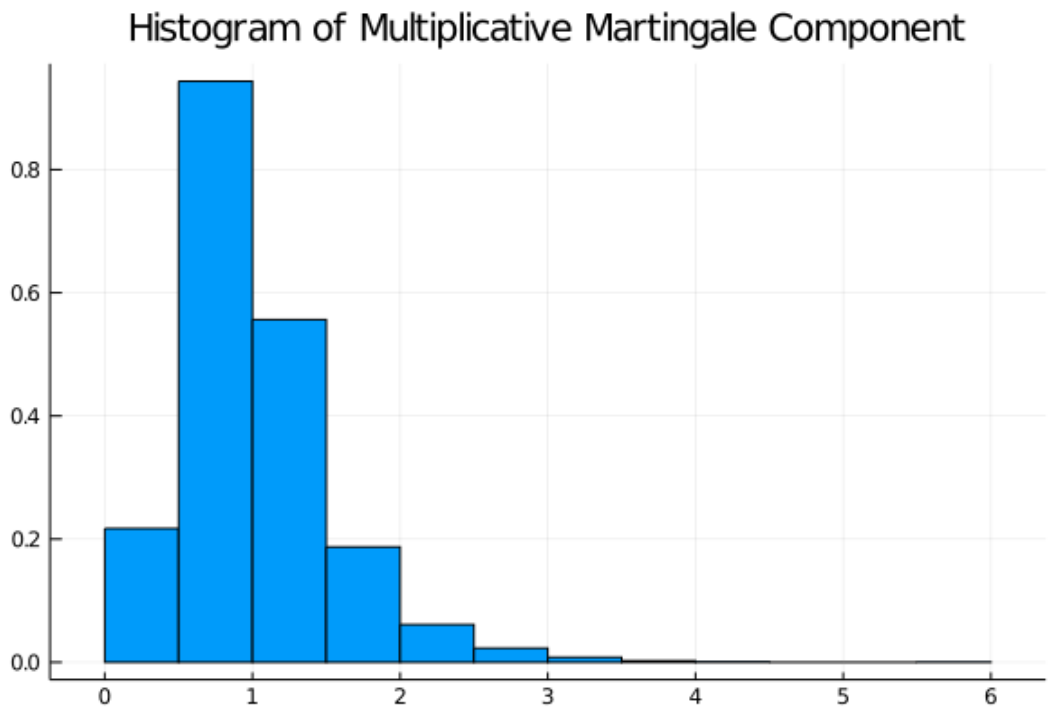
Out[13]:



Here's a histogram of the multiplicative martingale component

```
In [14]: plot(seriestype = :histogram, mmcT, bin = 25, normed = true, label = "")
         plot!(title = "Histogram of Multiplicative Martingale Component")
```

Out[14]:



57.4.3 Representing the likelihood ratio process

The likelihood ratio process $\{\widetilde{M}_t\}_{t=0}^{\infty}$ can be represented as

$$\widetilde{M}_t = \exp\left(\sum_{j=1}^{t}\left(H \cdot z_j - \frac{H \cdot H}{2}\right)\right), \quad \widetilde{M}_0 = 1,$$

where $H = [F + B'(I - A')^{-1}D]$.

It follows that $\log \widetilde{M}_t \sim \mathcal{N}(-\frac{tH \cdot H}{2}, tH \cdot H)$ and that consequently $\widetilde{M}_t$ is log normal.

Let's plot the probability density functions for $\log \widetilde{M}_t$ for $t = 100, 500, 1000, 10000, 100000$.

Then let's use the plots to investigate how these densities evolve through time.

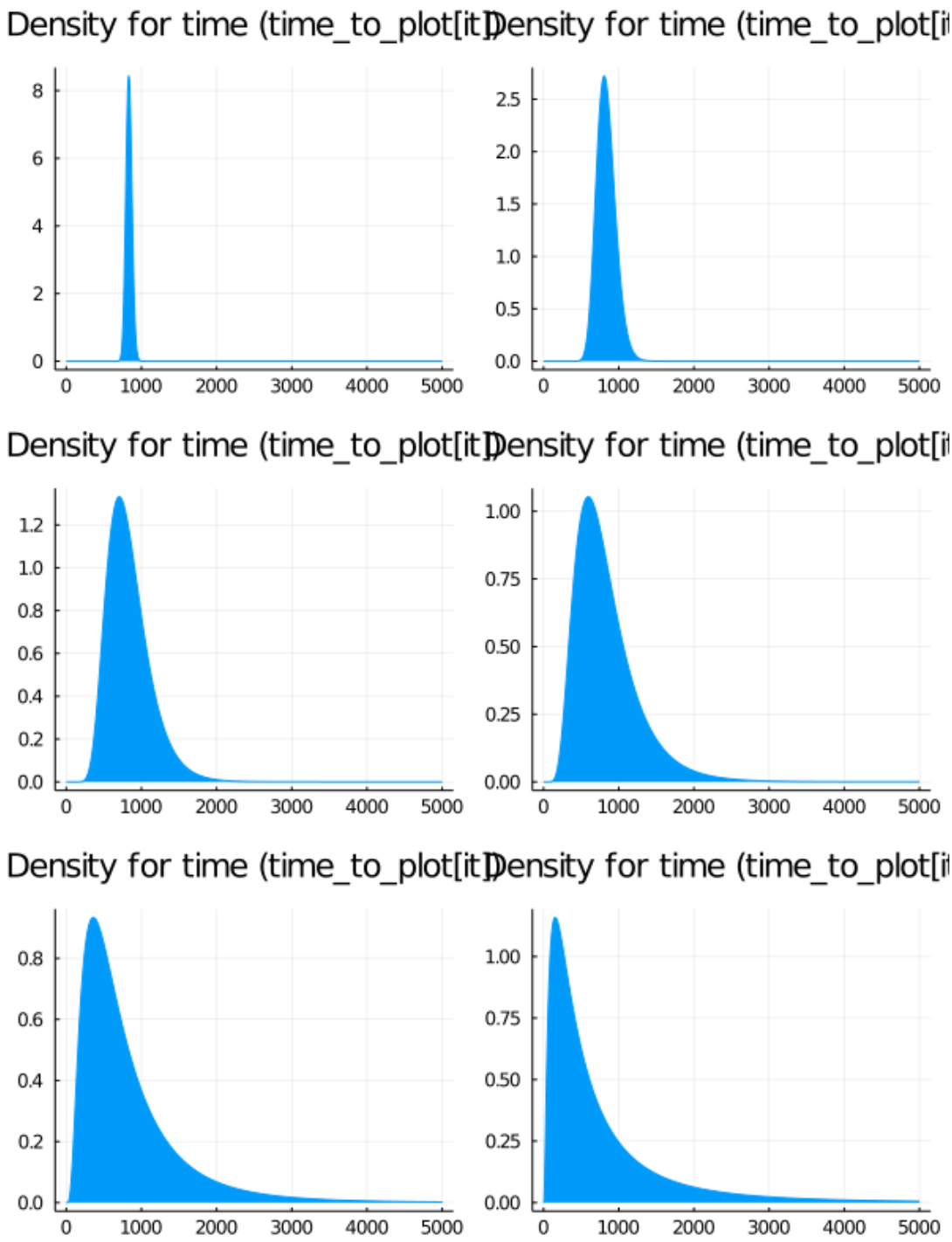
We will plot the densities of $\log \widetilde{M}_t$ for different values of t.

Here is some code that tackles these tasks

```
In [15]: function Mtilde_t_density(amf, t; xmin = 1e-8, xmax = 5.0, npts = 5000)

             # Pull out the multiplicative decomposition
             νtilde, H, g =
                 multiplicative_decomp(amf.A, amf.B, amf.D, amf.F, amf.ν)
             H2 = H*H

             # The distribution
             mdist = LogNormal(-t * H2 / 2, sqrt(t * H2))
             x = range(xmin,  xmax, length = npts)
             p = pdf.(mdist, x)

             return x, p
         end
```

```
        function logMtilde_t_density(amf, t; xmin = -15.0, xmax = 15.0, npts =
↪5000)

            # Pull out the multiplicative decomposition
            @unpack A, B, D, F, ν = amf
            νtilde, H, g = multiplicative_decomp(A, B, D, F, ν)
            H2 = H * H

            # The distribution
            lmdist = Normal(-t * H2 / 2, sqrt(t * H2))
            x = range(xmin,  xmax, length = npts)
            p = pdf.(lmdist, x)

            return x, p
        end

        times_to_plot = [10, 100, 500, 1000, 2500, 5000]
        dens_to_plot = [Mtilde_t_density(amf_2, t, xmin=1e-8, xmax=6.0) for t in
↪times_to_plot]
        ldens_to_plot = [logMtilde_t_density(amf_2, t, xmin=-10.0, xmax=10.0) for
↪t in
        times_to_plot]

        # plot_title = "Densities of M_t^tilda" is required, however, plot_title
↪is not yet
        # supported in Plots
        plots = plot(layout = (3,2), size = (600,800))

        for (it, dens_t) in enumerate(dens_to_plot)
            x, pdf = dens_t
            plot!(plots[it], title = "Density for time (time_to_plot[it])")
            plot!(plots[it], pdf, fillrange = [[0], pdf], label = "")
        end
        plot(plots)
```

Out[15]:



These probability density functions illustrate a **peculiar property** of log likelihood ratio processes:

- With respect to the true model probabilities, they have mathematical expectations equal to 1 for all $t \geq 0$.
- They almost surely converge to zero.

57.4.4 Welfare benefits of reduced random aggregate fluctuations

Suppose in the tradition of a strand of macroeconomics (for example Tallarini [103], [70]) we want to estimate the welfare benefits from removing random fluctuations around trend growth.

We shall compute how much initial consumption c_0 a representative consumer who ranks consumption streams according to (1) would be willing to sacrifice to enjoy the consumption stream

$$\frac{c_t}{c_0} = \exp(\tilde{\nu} t)$$

rather than the stream described by equation (2).

We want to compute the implied percentage reduction in c_0 that the representative consumer would accept.

To accomplish this, we write a function that computes the coefficients U and u for the original values of A, B, D, F, ν, but also for the case that $A, B, D, F = [0, 0, 0, 0]$ and $\nu = \tilde{\nu}$.

Here's our code

In [16]:
```
function Uu(amf, δ, γ)
    @unpack A, B, D, F, ν = amf
    ν_tilde, H, g = multiplicative_decomp(A, B, D, F, ν)

    resolv = 1 / (1 - exp(-δ) * A)
    vect = F + D * resolv * B

    U_risky = exp(-δ) * resolv * D
    u_risky = exp(-δ) / (1 - exp(-δ)) * (ν + 0.5 * (1 - γ) * (vect^2))

    U_det = 0
    u_det = exp(-δ) / (1 - exp(-δ))  * ν_tilde

    return U_risky, u_risky, U_det, u_det
end

# Set remaining parameters
δ = 0.02
γ = 2.0

# Get coeffs
U_r, u_r, U_d, u_d = Uu(amf_2, δ, γ)
```

Out[16]:
```
(4.54129843114712, 0.24220854072375247, 0, 0.25307727077652764)
```

The values of the two processes are

$$\log V_0^r = \log c_0^r + U^r x_0 + u^r$$
$$\log V_0^d = \log c_0^d + U^d x_0 + u^d$$

We look for the ratio $\frac{c_0^r - c_0^d}{c_0^r}$ that makes $\log V_0^r - \log V_0^d = 0$

$$\underbrace{\log V_0^r - \log V_0^d}_{=0} + \log c_0^d - \log c_0^r = (U^r - U^d)x_0 + u^r - u^d$$

$$\frac{c_0^d}{c_0^r} = \exp\left((U^r - U^d)x_0 + u^r - u^d\right)$$

Hence, the implied percentage reduction in c_0 that the representative consumer would accept is given by

$$\frac{c_0^r - c_0^d}{c_0^r} = 1 - \exp\left((U^r - U^d)x_0 + u^r - u^d\right)$$

Let's compute this

In [17]:
```
x0 = 0.0  # initial conditions
logVC_r = U_r * x0 + u_r
logVC_d = U_d * x0 + u_d

perc_reduct = 100 * (1 - exp(logVC_r - logVC_d))
perc_reduct
```

Out[17]:
```
1.0809878812017448
```

We find that the consumer would be willing to take a percentage reduction of initial consumption equal to around 1.081.

Chapter 58

Classical Control with Linear Algebra

58.1 Contents

58.2 Overview

In an earlier lecture Linear Quadratic Dynamic Programming Problems we have studied how to solve a special class of dynamic optimization and prediction problems by applying the method of dynamic programming. In this class of problems

- the objective function is **quadratic** in **states** and **controls**
- the one-step transition function is **linear**
- shocks are i.i.d. Gaussian or martingale differences

In this lecture and a companion lecture Classical Filtering with Linear Algebra, we study the classical theory of linear-quadratic (LQ) optimal control problems.

The classical approach does not use the two closely related methods – dynamic programming and Kalman filtering – that we describe in other lectures, namely, Linear Quadratic Dynamic Programming Problems and A First Look at the Kalman Filter.

Instead they use either.

- z-transform and lag operator methods, or.
- matrix decompositions applied to linear systems of first-order conditions for optimum problems.

In this lecture and the sequel Classical Filtering with Linear Algebra, we mostly rely on elementary linear algebra.

The main tool from linear algebra we'll put to work here is LU decomposition.

We'll begin with discrete horizon problems.

Then we'll view infinite horizon problems as appropriate limits of these finite horizon problems.

Later, we will examine the close connection between LQ control and least squares prediction and filtering problems.

These classes of problems are connected in the sense that to solve each, essentially the same mathematics is used.

58.2.1 References

Useful references include [107], [44], [82], [6], and [80].

58.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")

In [2]: using Polynomials, Plots, Random, Parameters
        using LinearAlgebra, Statistics
```

58.3 A Control Problem

Let L be the **lag operator**, so that, for sequence $\{x_t\}$ we have $Lx_t = x_{t-1}$.

More generally, let $L^k x_t = x_{t-k}$ with $L^0 x_t = x_t$ and

$$d(L) = d_0 + d_1 L + ... + d_m L^m$$

where $d_0, d_1, ..., d_m$ is a given scalar sequence.

Consider the discrete time control problem

$$\max_{\{y_t\}} \lim_{N\to\infty} \sum_{t=0}^{N} \beta^t \left\{ a_t y_t - \frac{1}{2} h y_t^2 - \frac{1}{2} \left[d(L) y_t \right]^2 \right\}, \tag{1}$$

where

- h is a positive parameter and $\beta \in (0,1)$ is a discount factor
- $\{a_t\}_{t\geq 0}$ is a sequence of exponential order less than $\beta^{-1/2}$, by which we mean $\lim_{t\to\infty} \beta^{\frac{t}{2}} a_t = 0$

Maximization in (1) is subject to initial conditions for $y_{-1}, y_{-2} ..., y_{-m}$.

Maximization is over infinite sequences $\{y_t\}_{t\geq 0}$.

58.3.1 Example

The formulation of the LQ problem given above is broad enough to encompass many useful models.

As a simple illustration, recall that in lqcontrol we consider a monopolist facing stochastic demand shocks and adjustment costs.

Let's consider a deterministic version of this problem, where the monopolist maximizes the discounted sum

$$\sum_{t=0}^{\infty} \beta^t \pi_t$$

and

$$\pi_t = p_t q_t - c q_t - \gamma (q_{t+1} - q_t)^2 \quad \text{with} \quad p_t = \alpha_0 - \alpha_1 q_t + d_t$$

In this expression, q_t is output, c is average cost of production, and d_t is a demand shock.

The term $\gamma (q_{t+1} - q_t)^2$ represents adjustment costs.

You will be able to confirm that the objective function can be rewritten as (1) when

- $a_t := \alpha_0 + d_t - c$
- $h := 2\alpha_1$
- $d(L) := \sqrt{2\gamma}(I - L)$

Further examples of this problem for factor demand, economic growth, and government policy problems are given in ch. IX of [94].

58.4 Finite Horizon Theory

We first study a finite N version of the problem.

Later we will study an infinite horizon problem solution as a limiting version of a finite horizon problem.

(This will require being careful because the limits as $N \to \infty$ of the necessary and sufficient conditions for maximizing finite N versions of (1) are not sufficient for maximizing (1))

We begin by

1. fixing $N > m$,
2. differentiating the finite version of (1) with respect to $y_0, y_1, \ldots, y_N$, and
3. setting these derivatives to zero

For $t = 0, \ldots, N - m$ these first-order necessary conditions are the *Euler equations*.

For $t = N - m + 1, \ldots, N$, the first-order conditions are a set of *terminal conditions*.

Consider the term

$$
\begin{aligned}
J &= \sum_{t=0}^{N} \beta^t [d(L)y_t][d(L)y_t] \\
&= \sum_{t=0}^{N} \beta^t \left(d_0\, y_t + d_1\, y_{t-1} + \cdots + d_m\, y_{t-m}\right)\left(d_0\, y_t + d_1\, y_{t-1} + \cdots + d_m\, y_{t-m}\right)
\end{aligned}
$$

Differentiating J with respect to y_t for $t = 0,\ 1,\ \ldots,\ N - m$ gives

$$
\begin{aligned}
\frac{\partial J}{\partial y_t} &= 2\beta^t\, d_0\, d(L)y_t + 2\beta^{t+1}\, d_1\, d(L)y_{t+1} + \cdots + 2\beta^{t+m}\, d_m\, d(L)y_{t+m} \\
&= 2\beta^t \left(d_0 + d_1\, \beta L^{-1} + d_2\, \beta^2\, L^{-2} + \cdots + d_m\, \beta^m\, L^{-m}\right) d(L)y_t
\end{aligned}
$$

We can write this more succinctly as

$$
\frac{\partial J}{\partial y_t} = 2\beta^t\, d(\beta L^{-1})\, d(L)y_t \tag{2}
$$

Differentiating J with respect to y_t for $t = N - m + 1, \ldots, N$ gives

$$
\begin{aligned}
\frac{\partial J}{\partial y_N} &= 2\beta^N\, d_0\, d(L)y_N \\
\frac{\partial J}{\partial y_{N-1}} &= 2\beta^{N-1} \left[d_0 + \beta\, d_1\, L^{-1}\right] d(L)y_{N-1} \\
&\vdots \qquad \vdots \\
\frac{\partial J}{\partial y_{N-m+1}} &= 2\beta^{N-m+1} \left[d_0 + \beta L^{-1}\, d_1 + \cdots + \beta^{m-1}\, L^{-m+1}\, d_{m-1}\right] d(L)y_{N-m+1}
\end{aligned} \tag{3}
$$

With these preliminaries under our belts, we are ready to differentiate (1).

Differentiating (1) with respect to y_t for $t = 0, \ldots, N - m$ gives the Euler equations

$$
[h + d\,(\beta L^{-1})\, d(L)]y_t = a_t, \quad t = 0,\ 1,\ \ldots, N - m \tag{4}
$$

The system of equations (4) form a $2 \times m$ order linear *difference equation* that must hold for the values of t indicated.

Differentiating (1) with respect to y_t for $t = N - m + 1, \ldots, N$ gives the terminal conditions

$$
\begin{aligned}
\beta^N (a_N - h y_N - d_0\, d(L)y_N) &= 0 \\
\beta^{N-1} \left(a_{N-1} - h y_{N-1} - \left(d_0 + \beta\, d_1\, L^{-1}\right) d(L)\, y_{N-1}\right) &= 0 \\
&\vdots\vdots \\
\beta^{N-m+1} \left(a_{N-m+1} - h y_{N-m+1} - (d_0 + \beta L^{-1} d_1 + \cdots + \beta^{m-1} L^{-m+1} d_{m-1}) d(L) y_{N-m+1}\right) &= 0
\end{aligned} \tag{5}
$$

In the finite N problem, we want simultaneously to solve (4) subject to the m initial conditions $y_{-1}, \ldots, y_{-m}$ and the m terminal conditions (5).

These conditions uniquely pin down the solution of the finite N problem.

That is, for the finite N problem, conditions (4) and (5) are necessary and sufficient for a maximum, by concavity of the objective function.

Next we describe how to obtain the solution using matrix methods.

58.4.1 Matrix Methods

Let's look at how linear algebra can be used to tackle and shed light on the finite horizon LQ control problem.

A Single Lag Term

Let's begin with the special case in which $m = 1$.

We want to solve the system of $N + 1$ linear equations

$$\begin{aligned} [h + d\,(\beta L^{-1})\,d\,(L)]y_t &= a_t, \quad t = 0,\ 1,\ \ldots,\ N-1 \\ \beta^N[a_N - h\,y_N - d_0\,d\,(L)y_N] &= 0 \end{aligned} \tag{6}$$

where $d(L) = d_0 + d_1 L$.

These equations are to be solved for $y_0, y_1, \ldots, y_N$ as functions of $a_0, a_1, \ldots, a_N$ and y_{-1}.

Let

$$\phi(L) = \phi_0 + \phi_1 L + \beta\phi_1 L^{-1} = h + d(\beta L^{-1})d(L) = (h + d_0^2 + d_1^2) + d_1 d_0 L + d_1 d_0 \beta L^{-1}$$

Then we can represent (6) as the matrix equation

$$\begin{bmatrix} (\phi_0 - d_1^2) & \phi_1 & 0 & 0 & \ldots & \ldots & 0 \\ \beta\phi_1 & \phi_0 & \phi_1 & 0 & \ldots & \ldots & 0 \\ 0 & \beta\phi_1 & \phi_0 & \phi_1 & \ldots & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \ldots & \ldots & \ldots & \beta\phi_1 & \phi_0 & \phi_1 \\ 0 & \ldots & \ldots & \ldots & 0 & \beta\phi_1 & \phi_0 \end{bmatrix} \begin{bmatrix} y_N \\ y_{N-1} \\ y_{N-2} \\ \vdots \\ y_1 \\ y_0 \end{bmatrix} = \begin{bmatrix} a_N \\ a_{N-1} \\ a_{N-2} \\ \vdots \\ a_1 \\ a_0 - \phi_1 y_{-1} \end{bmatrix} \tag{7}$$

or

$$W\bar{y} = \bar{a} \tag{8}$$

Notice how we have chosen to arrange the y_t's in reverse time order.

The matrix W on the left side of (7) is "almost" a Toeplitz matrix (where each descending diagonal is constant).

There are two sources of deviation from the form of a Toeplitz matrix.

1. The first element differs from the remaining diagonal elements, reflecting the terminal condition.

2. The subdiagonal elements equal β time the superdiagonal elements.

The solution of (8) can be expressed in the form

$$\bar{y} = W^{-1}\bar{a} \tag{9}$$

which represents each element y_t of $\bar{y}$ as a function of the entire vector $\bar{a}$.

That is, y_t is a function of past, present, and future values of a's, as well as of the initial condition y_{-1}.

An Alternative Representation

An alternative way to express the solution to (7) or (8) is in so called **feedback-feedforward** form.

The idea here is to find a solution expressing y_t as a function of *past* y's and *current* and *future* a's.

To achieve this solution, one can use an LU decomposition of W.

There always exists a decomposition of W of the form $W = LU$ where

- L is an $(N+1) \times (N+1)$ lower trangular matrix
- U is an $(N+1) \times (N+1)$ upper trangular matrix.

The factorization can be normalized so that the diagonal elements of U are unity.

Using the LU representation in (9), we obtain

$$U\bar{y} = L^{-1}\bar{a} \tag{10}$$

Since L^{-1} is lower trangular, this representation expresses y_t as a function of

- lagged y's (via the term $U\bar{y}$), and
- current and future a's (via the term $L^{-1}\bar{a}$)

Because there are zeros everywhere in the matrix on the left of (7) except on the diagonal, superdiagonal, and subdiagonal, the LU decomposition takes

- L to be zero except in the diagional and the leading subdiagonal
- U to be zero except on the diagonal and the superdiagional

Thus, (10) has the form

$$\begin{bmatrix} 1 & U_{12} & 0 & 0 & \dots & 0 & 0 \\ 0 & 1 & U_{23} & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & U_{34} & \dots & 0 & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 & U_{N,N+1} \\ 0 & 0 & 0 & 0 & \dots & 0 & 1 \end{bmatrix} \begin{bmatrix} y_N \\ y_{N-1} \\ y_{N-2} \\ y_{N-3} \\ \vdots \\ y_1 \\ y_0 \end{bmatrix} =$$

$$\begin{bmatrix} L_{11}^{-1} & 0 & 0 & ... & 0 \\ L_{21}^{-1} & L_{22}^{-1} & 0 & ... & 0 \\ L_{31}^{-1} & L_{32}^{-1} & L_{33}^{-1} & ... & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ L_{N,1}^{-1} & L_{N,2}^{-1} & L_{N,3}^{-1} & ... & 0 \\ L_{N+1,1}^{-1} & L_{N+1,2}^{-1} & L_{N+1,3}^{-1} & ... & L_{N+1\,N+1}^{-1} \end{bmatrix} \begin{bmatrix} a_N \\ a_{N-1} \\ a_{N-2} \\ \vdots \\ a_1 \\ a_0 - \phi_1 y_{-1} \end{bmatrix}$$

where L_{ij}^{-1} is the (i,j) element of L^{-1} and U_{ij} is the (i,j) element of U.

Note how the left side for a given t involves y_t and one lagged value y_{t-1} while the right side involves all future values of the forcing process $a_t, a_{t+1}, ..., a_N$.

Additional Lag Terms

We briefly indicate how this approach extends to the problem with $m > 1$.

Assume that $\beta = 1$ and let D_{m+1} be the $(m+1) \times (m+1)$ symmetric matrix whose elements are determined from the following formula:

$$D_{jk} = d_0 d_{k-j} + d_1 d_{k-j+1} + ... + d_{j-1} d_{k-1}, \qquad k \geq j$$

Let I_{m+1} be the $(m+1) \times (m+1)$ identity matrix.

Let ϕ_j be the coefficients in the expansion $\phi(L) = h + d(L^{-1})d(L)$.

Then the first order conditions (4) and (5) can be expressed as:

$$(D_{m+1} + hI_{m+1}) \begin{bmatrix} y_N \\ y_{N-1} \\ \vdots \\ y_{N-m} \end{bmatrix} = \begin{bmatrix} a_N \\ a_{N-1} \\ \vdots \\ a_{N-m} \end{bmatrix} + M \begin{bmatrix} y_{N-m+1} \\ y_{N-m-2} \\ \vdots \\ y_{N-2m} \end{bmatrix}$$

where M is $(m+1) \times m$ and

$$M_{ij} = \begin{cases} D_{i-j,\,m+1} \text{ for } i > j \\ 0 \text{ for } i \leq j \end{cases}$$

$$\begin{aligned} \phi_m y_{N-1} + \phi_{m-1} y_{N-2} + ... + \phi_0 y_{N-m-1} + \phi_1 y_{N-m-2} + \\ ... + \phi_m y_{N-2m-1} = a_{N-m-1} \\ \phi_m y_{N-2} + \phi_{m-1} y_{N-3} + ... + \phi_0 y_{N-m-2} + \phi_1 y_{N-m-3} + \\ ... + \phi_m y_{N-2m-2} = a_{N-m-2} \\ \vdots \\ \phi_m y_{m+1} + \phi_{m-1} y_m + + ... + \phi_0 y_1 + \phi_1 y_0 + \phi_m y_{-m+1} = a_1 \\ \phi_m y_m + \phi_{m-1} y_{m-1} + \phi_{m-2} + ... + \phi_0 y_0 + \phi_1 y_{-1} + ... + \phi_m y_{-m} = a_0 \end{aligned}$$

As before, we can express this equation as $W\bar{y} = \bar{a}$.

The matrix on the left of this equation is "almost" Toeplitz, the exception being the leading $m \times m$ sub matrix in the upper left hand corner.

We can represent the solution in feedback-feedforward form by obtaining a decomposition $LU = W$, and obtain

$$U\bar{y} = L^{-1}\bar{a} \tag{11}$$

$$\sum_{j=0}^{t} U_{-t+N+1,\,-t+N+j+1}\, y_{t-j} = \sum_{j=0}^{N-t} L_{-t+N+1,\,-t+N+1-j}\, \bar{a}_{t+j} \ , \qquad t = 0, 1, \ldots, N$$

where $L^{-1}_{t,s}$ is the element in the (t, s) position of L, and similarly for U.

The left side of equation (11) is the "feedback" part of the optimal control law for y_t, while the right-hand side is the "feedforward" part.

We note that there is a different control law for each t.

Thus, in the finite horizon case, the optimal control law is time dependent.

It is natural to suspect that as $N \to \infty$, (11) becomes equivalent to the solution of our infinite horizon problem, which below we shall show can be expressed as

$$c(L)y_t = c(\beta L^{-1})^{-1} a_t \ ,$$

so that as $N \to \infty$ we expect that for each fixed $t, U^{-1}_{t,t-j} \to c_j$ and $L_{t,t+j}$ approaches the coefficient on L^{-j} in the expansion of $c(\beta L^{-1})^{-1}$.

This suspicion is true under general conditions that we shall study later.

For now, we note that by creating the matrix W for large N and factoring it into the LU form, good approximations to $c(L)$ and $c(\beta L^{-1})^{-1}$ can be obtained.

58.5 The Infinite Horizon Limit

For the infinite horizon problem, we propose to discover first-order necessary conditions by taking the limits of (4) and (5) as $N \to \infty$.

This approach is valid, and the limits of (4) and (5) as N approaches infinity are first-order necessary conditions for a maximum.

However, for the infinite horizon problem with $\beta < 1$, the limits of (4) and (5) are, in general, not sufficient for a maximum.

That is, the limits of (5) do not provide enough information uniquely to determine the solution of the Euler equation (4) that maximizes (1).

As we shall see below, a side condition on the path of y_t that together with (4) is sufficient for an optimum is

$$\sum_{t=0}^{\infty} \beta^t\, h y_t^2 < \infty \tag{12}$$

All paths that satisfy the Euler equations, except the one that we shall select below, violate

this condition and, therefore, evidently lead to (much) lower values of (1) than does the optimal path selected by the solution procedure below.

Consider the *characteristic equation* associated with the Euler equation

$$h + d\left(\beta z^{-1}\right) d\left(z\right) = 0 \tag{13}$$

Notice that if $\tilde{z}$ is a root of equation (13), then so is $\beta\tilde{z}^{-1}$.

Thus, the roots of (13) come in "β-reciprocal" pairs.

Assume that the roots of (13) are distinct.

Let the roots be, in descending order according to their moduli, $z_1, z_2, \ldots, z_{2m}$.

From the reciprocal pairs property and the assumption of distinct roots, it follows that $|z_j| > \sqrt{\beta}$ for $j \leq m$ and $|z_j| < \sqrt{\beta}$ for $j > m$.

It also follows that $z_{2m-j} = \beta z_{j+1}^{-1}, j = 0, 1, \ldots, m-1$.

Therefore, the characteristic polynomial on the left side of (13) can be expressed as

$$\begin{aligned} h + d(\beta z^{-1})d(z) &= z^{-m} z_0 (z - z_1) \cdots (z - z_m)(z - z_{m+1}) \cdots (z - z_{2m}) \\ &= z^{-m} z_0 (z - z_1)(z - z_2) \cdots (z - z_m)(z - \beta z_m^{-1}) \cdots (z - \beta z_2^{-1})(z - \beta z_1^{-1}) \end{aligned} \tag{14}$$

where z_0 is a constant.

In (14), we substitute $(z - z_j) = -z_j(1 - \frac{1}{z_j}z)$ and $(z - \beta z_j^{-1}) = z(1 - \frac{\beta}{z_j}z^{-1})$ for $j = 1, \ldots, m$ to get

$$h + d(\beta z^{-1})d(z) = (-1)^m (z_0 z_1 \cdots z_m)(1 - \frac{1}{z_1}z) \cdots (1 - \frac{1}{z_m}z)(1 - \frac{1}{z_1}\beta z^{-1}) \cdots (1 - \frac{1}{z_m}\beta z^{-1})$$

Now define $c(z) = \sum_{j=0}^{m} c_j z^j$ as

$$c\left(z\right) = \left[(-1)^m z_0 \, z_1 \cdots z_m\right]^{1/2} (1 - \frac{z}{z_1}) \, (1 - \frac{z}{z_2}) \cdots (1 - \frac{z}{z_m}) \tag{15}$$

Notice that (14) can be written

$$h + d\ (\beta z^{-1})\ d\ (z) = c\left(\beta z^{-1}\right) c\left(z\right) \tag{16}$$

It is useful to write (15) as

$$c(z) = c_0(1 - \lambda_1 \, z) \ldots (1 - \lambda_m z) \tag{17}$$

where

$$c_0 = \left[(-1)^m \, z_0 \, z_1 \cdots z_m\right]^{1/2}; \quad \lambda_j = \frac{1}{z_j}, \ \ j = 1, \ldots, m$$

Since $|z_j| > \sqrt{\beta}$ for $j = 1, \ldots, m$ it follows that $|\lambda_j| < 1/\sqrt{\beta}$ for $j = 1, \ldots, m$.

Using (17), we can express the factorization (16) as

$$h + d(\beta z^{-1})d(z) = c_0^2(1 - \lambda_1 z)\cdots(1 - \lambda_m z)(1 - \lambda_1 \beta z^{-1})\cdots(1 - \lambda_m \beta z^{-1})$$

In sum, we have constructed a factorization (16) of the characteristic polynomial for the Euler equation in which the zeros of $c(z)$ exceed $\beta^{1/2}$ in modulus, and the zeros of $c\left(\beta z^{-1}\right)$ are less than $\beta^{1/2}$ in modulus.

Using (16), we now write the Euler equation as

$$c(\beta L^{-1})\, c\left(L\right) y_t = a_t$$

The unique solution of the Euler equation that satisfies condition (12) is

$$c(L)\, y_t = c\left(\beta L^{-1}\right)^{-1} a_t \tag{18}$$

This can be established by using an argument paralleling that in chapter IX of [94].

To exhibit the solution in a form paralleling that of [94], we use (17) to write (18) as

$$(1 - \lambda_1 L)\cdots(1 - \lambda_m L) y_t = \frac{c_0^{-2} a_t}{(1 - \beta\lambda_1 L^{-1})\cdots(1 - \beta\lambda_m L^{-1})} \tag{19}$$

Using partial fractions, we can write the characteristic polynomial on the right side of (19) as

$$\sum_{j=1}^{m} \frac{A_j}{1 - \lambda_j \beta L^{-1}} \quad \text{where} \quad A_j := \frac{c_0^{-2}}{\prod_{i \neq j}(1 - \frac{\lambda_i}{\lambda_j})}$$

Then (19) can be written

$$(1 - \lambda_1 L)\cdots(1 - \lambda_m L) y_t = \sum_{j=1}^{m} \frac{A_j}{1 - \lambda_j \beta L^{-1}} a_t$$

or

$$(1 - \lambda_1 L)\cdots(1 - \lambda_m L) y_t = \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} (\lambda_j \beta)^k \, a_{t+k} \tag{20}$$

Equation (20) expresses the optimum sequence for y_t in terms of m lagged y's, and m weighted infinite geometric sums of future a_t's.

Furthermore, (20) is the unique solution of the Euler equation that satisfies the initial conditions and condition (12).

In effect, condition (12) compels us to solve the "unstable" roots of $h + d(\beta z^{-1})d(z)$ forward (see [94]).

The step of factoring the polynomial $h + d(\beta z^{-1})\, d(z)$ into $c\left(\beta z^{-1}\right)c\left(z\right)$, where the zeros of $c\left(z\right)$ all have modulus exceeding $\sqrt{\beta}$, is central to solving the problem.

We note two features of the solution (20)

- Since $|\lambda_j| < 1/\sqrt{\beta}$ for all j, it follows that $(\lambda_j\ \beta) < \sqrt{\beta}$.
- The assumption that $\{a_t\}$ is of exponential order less than $1/\sqrt{\beta}$ is sufficient to guarantee that the geometric sums of future a_t's on the right side of (20) converge.

We immediately see that those sums will converge under the weaker condition that $\{a_t\}$ is of exponential order less than ϕ^{-1} where $\phi = \max\{\beta\lambda_i, i = 1, \ldots, m\}$.

Note that with a_t identically zero, (20) implies that in general $|y_t|$ eventually grows exponentially at a rate given by $\max_i |\lambda_i|$.

The condition $\max_i |\lambda_i| < 1/\sqrt{\beta}$ guarantees that condition (12) is satisfied.

In fact, $\max_i |\lambda_i| < 1/\sqrt{\beta}$ is a necessary condition for (12) to hold.

Were (12) not satisfied, the objective function would diverge to $-\infty$, implying that the y_t path could not be optimal.

For example, with $a_t = 0$, for all t, it is easy to describe a naive (nonoptimal) policy for $\{y_t, t \geq 0\}$ that gives a finite value of (17).

We can simply let $y_t = 0$ for $t \geq 0$.

This policy involves at most m nonzero values of hy_t^2 and $[d(L)y_t]^2$, and so yields a finite value of (1).

Therefore it is easy to dominate a path that violates (12).

58.6 Undiscounted Problems

It is worthwhile focusing on a special case of the LQ problems above: the undiscounted problem that emerges when $\beta = 1$.

In this case, the Euler equation is

$$\left(h + d(L^{-1})d(L)\right) y_t = a_t$$

The factorization of the characteristic polynomial (16) becomes

$$\left(h + d\left(z^{-1}\right)d(z)\right) = c\left(z^{-1}\right) c\left(z\right)$$

where

$$\begin{aligned} c\left(z\right) &= c_0(1 - \lambda_1 z) \ldots (1 - \lambda_m z) \\ c_0 &= \left[(-1)^m z_0 z_1 \ldots z_m\right] \\ |\lambda_j| &< 1 \ \text{ for } \ j = 1, \ldots, m \\ \lambda_j &= \frac{1}{z_j} \text{ for } j = 1, \ldots, m \\ z_0 &= \ \text{constant} \end{aligned}$$

The solution of the problem becomes

$$(1-\lambda_1 L)\cdots(1-\lambda_m L)y_t = \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} \lambda_j^k a_{t+k}$$

58.6.1 Transforming discounted to undiscounted problem

Discounted problems can always be converted into undiscounted problems via a simple transformation.

Consider problem (1) with $0 < \beta < 1$.

Define the transformed variables

$$\tilde{a}_t = \beta^{t/2} a_t,\ \tilde{y}_t = \beta^{t/2} y_t \tag{21}$$

Then notice that $\beta^t \left[d\left(L\right) y_t\right]^2 = \left[\tilde{d}\left(L\right)\tilde{y}_t\right]^2$ with $\tilde{d}\left(L\right) = \sum_{j=0}^{m} \tilde{d}_j L^j$ and $\tilde{d}_j = \beta^{j/2} d_j$.

Then the original criterion function (1) is equivalent to

$$\lim_{N\to\infty} \sum_{t=0}^{N} \{\tilde{a}_t\, \tilde{y}_t - \frac{1}{2} h\, \tilde{y}_t^2 - \frac{1}{2}[\tilde{d}\left(L\right) \tilde{y}_t]^2\} \tag{22}$$

which is to be maximized over sequences $\{\tilde{y}_t,\ t = 0, ...\}$ subject to $\tilde{y}_{-1}, \cdots, \tilde{y}_{-m}$ given and $\{\tilde{a}_t,\ t = 1, ...\}$ a known bounded sequence.

The Euler equation for this problem is $\left[h + \tilde{d}\left(L^{-1}\right) \tilde{d}\left(L\right)\right] \tilde{y}_t = \tilde{a}_t$.

The solution is

$$(1-\tilde{\lambda}_1 L)\cdots(1-\tilde{\lambda}_m L)\,\tilde{y}_t = \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k\, \tilde{a}_{t+k}$$

or

$$\tilde{y}_t = \tilde{f}_1\, \tilde{y}_{t-1} + \cdots + \tilde{f}_m\, \tilde{y}_{t-m} + \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k\, \tilde{a}_{t+k}, \tag{23}$$

where $\tilde{c}\left(z^{-1}\right)\tilde{c}\left(z\right) = h + \tilde{d}\left(z^{-1}\right)\tilde{d}\left(z\right)$, and where

$$\left[(-1)^m\, \tilde{z}_0 \tilde{z}_1 \ldots \tilde{z}_m\right]^{1/2} (1-\tilde{\lambda}_1\, z) \ldots (1-\tilde{\lambda}_m\, z) = \tilde{c}\left(z\right),\ \text{where}\ \ |\tilde{\lambda}_j| < 1$$

We leave it to the reader to show that (23) implies the equivalent form of the solution

$$y_t = f_1\, y_{t-1} + \cdots + f_m\, y_{t-m} + \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} \left(\lambda_j\, \beta\right)^k a_{t+k}$$

where

$$f_j = \tilde{f}_j\, \beta^{-j/2},\ A_j = \tilde{A}_j,\ \lambda_j = \tilde{\lambda}_j\, \beta^{-1/2} \tag{24}$$

The transformations (21) and the inverse formulas (24) allow us to solve a discounted problem by first solving a related undiscounted problem.

58.7 Implementation

Code that computes solutions to the LQ problem using the methods described above can be found in file control_and_filter.jl.

Here's how it looks

```
In [3]: function LQFilter(d, h, y_m;
                          r = nothing,
                          β = nothing,
                          h_eps = nothing)

            m = length(d) - 1
            m == length(y_m) || throw(ArgumentError("y_m and d must be of same␣
          ↪length = $m"))

            # define the coefficients of ☒ up front
            ϕ = zeros(2m + 1)
            for i in -m:m
                ϕ[m-i+1] = sum(diag(d*d', -i))
            end
            ϕ[m+1] = ϕ[m+1] + h

            # if r is given calculate the vector ☒_r
            if isnothing(r)
                k = nothing
                ϕ_r = nothing
            else
                k = size(r, 1) - 1
                ϕ_r = zeros(2k + 1)

                for i = -k:k
                    ϕ_r[k-i+1] = sum(diag(r*r', -i))
                end

                if h_eps != nothing
                    ϕ_r[k+1] = ϕ_r[k+1] + h_eps
                end
            end

            # if β is given, define the transformed variables
            if isnothing(β)
                β = 1.0
            else
                d = β.^(collect(0:m)/2) * d
                y_m = y_m * β.^(- collect(1:m)/2)
            end

            return (d = d, h = h, y_m = y_m, m = m, ϕ = ϕ, β = β, ϕ_r = ϕ_r, k = k)
        end

        function construct_W_and_Wm(lqf, N)
```

```
    @unpack d, m = lqf
    W = zeros(N + 1, N + 1)
    W_m = zeros(N + 1, m)

    # terminal conditions
    D_m1 = zeros(m + 1, m + 1)
    M = zeros(m + 1, m)

    # (1) Constuct the D_{m+1} matrix using the formula

    for j in 1:(m+1)
        for k in j:(m+1)
            D_m1[j, k] = dot(d[1:j, 1], d[k-j+1:k, 1])
        end
    end

    # Make the matrix symmetric
    D_m1 = D_m1 + D_m1' - Diagonal(diag(D_m1))

    # (2) Construct the M matrix using the entries of D_m1

    for j in 1:m
        for i in (j + 1):(m + 1)
            M[i, j] = D_m1[i-j, m+1]
        end
    end
    M

    # Euler equations for t = 0, 1, ..., N-(m+1)
    @unpack ϕ, h = lqf

    W[1:(m + 1), 1:(m + 1)] = D_m1 + h * I
    W[1:(m + 1), (m + 2):(2m + 1)] = M

    for (i, row) in enumerate((m + 2):(N + 1 - m))
        W[row, (i + 1):(2m + 1 + i)] = ϕ'
    end

    for i in 1:m
        W[N - m + i + 1 , end-(2m + 1 - i)+1:end] = ϕ[1:end-i]
    end

    for i in 1:m
        W_m[N - i + 2, 1:(m - i)+1] = ϕ[(m + 1 + i):end]
    end

    return W, W_m
end

function roots_of_characteristic(lqf)
    @unpack m, ϕ = lqf

    # Calculate the roots of the 2m-polynomial
    ϕ_poly=Polynomial(ϕ[end:-1:1])
    proots = roots(ϕ_poly)

    # sort the roots according to their length (in descending order)
    roots_sorted = sort(proots, by=abs)[end:-1:1]
```

```
        z_0 = sum(ϕ) / (fromroots(proots))(1.0)
        z_1_to_m = roots_sorted[1:m]     # we need only those outside the unit
↪circle
        λ = 1 ./ z_1_to_m
        return z_1_to_m, z_0, λ
    end

    function coeffs_of_c(lqf)
        m = lqf.m
        z_1_to_m, z_0, λ = roots_of_characteristic(lqf)
        c_0 = (z_0 * prod(z_1_to_m) * (-1.0)^m)^(0.5)
        c_coeffs = coeffs(Polynomial(z_1_to_m)) * z_0 / c_0
        return c_coeffs
    end

    function solution(lqf)
        z_1_to_m, z_0, λ = roots_of_characteristic(lqf)
        c_0 = coeffs_of_c(lqf)[end]
        A = zeros(lqf.m)
        for j in 1:m
            denom = 1 - λ/λ[j]
            A[j] = c_0^(-2) / prod(denom[1:m .!= j])
        end
        return λ, A
    end

    function construct_V(lqf; N=nothing)
        @unpack ϕ_r, k = lqf
        V = zeros(N, N)
        for i in 1:N
            for j in 1:N
                if abs(i-j) <= k
                    V[i, j] = ϕ_r[k + abs(i-j)+1]
                end
            end
        end
        return V
    end

    function simulate_a(lqf, N)
        V = construct_V(lqf, N + 1)
        d = MVNSampler(zeros(N + 1), V)
        return rand(d)
    end

    function predict(lqf, a_hist, t)
        N = length(a_hist) - 1
        V = construct_V(lqf, N + 1)

        aux_matrix = zeros(N + 1, N + 1)
        aux_matrix[1:t+1 , 1:t+1 ] .= I + zeros(t+1, t+1)
        L = chol(V)'
        Ea_hist = inv(L) * aux_matrix * L * a_hist

        return Ea_hist
    end

    function optimal_y(lqf, a_hist, t = nothing)
```

```
    @unpack β, y_m, m = lqf

    N = length(a_hist) - 1
    W, W_m = construct_W_and_Wm(lqf, N)

    F = lu(W)

    L, U = F.L, F.U
    D = Diagonal(1.0./diag(U))
    U = D * U
    L = L * Diagonal(1.0./diag(D))

    J = reverse(I + zeros(N+1, N + 1), dims = 2)

    if isnothing(t)                      # if the problem is deterministic
        a_hist = J * a_hist

        # transform the a sequence if β is given
        if β != 1
            a_hist =  reshape(a_hist * (β^(collect(N:0)/ 2)), N + 1, 1)
        end

        ā = a_hist - W_m * y_m          # ā from the lecutre
        Uy = \(L, ā)                    # U @ ȳ = L^{-1}ā from the lecture
        ȳ = \(U, Uy)                    # ȳ = U^{-1}L^{-1}ā
        # Reverse the order of ȳ with the matrix J
        J = reverse(I + zeros(N+m+1, N + m + 1), dims = 2)
        y_hist = J * vcat(ȳ, y_m)       # y_hist : concatenated y_m and ȳ
        # transform the optimal sequence back if β is given
        if β != 1
            y_hist = y_hist .* β.^(- collect(-m:N)/2)
        end

    else  # if the problem is stochastic and we look at it
        Ea_hist = reshape(predict(lqf, a_hist, t), N + 1, 1)
        Ea_hist = J * Ea_hist

        ā = Ea_hist - W_m * y_m         # ā from the lecutre
        Uy = \(L, ā)                    # U @ ȳ = L^{-1}ā from the lecture
        ȳ = \(U, Uy)                    # ȳ = U^{-1}L^{-1}ā

        # Reverse the order of ȳ with the matrix J
        J = reverse(I + zeros(N + m + 1, N + m + 1), dims = 2)
        y_hist = J * vcat(ȳ, y_m)       # y_hist : concatenated y_m and ȳ
    end
    return y_hist, L, U, ȳ
end
```

```
Out[3]: optimal_y (generic function with 2 methods)
```

58.7.1 Example

In this application we'll have one lag, with

$$d(L)y_t = \gamma(I - L)y_t = \gamma(y_t - y_{t-1})$$

Suppose for the moment that $\gamma = 0$.

Then the intertemporal component of the LQ problem disappears, and the agent simply wants to maximize $a_t y_t - h y_t^2/2$ in each period.

This means that the agent chooses $y_t = a_t/h$.

In the following we'll set $h = 1$, so that the agent just wants to track the $\{a_t\}$ process.

However, as we increase γ, the agent gives greater weight to a smooth time path.

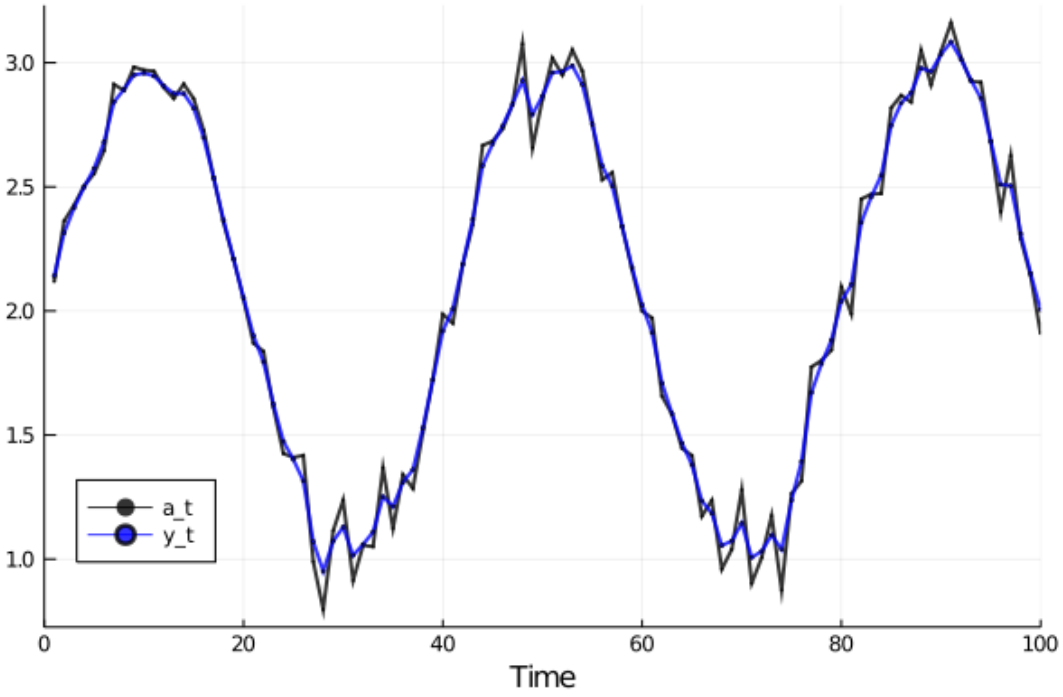
Hence $\{y_t\}$ evolves as a smoothed version of $\{a_t\}$.

The $\{a_t\}$ sequence we'll choose as a stationary cyclic process plus some white noise.

Here's some code that generates a plot when $\gamma = 0.8$

In [4]:
```
gr(fmt=:png);

        # set seed and generate a_t sequence
        Random.seed!(123)
        n = 100
        a_seq = sin.(range(0,  5 * pi, length = n)) .+ 2 + 0.1 * randn(n)

        function plot_simulation(;γ=0.8, m=1, h=1., y_m=2.)
          d = γ * [1, -1]
          y_m = [y_m]

          testlq = LQFilter(d, h, y_m)
          y_hist, L, U, y = optimal_y(testlq, a_seq)
          y = y[end:-1:1]  # reverse y

          # plot simulation results
          time = 1:length(y)
          plt = plot(time, a_seq / h, lw=2, color=:black, alpha=0.8, marker = :
↪circle,
                     markersize = 2, label="a_t")
          plot!(plt, time, y, lw=2, color=:blue, marker = :circle,  markersize =
↪2, alpha=0.8,
                label="y_t")
          plot!(plt, xlabel="Time", grid=true, xlim=(0,maximum(time)), legend=:
↪bottomleft)
        end

        plot_simulation()
```

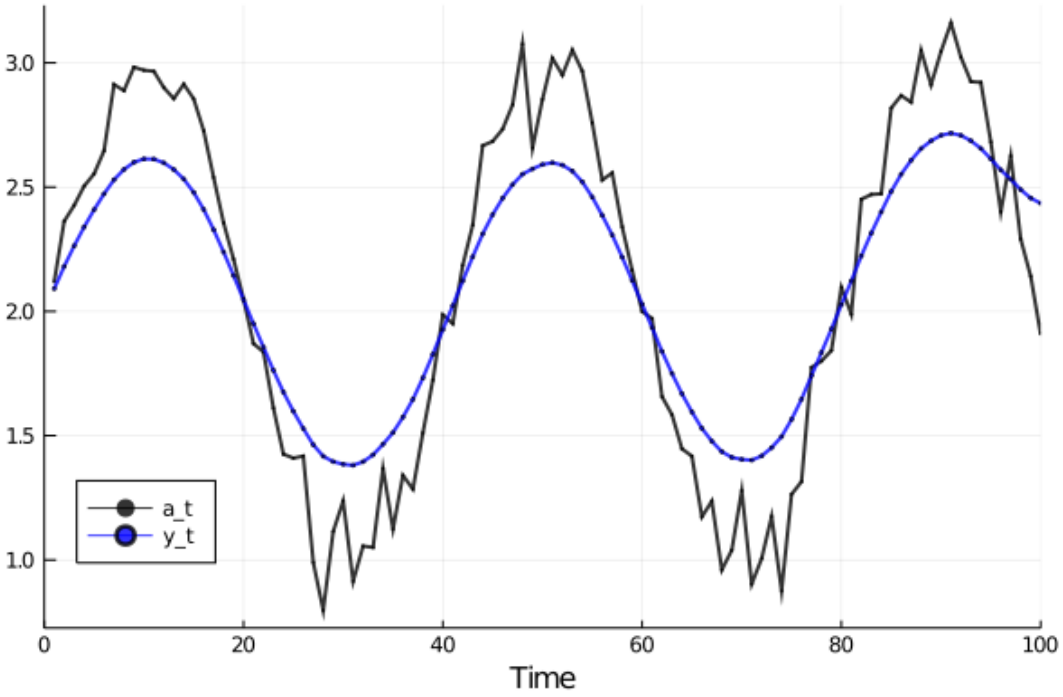
Out[4]:



Here's what happens when we change γ to 5.0

```
In [5]: plot_simulation(γ=5.0)
```

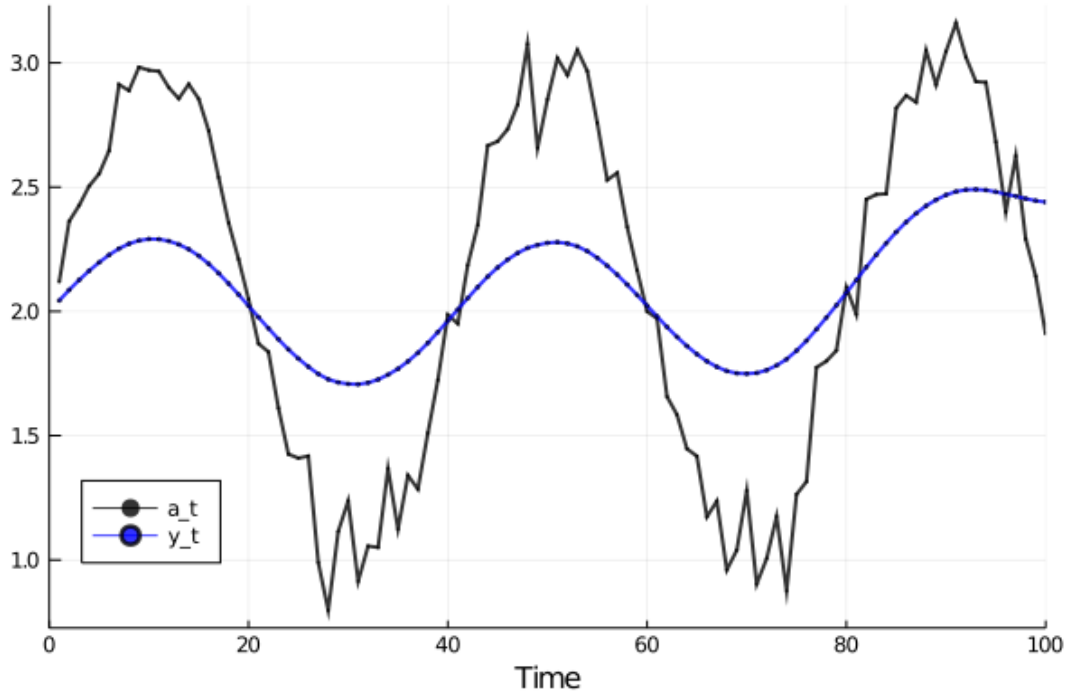
Out[5]:



And here's $\gamma = 10$

```
In [6]: plot_simulation(γ=10.0)
```

Out[6]:



58.8 Exercises

58.8.1 Exercise 1

Consider solving a discounted version ($\beta < 1$) of problem (1), as follows.

Convert (1) to the undiscounted problem (22).

Let the solution of (22) in feedback form be

$$(1 - \tilde{\lambda}_1 L) \cdots (1 - \tilde{\lambda}_m L)\tilde{y}_t = \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k \tilde{a}_{t+k}$$

or

$$\tilde{y}_t = \tilde{f}_1 \tilde{y}_{t-1} + \cdots + \tilde{f}_m \tilde{y}_{t-m} + \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k \tilde{a}_{t+k} \tag{25}$$

Here

- $h + \tilde{d}(z^{-1})\tilde{d}(z) = \tilde{c}(z^{-1})\tilde{c}(z)$
- $\tilde{c}(z) = [(-1)^m \tilde{z}_0 \tilde{z}_1 \cdots \tilde{z}_m]^{1/2}(1 - \tilde{\lambda}_1 z) \cdots (1 - \tilde{\lambda}_m z)$

where the $\tilde{z}_j$ are the zeros of $h + \tilde{d}(z^{-1})\,\tilde{d}(z)$.

Prove that (25) implies that the solution for y_t in feedback form is

$$y_t = f_1 y_{t-1} + ... + f_m y_{t-m} + \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} \beta^k \lambda_j^k a_{t+k}$$

where $f_j = \tilde{f}_j \beta^{-j/2}$, $A_j = \tilde{A}_j$, and $\lambda_j = \tilde{\lambda}_j \beta^{-1/2}$.

58.8.2 Exercise 2

Solve the optimal control problem, maximize

$$\sum_{t=0}^{2} \left\{ a_t y_t - \frac{1}{2}[(1-2L)y_t]^2 \right\}$$

subject to y_{-1} given, and $\{a_t\}$ a known bounded sequence.

Express the solution in the "feedback form" (20), giving numerical values for the coefficients.

Make sure that the boundary conditions (5) are satisfied.

(Note: this problem differs from the problem in the text in one important way: instead of $h > 0$ in (1), $h = 0$. This has an important influence on the solution.)

58.8.3 Exercise 3

Solve the infinite time optimal control problem to maximize

$$\lim_{N\to\infty} \sum_{t=0}^{N} -\frac{1}{2}[(1-2L)y_t]^2,$$

subject to y_{-1} given. Prove that the solution is

$$y_t = 2y_{t-1} = 2^{t+1} y_{-1} \qquad t > 0$$

58.8.4 Exercise 4

Solve the infinite time problem, to maximize

$$\lim_{N\to\infty} \sum_{t=0}^{N} (.0000001)\, y_t^2 - \frac{1}{2}[(1-2L)y_t]^2$$

subject to y_{-1} given. Prove that the solution $y_t = 2y_{t-1}$ violates condition (12), and so is not optimal.

Prove that the optimal solution is approximately $y_t = .5y_{t-1}$.

Chapter 59

Classical Filtering With Linear Algebra

59.1 Contents

59.2 Overview

This is a sequel to the earlier lecture Classical Control with Linear Algebra.

That lecture used linear algebra – in particular, the LU decomposition – to formulate and solve a class of linear-quadratic optimal control problems.

In this lecture, we'll be using a closely related decomposition, the Cholesky decomposition , to solve linear prediction and filtering problems.

We exploit the useful fact that there is an intimate connection between two superficially different classes of problems:

- deterministic linear-quadratic (LQ) optimal control problems
- linear least squares prediction and filtering problems

The first class of problems involves no randomness, while the second is all about randomness.

Nevertheless, essentially the same mathematics solves both type of problem.

This connection, which is often termed "duality," is present whether one uses "classical" or "recursive" solution procedures.

In fact we saw duality at work earlier when we formulated control and prediction problems recursively in lectures LQ dynamic programming problems, A first look at the Kalman filter, and The permanent income model.

A useful consequence of duality is that

- With every LQ control problem there is implicitly affiliated a linear least squares pre-

diction or filtering problem.
- With every linear least squares prediction or filtering problem there is implicitly affiliated a LQ control problem.

An understanding of these connections has repeatedly proved useful in cracking interesting applied problems.

For example, Sargent [94] [chs. IX, XIV] and Hansen and Sargent [44] formulated and solved control and filtering problems using z-transform methods.

In this lecture we investigate these ideas using mostly elementary linear algebra.

59.2.1 References

Useful references include [107], [44], [82], [6], and [80].

59.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

59.3 Infinite Horizon Prediction and Filtering Problems

We pose two related prediction and filtering problems.

We let Y_t be a univariate m^{th} order moving average, covariance stationary stochastic process,

$$Y_t = d(L)u_t \tag{1}$$

where $d(L) = \sum_{j=0}^{m} d_j L^j$, and u_t is a serially uncorrelated stationary random process satisfying

$$\begin{aligned} \mathbb{E}u_t &= 0 \\ \mathbb{E}u_t u_s &= \begin{cases} 1 & \text{if } t = s \\ 0 & \text{otherwise} \end{cases} \end{aligned} \tag{2}$$

We impose no conditions on the zeros of $d(z)$.

A second covariance stationary process is X_t given by

$$X_t = Y_t + \varepsilon_t \tag{3}$$

where ε_t is a serially uncorrelated stationary random process with $\mathbb{E}\varepsilon_t = 0$ and $\mathbb{E}\varepsilon_t\varepsilon_s = 0$ for all distinct t and s.

We also assume that $\mathbb{E}\varepsilon_t u_s = 0$ for all t and s.

The **linear least squares prediction problem** is to find the L_2 random variable $\hat{X}_{t+j}$ among linear combinations of $\{X_t,\ X_{t-1}, ...\}$ that minimizes $\mathbb{E}(\hat{X}_{t+j} - X_{t+j})^2$.

That is, the problem is to find a $\gamma_j(L) = \sum_{k=0}^{\infty} \gamma_{jk} L^k$ such that $\sum_{k=0}^{\infty} |\gamma_{jk}|^2 < \infty$ and $\mathbb{E}[\gamma_j(L)X_t - X_{t+j}]^2$ is minimized.

The **linear least squares filtering problem** is to find a $b(L) = \sum_{j=0}^{\infty} b_j L^j$ such that $\sum_{j=0}^{\infty} |b_j|^2 < \infty$ and $\mathbb{E}[b(L)X_t - Y_t]^2$ is minimized.

Interesting versions of these problems related to the permanent income theory were studied by [80].

59.3.1 Problem formulation

These problems are solved as follows.

The covariograms of Y and X and their cross covariogram are, respectively,

$$\begin{aligned} C_X(\tau) &= \mathbb{E}X_t X_{t-\tau} \\ C_Y(\tau) &= \mathbb{E}Y_t Y_{t-\tau} \qquad \tau = 0, \pm 1, \pm 2, ... \\ C_{Y,X}(\tau) &= \mathbb{E}Y_t X_{t-\tau} \end{aligned} \tag{4}$$

The covariance and cross covariance generating functions are defined as

$$\begin{aligned} g_X(z) &= \sum_{\tau=-\infty}^{\infty} C_X(\tau) z^\tau \\ g_Y(z) &= \sum_{\tau=-\infty}^{\infty} C_Y(\tau) z^\tau \\ g_{YX}(z) &= \sum_{\tau=-\infty}^{\infty} C_{YX}(\tau) z^\tau \end{aligned} \tag{5}$$

The generating functions can be computed by using the following facts.

Let v_{1t} and v_{2t} be two mutually and serially uncorrelated white noises with unit variances.

That is, $\mathbb{E}v_{1t}^2 = \mathbb{E}v_{2t}^2 = 1, \mathbb{E}v_{1t} = \mathbb{E}v_{2t} = 0, \mathbb{E}v_{1t}v_{2s} = 0$ for all t and s, $\mathbb{E}v_{1t}v_{1t-j} = \mathbb{E}v_{2t}v_{2t-j} = 0$ for all $j \neq 0$.

Let x_t and y_t be two random process given by

$$\begin{aligned} y_t &= A(L)v_{1t} + B(L)v_{2t} \\ x_t &= C(L)v_{1t} + D(L)v_{2t} \end{aligned}$$

Then, as shown for example in [94] [ch. XI], it is true that

$$\begin{aligned} g_y(z) &= A(z)A(z^{-1}) + B(z)B(z^{-1}) \\ g_x(z) &= C(z)C(z^{-1}) + D(z)D(z^{-1}) \\ g_{yx}(z) &= A(z)C(z^{-1}) + B(z)D(z^{-1}) \end{aligned} \tag{6}$$

Applying these formulas to (1) – (4), we have

$$\begin{aligned} g_Y(z) &= d(z)d(z^{-1}) \\ g_X(z) &= d(z)d(z^{-1}) + h \\ g_{YX}(z) &= d(z)d(z^{-1}) \end{aligned} \tag{7}$$

The key step in obtaining solutions to our problems is to factor the covariance generating function $g_X(z)$ of X.

The solutions of our problems are given by formulas due to Wiener and Kolmogorov.

These formulas utilize the Wold moving average representation of the X_t process,

$$X_t = c\left(L\right)\eta_t \tag{8}$$

where $c(L) = \sum_{j=0}^{m} c_j L^j$, with

$$c_0\eta_t = X_t - \hat{\mathbb{E}}[X_t|X_{t-1}, X_{t-2}, ...] \tag{9}$$

Here $\hat{\mathbb{E}}$ is the linear least squares projection operator.

Equation (9) is the condition that $c_0\eta_t$ can be the one-step ahead error in predicting X_t from its own past values.

Condition (9) requires that η_t lie in the closed linear space spanned by $[X_t,\ X_{t-1}, ...]$.

This will be true if and only if the zeros of $c(z)$ do not lie inside the unit circle.

It is an implication of (9) that η_t is a serially uncorrelated random process, and that a normalization can be imposed so that $\mathbb{E}\eta_t^2 = 1$.

Consequently, an implication of (8) is that the covariance generating function of X_t can be expressed as

$$g_X(z) = c\left(z\right)c\left(z^{-1}\right) \tag{10}$$

It remains to discuss how $c(L)$ is to be computed.

Combining (6) and (10) gives

$$d(z)\,d(z^{-1}) + h = c\left(z\right)c\left(z^{-1}\right) \tag{11}$$

Therefore, we have already showed constructively how to factor the covariance generating function $g_X(z) = d(z)\,d\left(z^{-1}\right) + h$.

We now introduce the **annihilation operator**:

$$\left[\sum_{j=-\infty}^{\infty} f_j L^j\right]_+ \equiv \sum_{j=0}^{\infty} f_j L^j \tag{12}$$

In words, $[\quad]_+$ means "ignore negative powers of L".

We have defined the solution of the prediction problem as $\hat{\mathbb{E}}[X_{t+j}|X_t,\ X_{t-1}, ...] = \gamma_j\left(L\right)X_t$.

Assuming that the roots of $c(z) = 0$ all lie outside the unit circle, the Wiener-Kolmogorov formula for $\gamma_j(L)$ holds:

$$\gamma_j(L) = \left[\frac{c(L)}{L^j}\right]_+ c(L)^{-1} \tag{13}$$

We have defined the solution of the filtering problem as $\hat{\mathbb{E}}[Y_t \mid X_t, X_{t-1}, ...] = b(L)X_t$.

The Wiener-Kolomogorov formula for $b(L)$ is

$$b(L) = \left(\frac{g_{YX}(L)}{c(L^{-1})}\right)_+ c(L)^{-1}$$

or

$$b(L) = \left[\frac{d(L)d(L^{-1})}{c(L^{-1})}\right]_+ c(L)^{-1} \tag{14}$$

Formulas (13) and (14) are discussed in detail in [108] and [94].

The interested reader can there find several examples of the use of these formulas in economics Some classic examples using these formulas are due to [80].

As an example of the usefulness of formula (14), we let X_t be a stochastic process with Wold moving average representation

$$X_t = c(L)\eta_t$$

where $\mathbb{E}\eta_t^2 = 1$, and $c_0\eta_t = X_t - \hat{\mathbb{E}}[X_t|X_{t-1}, ...], c(L) = \sum_{j=0}^m c_j L$.

Suppose that at time t, we wish to predict a geometric sum of future X's, namely

$$y_t \equiv \sum_{j=0}^{\infty} \delta^j X_{t+j} = \frac{1}{1-\delta L^{-1}} X_t$$

given knowledge of $X_t, X_{t-1}, ...$

We shall use (14) to obtain the answer.

Using the standard formulas (6), we have that

$$\begin{aligned} g_{yx}(z) &= (1-\delta z^{-1})c(z)c(z^{-1}) \\ g_x(z) &= c(z)c(z^{-1}) \end{aligned}$$

Then (14) becomes

$$b(L) = \left[\frac{c(L)}{1-\delta L^{-1}}\right]_+ c(L)^{-1} \tag{15}$$

In order to evaluate the term in the annihilation operator, we use the following result from [44].

Proposition Let

- $g(z) = \sum_{j=0}^{\infty} g_j z^j$ where $\sum_{j=0}^{\infty} |g_j|^2 < +\infty$
- $h(z^{-1}) = (1-\delta_1 z^{-1}) ... (1-\delta_n z^{-1})$, where $|\delta_j| < 1$, for $j = 1, ..., n$

Then

$$\left[\frac{g(z)}{h(z^{-1})}\right]_+ = \frac{g(z)}{h(z^{-1})} - \sum_{j=1}^{n} \frac{\delta_j g(\delta_j)}{\prod_{\substack{k=1 \\ k\neq j}}^{n}(\delta_j - \delta_k)} \left(\frac{1}{z-\delta_j}\right) \tag{16}$$

and, alternatively,

$$\left[\frac{g(z)}{h(z^{-1})}\right]_+ = \sum_{j=1}^{n} B_j \left(\frac{z g(z) - \delta_j g(\delta_j)}{z-\delta_j}\right) \tag{17}$$

where $B_j = 1/\prod_{\substack{k=1 \\ k+j}}^{n}(1-\delta_k/\delta_j)$.

Applying formula (17) of the proposition to evaluating (15) with $g(z) = c(z)$ and $h(z^{-1}) = 1 - \delta z^{-1}$ gives

$$b(L) = \left[\frac{Lc(L) - \delta c(\delta)}{L-\delta}\right] c(L)^{-1}$$

or

$$b(L) = \left[\frac{1 - \delta c(\delta) L^{-1} c(L)^{-1}}{1 - \delta L^{-1}}\right]$$

Thus, we have

$$\hat{\mathbb{E}}\left[\sum_{j=0}^{\infty} \delta^j X_{t+j} | X_t,\, x_{t-1}, ...\right] = \left[\frac{1 - \delta c(\delta) L^{-1} c(L)^{-1}}{1 - \delta L^{-1}}\right] X_t \tag{18}$$

This formula is useful in solving stochastic versions of problem 1 of lecture Classical Control with Linear Algebra in which the randomness emerges because $\{a_t\}$ is a stochastic process.

The problem is to maximize

$$\mathbb{E}_0 \lim_{N\to\infty} \sum_{t-0}^{N} \beta^t \left[a_t\, y_t - \frac{1}{2}\, h y_t^2 - \frac{1}{2}\, [d(L) y_t]^2\right] \tag{19}$$

where $\mathbb{E}_t$ is mathematical expectation conditioned on information known at t, and where $\{a_t\}$ is a covariance stationary stochastic process with Wold moving average representation

$$a_t = c(L)\, \eta_t$$

where

$$c(L) = \sum_{j=0}^{\tilde{n}} c_j L^j$$

and

$$\eta_t = a_t - \hat{\mathbb{E}}[a_t | a_{t-1}, ...]$$

The problem is to maximize (19) with respect to a contingency plan expressing y_t as a function of information known at t, which is assumed to be $(y_{t-1},\ y_{t-2}, \dots, a_t,\ a_{t-1}, \dots)$.

The solution of this problem can be achieved in two steps.

First, ignoring the uncertainty, we can solve the problem assuming that $\{a_t\}$ is a known sequence.

The solution is, from above,

$$c(L)y_t = c(\beta L^{-1})^{-1}a_t$$

or

$$(1-\lambda_1 L)\dots(1-\lambda_m L)y_t = \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty}(\lambda_j\beta)^k\, a_{t+k} \tag{20}$$

Second, the solution of the problem under uncertainty is obtained by replacing the terms on the right-hand side of the above expressions with their linear least squares predictors.

Using (18) and (20), we have the following solution

$$(1-\lambda_1 L)\dots(1-\lambda_m L)y_t = \sum_{j=1}^{m} A_j \left[\frac{1-\beta\lambda_j\, c(\beta\lambda_j)L^{-1}c(L)^{-1}}{1-\beta\lambda_j L^{-1}}\right] a_t$$

59.4 Finite Dimensional Prediction

Let $(x_1, x_2, \dots, x_T)' = x$ be a $T \times 1$ vector of random variables with mean $\mathbb{E}x = 0$ and covariance matrix $\mathbb{E}xx' = V$.

Here V is a $T \times T$ positive definite matrix.

We shall regard the random variables as being ordered in time, so that x_t is thought of as the value of some economic variable at time t.

For example, x_t could be generated by the random process described by the Wold representation presented in equation (8).

In this case, V_{ij} is given by the coefficient on $z^{|i-j|}$ in the expansion of $g_x(z) = d(z)\, d(z^{-1}) + h$, which equals $h + \sum_{k=0}^{\infty} d_k d_{k+|i-j|}$.

We shall be interested in constructing j step ahead linear least squares predictors of the form

$$\hat{\mathbb{E}}\left[x_T | x_{T-j}, x_{T-j+1}, \dots, x_1\right]$$

where $\hat{\mathbb{E}}$ is the linear least squares projection operator.

The solution of this problem can be exhibited by first constructing an orthonormal basis of random variables ε for x.

Since V is a positive definite and symmetric, we know that there exists a (Cholesky) decomposition of V such that

$$V = L^{-1}(L^{-1})'$$

or

$$L V L' = I$$

where L is lower-trangular, and therefore so is L^{-1}.

Form the random variable $Lx = \varepsilon$.

Then ε is an orthonormal basis for x, since L is nonsingular, and $\mathbb{E}\,\varepsilon\varepsilon' = L\mathbb{E}xx'L' = I$.

It is convenient to write out the equations $Lx = \varepsilon$ and $L^{-1}\varepsilon = x$

$$\begin{aligned} L_{11}x_1 &= \varepsilon_1 \\ L_{21}x_1 + L_{22}x_2 &= \varepsilon_2 \\ &\vdots \\ L_{T1}\,x_1 \ \ldots\ + L_{TTx_T} &= \varepsilon_T \end{aligned} \tag{21}$$

or

$$\sum_{j=0}^{t-1} L_{t,t-j}\,x_{t-j} = \varepsilon_t, \quad t = 1,\, 2, \ldots T \tag{22}$$

We also have

$$x_t = \sum_{j=0}^{t-1} L^{-1}_{t,t-j}\,\varepsilon_{t-j}\ . \tag{23}$$

Notice from (23) that x_t is in the space spanned by ε_t, $\varepsilon_{t-1}, \ldots, \varepsilon_1$, and from (22) that ε_t is in the space spanned by x_t, $x_{t-1}, \ldots,\, x_1$.

Therefore, we have that for $t-1 \geq m \geq 1$

$$\hat{\mathbb{E}}[x_t \mid x_{t-m},\, x_{t-m-1}, \ldots, x_1] = \hat{\mathbb{E}}[x_t \mid \varepsilon_{t-m}, \varepsilon_{t-m-1}, \ldots, \varepsilon_1] \tag{24}$$

For $t-1 \geq m \geq 1$ rewrite (23) as

$$x_t = \sum_{j=0}^{m-1} L^{-1}_{t,t-j}\,\varepsilon_{t-j} + \sum_{j=m}^{t-1} L^{-1}_{t,t-j}\,\varepsilon_{t-j} \tag{25}$$

Representation (25) is an orthogonal decomposition of x_t into a part $\sum_{j=m}^{t-1} L^{-1}_{t,t-j}\,\varepsilon_{t-j}$ that lies in the space spanned by $[x_{t-m},\, x_{t-m+1},\, \ldots, x_1]$, and an orthogonal component not in this space.

59.4.1 Implementation

Code that computes solutions to LQ control and filtering problems using the methods described here and in Classical Control with Linear Algebra can be found in the file control_and_filter.jl.

Here's how it looks

In [3]:
```
using Polynomials.PolyCompat, LinearAlgebra
import Polynomials.PolyCompat: roots, coeffs

function LQFilter(d, h, y_m;
                  r = nothing,
                  β = nothing,
                  h_eps = nothing)

    m = length(d) - 1
    m == length(y_m) ||
        throw(ArgumentError("y_m and d must be of same length = $m"))

    # define the coefficients of ⊠ up front
    ϕ = zeros(2m + 1)
    for i in -m:m
        ϕ[m-i+1] = sum(diag(d*d', -i))
    end
    ϕ[m+1] = ϕ[m+1] + h

    # if r is given calculate the vector ⊠_r
    if isnothing(r)
        k = nothing
        ϕ_r = nothing
    else
        k = size(r, 1) - 1
        ϕ_r = zeros(2k + 1)

        for i = -k:k
            ϕ_r[k-i+1] = sum(diag(r*r', -i))
        end

        if isnothing(h_eps) == false
            ϕ_r[k+1] = ϕ_r[k+1] + h_eps
        end
    end

    # if β is given, define the transformed variables
    if isnothing(β)
        β = 1.0
    else
        d = β.^(collect(0:m)/2) * d
        y_m = y_m * β.^(- collect(1:m)/2)
    end

    return (d = d, h = h, y_m = y_m, m = m, ϕ = ϕ, β = β,
            ϕ_r = ϕ_r, k = k)
end

function construct_W_and_Wm(lqf, N)

    d, m = lqf.d, lqf.m

    W = zeros(N + 1, N + 1)
    W_m = zeros(N + 1, m)

    # terminal conditions
    D_m1 = zeros(m + 1, m + 1)
    M = zeros(m + 1, m)
```

```
        # (1) constuct the D_{m+1} matrix using the formula

        for j in 1:(m+1)
            for k in j:(m+1)
                D_m1[j, k] = dot(d[1:j, 1], d[k-j+1:k, 1])
            end
        end

        # Make the matrix symmetric
        D_m1 = D_m1 + D_m1' - Diagonal(diag(D_m1))

        # (2) Construct the M matrix using the entries of D_m1

        for j in 1:m
            for i in (j + 1):(m + 1)
                M[i, j] = D_m1[i-j, m+1]
            end
        end
        M

        # Euler equations for t = 0, 1, ..., N-(m+1)
        ϕ, h = lqf.ϕ, lqf.h

        W[1:(m + 1), 1:(m + 1)] = D_m1 + h * I
        W[1:(m + 1), (m + 2):(2m + 1)] = M

        for (i, row) in enumerate((m + 2):(N + 1 - m))
            W[row, (i + 1):(2m + 1 + i)] = ϕ'
        end

        for i in 1:m
            W[N - m + i + 1 , end-(2m + 1 - i)+1:end] = ϕ[1:end-i]
        end

        for i in 1:m
            W_m[N - i + 2, 1:(m - i)+1] = ϕ[(m + 1 + i):end]
        end

        return W, W_m
    end

    function roots_of_characteristic(lqf)
        m, ϕ = lqf.m, lqf.ϕ

        # Calculate the roots of the 2m-polynomial
        ϕ_poly = Poly(ϕ[end:-1:1])
        proots = roots(ϕ_poly)
        # sort the roots according to their length (in descending order)
        roots_sorted = sort(proots, by=abs)[end:-1:1]
       z_0 = sum(ϕ) / polyval(poly(proots), 1.0)
        z_1_to_m = roots_sorted[1:m]     # we need only those outside the unit
↪circle
        λ = 1 ./ z_1_to_m
        return z_1_to_m, z_0, λ
    end

    function coeffs_of_c(lqf)
```

```
    m = lqf.m
    z_1_to_m, z_0, λ = roots_of_characteristic(lqf)
    c_0 = (z_0 * prod(z_1_to_m) * (-1.0)^m)^(0.5)
    c_coeffs = coeffs(poly(z_1_to_m)) * z_0 / c_0
    return c_coeffs
end

function solution(lqf)
    z_1_to_m, z_0, λ = roots_of_characteristic(lqf)
    c_0 = coeffs_of_c(lqf)[end]
    A = zeros(lqf.m)
    for j in 1:m
        denom = 1 - λ/λ[j]
        A[j] = c_0^(-2) / prod(denom[1:m .!= j])
    end
    return λ, A
end

function construct_V(lqf; N = nothing)
    if isnothing(N)
        error("N must be provided!!")
    end
    if !(N isa Integer)
        throw(ArgumentError("N must be Integer!"))
    end

    ϕ_r, k = lqf.ϕ_r, lqf.k
    V = zeros(N, N)
    for i in 1:N
        for j in 1:N
            if abs(i-j) ≤ k
                V[i, j] = ϕ_r[k + abs(i-j)+1]
            end
        end
    end
    return V
end

function simulate_a(lqf, N)
    V = construct_V(N + 1)
    d = MVNSampler(zeros(N + 1), V)
    return rand(d)
end

function predict(lqf, a_hist, t)
    N = length(a_hist) - 1
    V = construct_V(N + 1)

    aux_matrix = zeros(N + 1, N + 1)
    aux_matrix[1:t+1 , 1:t+1 ] = Matrix(I, t + 1, t + 1)
    L = cholesky(V).U'
    Ea_hist = inv(L) * aux_matrix * L * a_hist

    return Ea_hist
end

function optimal_y(lqf, a_hist, t = nothing)
    β, y_m, m = lqf.β, lqf.y_m, lqf.m
```

```
        N = length(a_hist) - 1
        W, W_m = construct_W_and_Wm(lqf, N)

        F = lu(W, Val(true))

        L, U = F
        D = diagm(0 => 1.0 ./ diag(U))
        U = D * U
        L = L * diagm(0 => 1.0 ./ diag(D))

        J = reverse(Matrix(I, N + 1, N + 1), dims = 2)

        if isnothing(t)                      # if the problem is deterministic
            a_hist = J * a_hist

            # transform the a sequence if β is given
            if β != 1
                a_hist =  reshape(a_hist * (β^(collect(N:0)/ 2)), N + 1, 1)
            end

            ā = a_hist - W_m * y_m         # ā from the lecutre
            Uy = \(L, ā)                   # U @ y̌ = L^{-1}ā from the lecture
            y̌ = \(U, Uy)                   # y̌ = U^{-1}L^{-1}ā
            # Reverse the order of y̌ with the matrix J
            J = reverse(Matrix(I, N + m + 1, N + m + 1), dims = 2)
            y_hist = J * vcat(y̌, y_m)      # y_hist : concatenated y_m and y̌
            # transform the optimal sequence back if β is given
            if β != 1
                y_hist = y_hist .* β.^(- collect(-m:N)/2)
            end

        else                                 # if the problem is stochastic and
↪we look at
        it
            Ea_hist = reshape(predict(a_hist, t), N + 1, 1)
            Ea_hist = J * Ea_hist

            ā = Ea_hist - W_m * y_m        # ā from the lecutre
            Uy = \(L, ā)                   # U @ y̌ = L^{-1}ā from the lecture
            y̌ = \(U, Uy)                   # y̌ = U^{-1}L^{-1}ā

            # Reverse the order of y̌ with the matrix J
            J = reverse(Matrix(I, N + m + 1, N + m + 1), dims = 2)
            y_hist = J * vcat(y̌, y_m)      # y_hist : concatenated y_m and y̌
        end
        return y_hist, L, U, y̌
    end
```

```
Out[3]: optimal_y (generic function with 2 methods)
```

Let's use this code to tackle two interesting examples.

59.4.2 Example 1

Consider a stochastic process with moving average representation

$$x_t = (1 - 2L)\varepsilon_t$$

where ε_t is a serially uncorrelated random process with mean zero and variance unity.

We want to use the Wiener-Kolmogorov formula (13) to compute the linear least squares forecasts $\mathbb{E}[x_{t+j} \mid x_t, x_{t-1}, ...]$, for $j = 1, 2$.

We can do everything we want by setting $d = r$, generating an instance of LQFilter, then invoking pertinent methods of LQFilter

```
In [4]: m = 1
        y_m = zeros(m)
        d = [1.0, -2.0]
        r = [1.0, -2.0]
        h = 0.0
        example = LQFilter(d, h, y_m, r=d)
```

```
Out[4]: (d = [1.0, -2.0], h = 0.0, y_m = [0.0], m = 1, ϕ = [-2.0, 5.0, -2.0], β =
  ↪1.0, ϕ_r =
        [-2.0, 5.0, -2.0], k = 1)
```

The Wold representation is computed by example.coefficients_of_c().

Let's check that it "flips roots" as required

```
In [5]: coeffs_of_c(example)
```

```
Out[5]: 2-element Array{Float64,1}:
          2.0
         -1.0
```

```
In [6]: roots_of_characteristic(example)
```

```
Out[6]: ([2.0], -2.0, [0.5])
```

Now let's form the covariance matrix of a time series vector of length N and put it in V.

Then we'll take a Cholesky decomposition of $V = L^{-1}L^{-1} = LiLi'$ and use it to form the vector of "moving average representations" $x = Li\varepsilon$ and the vector of "autoregressive representations" $Lx = \varepsilon$

```
In [7]: V = construct_V(example,N=5)
```

```
Out[7]: 5×5 Array{Float64,2}:
          5.0  -2.0   0.0   0.0   0.0
         -2.0   5.0  -2.0   0.0   0.0
          0.0  -2.0   5.0  -2.0   0.0
          0.0   0.0  -2.0   5.0  -2.0
          0.0   0.0   0.0  -2.0   5.0
```

Notice how the lower rows of the "moving average representations" are converging to the appropriate infinite history Wold representation

```
In [8]: F = cholesky(V)
        Li = F.L
```

```
Out[8]: 5×5 LowerTriangular{Float64,Array{Float64,2}}:
          2.23607     □          □          □          □
         -0.894427    2.04939    □          □          □
          0.0        -0.9759     2.01187    □          □
          0.0         0.0       -0.9941     2.00294    □
          0.0         0.0        0.0       -0.998533   2.00073
```

Notice how the lower rows of the "autoregressive representations" are converging to the appropriate infinite history autoregressive representation

```
In [9]: L = inv(Li)
```

```
Out[9]: 5×5 LowerTriangular{Float64,Array{Float64,2}}:
          0.447214    □          □          □          □
          0.19518     0.48795    □          □          □
          0.0946762   0.236691   0.49705    □          □
          0.0469898   0.117474   0.246696   0.499266   □
          0.0234518   0.0586295  0.123122   0.249176   0.499817
```

Remark Let $\pi(z) = \sum_{j=0}^{m} \pi_j z^j$ and let $z_1, \ldots, z_k$ be the zeros of $\pi(z)$ that are inside the unit circle, $k < m$.

Then define

$$\theta(z) = \pi(z) \left(\frac{(z_1 z - 1)}{(z - z_1)} \right) \left(\frac{(z_2 z - 1)}{(z - z_2)} \right) \ldots \left(\frac{(z_k z - 1)}{(z - z_k)} \right)$$

The term multiplying $\pi(z)$ is termed a "Blaschke factor".

Then it can be proved directly that

$$\theta(z^{-1})\theta(z) = \pi(z^{-1})\pi(z)$$

and that the zeros of $\theta(z)$ are not inside the unit circle.

59.4.3 Example 2

Consider a stochastic process X_t with moving average representation

$$X_t = (1 - \sqrt{2}L^2)\varepsilon_t$$

where ε_t is a serially uncorrelated random process with mean zero and variance unity.

Let's find a Wold moving average representation for x_t.

Let's use the Wiener-Kolomogorov formula (13) to compute the linear least squares forecasts $\hat{\mathbb{E}}\left[X_{t+j} \mid X_{t-1}, ...\right]$ for $j = 1, 2, 3$.

We proceed in the same way as example 1

```
In [10]: m = 2
         y_m = [0.0, 0.0]
         d = [1, 0, -sqrt(2)]
         r = [1, 0, -sqrt(2)]
         h = 0.0
         example = LQFilter(d, h, y_m, r = d)
```

```
Out[10]: (d = [1.0, 0.0, -1.4142135623730951], h = 0.0, y_m = [0.0, 0.0], m = 2, ϕ =
         [-1.4142135623730951, 0.0, 3.0000000000000004, 0.0, -1.4142135623730951],
  ↪β = 1.0, ϕ_r =
         [-1.4142135623730951, 0.0, 3.0000000000000004, 0.0, -1.4142135623730951],
  ↪k = 2)
```

```
In [11]: coeffs_of_c(example)
```

```
Out[11]: 3-element Array{Float64,1}:
           1.4142135623731003
          -0.0
          -1.0000000000000064
```

```
In [12]: roots_of_characteristic(example)
```

```
Out[12]: ([1.1892071150027195, -1.1892071150027195], -1.4142135623731096, [0.
  ↪8408964152537157,
         -0.8408964152537157])
```

```
In [13]: V = construct_V(example, N = 8)
```

```
Out[13]: 8×8 Array{Float64,2}:
           3.0       0.0      -1.41421   0.0       …   0.0       0.0       0.0
           0.0       3.0       0.0      -1.41421       0.0       0.0       0.0
          -1.41421   0.0       3.0       0.0           0.0       0.0       0.0
           0.0      -1.41421   0.0       3.0          -1.41421   0.0       0.0
           0.0       0.0      -1.41421   0.0           0.0      -1.41421   0.0
           0.0       0.0       0.0      -1.41421   …   3.0       0.0      -1.41421
           0.0       0.0       0.0       0.0           0.0       3.0       0.0
           0.0       0.0       0.0       0.0          -1.41421   0.0       3.0
```

```
In [14]: F = cholesky(V)
         Li = F.L
         Li[end-2:end, :]
```

```
Out[14]: 3×8 Array{Float64,2}:
          0.0  0.0  0.0  -0.92582   0.0        1.46385   0.0       0.0
          0.0  0.0  0.0   0.0      -0.966092   0.0       1.43759   0.0
          0.0  0.0  0.0   0.0       0.0       -0.966092  0.0       1.43759
```

```
In [15]: L = inv(Li)
```

```
Out[15]: 8×8 LowerTriangular{Float64,Array{Float64,2}}:
 0.57735    ⋅         ⋅         ⋅         …  ⋅         ⋅         ⋅
 0.0        0.57735   ⋅         ⋅            ⋅         ⋅         ⋅
 0.308607   0.0       0.654654  ⋅            ⋅         ⋅         ⋅
 0.0        0.308607  0.0       0.654654     ⋅         ⋅         ⋅
 0.19518    0.0       0.414039  0.0          ⋅         ⋅         ⋅
 0.0        0.19518   0.0       0.414039  …  0.68313   ⋅         ⋅
 0.131165   0.0       0.278243  0.0          0.0       0.695608  ⋅
 0.0        0.131165  0.0       0.278243     0.459078  0.0       0.695608
```

59.4.4 Prediction

It immediately follows from the "orthogonality principle" of least squares (see [6] or [94] [ch. X]) that

$$\begin{aligned}\hat{\mathbb{E}}[x_t \mid x_{t-m}, x_{t-m+1}, \dots x_1] &= \sum_{j=m}^{t-1} L^{-1}_{t,t-j}\,\varepsilon_{t-j} \\ &= [L^{-1}_{t,1}\, L^{-1}_{t,2}, \dots, L^{-1}_{t,t-m}\ 0\ 0 \dots 0] L\, x\end{aligned} \tag{26}$$

This can be interpreted as a finite-dimensional version of the Wiener-Kolmogorov m-step ahead prediction formula.

We can use (26) to represent the linear least squares projection of the vector x conditioned on the first s observations $[x_s, x_{s-1} \dots, x_1]$.

We have

$$\hat{\mathbb{E}}[x \mid x_s, x_{s-1}, \dots, x_1] = L^{-1} \begin{bmatrix} I_s & 0 \\ 0 & 0_{(t-s)} \end{bmatrix} Lx \tag{27}$$

This formula will be convenient in representing the solution of control problems under uncertainty.

Equation (23) can be recognized as a finite dimensional version of a moving average representation.

Equation (22) can be viewed as a finite dimension version of an autoregressive representation.

Notice that even if the x_t process is covariance stationary, so that V is such that V_{ij} depends only on $|i-j|$, the coefficients in the moving average representation are time-dependent, there being a different moving average for each t.

If x_t is a covariance stationary process, the last row of L^{-1} converges to the coefficients in the Wold moving average representation for $\{x_t\}$ as $T \to \infty$.

Further, if x_t is covariance stationary, for fixed k and $j > 0$, $L^{-1}_{T,T-j}$ converges to $L^{-1}_{T-k,T-k-j}$ as $T \to \infty$.

That is, the "bottom" rows of L^{-1} converge to each other and to the Wold moving average coefficients as $T \to \infty$.

This last observation gives one simple and widely-used practical way of forming a finite T approximation to a Wold moving average representation.

First, form the covariance matrix $\mathbb{E}xx' = V$, then obtain the Cholesky decomposition $L^{-1}L^{-1'}$ of V, which can be accomplished quickly on a computer.

The last row of L^{-1} gives the approximate Wold moving average coefficients.

This method can readily be generalized to multivariate systems.

59.5 Combined Finite Dimensional Control and Prediction

Consider the finite-dimensional control problem, maximize

$$\mathbb{E}\sum_{t=0}^{N}\left\{a_t y_t - \frac{1}{2}hy_t^2 - \frac{1}{2}[d(L)y_t]^2\right\}, \qquad h>0$$

where $d(L)=d_0+d_1L+\ldots+d_mL^m$, L is the lag operator, $\bar{a}=[a_N,a_{N-1}\ldots,a_1,a_0]'$ a random vector with mean zero and $\mathbb{E}\,\bar{a}\bar{a}'=V$.

The variables $y_{-1},\ldots,y_{-m}$ are given.

Maximization is over choices of $y_0,y_1\ldots,y_N$, where y_t is required to be a linear function of $\{y_{t-s-1}, t+m-1\geq 0;\ a_{t-s}, t\geq s\geq 0\}$.

We saw in the lecture Classical Control with Linear Algebra that the solution of this problem under certainty could be represented in feedback-feedforward form

$$U\bar{y}=L^{-1}\bar{a}+K\begin{bmatrix}y_{-1}\\ \vdots\\ y_{-m}\end{bmatrix}$$

for some $(N+1)\times m$ matrix K.

Using a version of formula (26), we can express $\hat{\mathbb{E}}[\bar{a}\mid a_s,\,a_{s-1},\ldots,a_0]$ as

$$\hat{\mathbb{E}}[\bar{a}\mid a_s,\,a_{s-1},\ldots,a_0]=\tilde{U}^{-1}\begin{bmatrix}0 & 0\\ 0 & I_{(s+1)}\end{bmatrix}\tilde{U}\bar{a}$$

where $I_{(s+1)}$ is the $(s+1)\times(s+1)$ identity matrix, and $V=\tilde{U}^{-1}\tilde{U}^{-1'}$, where $\tilde{U}$ is the *upper* trangular Cholesky factor of the covariance matrix V.

(We have reversed the time axis in dating the a's relative to earlier)

The time axis can be reversed in representation (27) by replacing L with L^T.

The optimal decision rule to use at time $0\leq t\leq N$ is then given by the $(N-t+1)^{\text{th}}$ row of

$$U\bar{y}=L^{-1}\tilde{U}^{-1}\begin{bmatrix}0 & 0\\ 0 & I_{(t+1)}\end{bmatrix}\tilde{U}\bar{a}+K\begin{bmatrix}y_{-1}\\ \vdots\\ y_{-m}\end{bmatrix}$$

59.6 Exercises

59.6.1 Exercise 1

Let $Y_t=(1-2L)u_t$ where u_t is a mean zero white noise with $\mathbb{E}u_t^2=1$. Let

$$X_t = Y_t + \varepsilon_t$$

where ε_t is a serially uncorrelated white noise with $\mathbb{E}\varepsilon_t^2 = 9$, and $\mathbb{E}\varepsilon_t u_s = 0$ for all t and s.

Find the Wold moving average representation for X_t.

Find a formula for the A_{1j}'s in

$$\mathbb{E}\widehat{X}_{t+1} \mid X_t, X_{t-1}, ... = \sum_{j=0}^{\infty} A_{1j} X_{t-j}$$

Find a formula for the A_{2j}'s in

$$\hat{\mathbb{E}} X_{t+2} \mid X_t, X_{t-1}, ... = \sum_{j=0}^{\infty} A_{2j} X_{t-j}$$

59.6.2 Exercise 2

(Multivariable Prediction) Let Y_t be an $(n \times 1)$ vector stochastic process with moving average representation

$$Y_t = D(L)U_t$$

where $D(L) = \sum_{j=0}^{m} D_j L^J, D_j$ an $n \times n$ matrix, U_t an $(n \times 1)$ vector white noise with :math: mathbb{E} U_t =0 for all t, $\mathbb{E}U_t U_s' = 0$ for all $s \neq t$, and $\mathbb{E}U_t U_t' = I$ for all t.

Let ε_t be an $n \times 1$ vector white noise with mean 0 and contemporaneous covariance matrix H, where H is a positive definite matrix.

Let $X_t = Y_t + \varepsilon_t$.

Define the covariograms as $C_X(\tau) = \mathbb{E}X_t X_{t-\tau}', C_Y(\tau) = \mathbb{E}Y_t Y_{t-\tau}', C_{YX}(\tau) = \mathbb{E}Y_t X_{t-\tau}'$.

Then define the matrix covariance generating function, as in (21), only interpret all the objects in (21) as matrices.

Show that the covariance generating functions are given by

$$\begin{aligned} g_y(z) &= D(z)D(z^{-1})' \\ g_X(z) &= D(z)D(z^{-1})' + H \\ g_{YX}(z) &= D(z)D(z^{-1})' \end{aligned}$$

A factorization of $g_X(z)$ can be found (see [91] or [108]) of the form

$$D(z)D(z^{-1})' + H = C(z)C(z^{-1})', \quad C(z) = \sum_{j=0}^{m} C_j z^j$$

where the zeros of $|C(z)|$ do not lie inside the unit circle.

A vector Wold moving average representation of X_t is then

$$X_t = C(L)\eta_t$$

where η_t is an $(n \times 1)$ vector white noise that is "fundamental" for X_t.

That is, $X_t - \hat{\mathbb{E}}\left[X_t \mid X_{t-1}, X_{t-2} ...\right] = C_0\, \eta_t$.

The optimum predictor of X_{t+j} is

$$\hat{\mathbb{E}}\left[X_{t+j} \mid X_t, X_{t-1}, ...\right] = \left[\frac{C(L)}{L^j}\right]_+ \eta_t$$

If $C(L)$ is invertible, i.e., if the zeros of det $C(z)$ lie strictly outside the unit circle, then this formula can be written

$$\hat{\mathbb{E}}\left[X_{t+j} \mid X_t, X_{t-1}, ...\right] = \left[\frac{C(L)}{L^J}\right]_+ C(L)^{-1}\, X_t$$

Part VIII

Dynamic Programming Squared

Chapter 60

Dynamic Stackelberg Problems

60.1 Contents

This notebook formulates and computes a plan that a **Stackelberg leader** uses to manipulate forward-looking decisions of a **Stackelberg follower** that depend on continuation sequences of decisions made once and for all by the Stackelberg leader at time 0.

To facilitate computation and interpretation, we formulate things in a context that allows us to apply linear optimal dynamic programming.

From the beginning we carry along a linear-quadratic model of duopoly in which firms face adjustment costs that make them want to forecast actions of other firms that influence future prices.

60.2 Duopoly

Time is discrete and is indexed by $t = 0, 1, \ldots$.

Two firms produce a single good whose demand is governed by the linear inverse demand curve

$$p_t = a_0 - a_1(q_{1t} + q_{2t})$$

where q_{it} is output of firm i at time t and a_0 and a_1 are both positive.

q_{10}, q_{20} are given numbers that serve as initial conditions at time 0.

By incurring a cost of change

$$\gamma v_{it}^2$$

where $\gamma > 0$, firm i can change its output according to

$$q_{it+1} = q_{it} + v_{it}$$

Firm i's profits at time t equal

$$\pi_{it} = p_t q_{it} - \gamma v_{it}^2$$

Firm i wants to maximize the present value of its profits

$$\sum_{t=0}^{\infty} \beta^t \pi_{it}$$

where $\beta \in (0,1)$ is a time discount factor.

60.2.1 Stackelberg Leader and Follower

Each firm $i = 1, 2$ chooses a sequence $\vec{q}_i \equiv \{q_{it+1}\}_{t=0}^{\infty}$ once and for all at time 0.

We let firm 2 be a **Stackelberg leader** and firm 1 be a **Stackelberg follower**.

The leader firm 2 goes first and chooses $\{q_{2t+1}\}_{t=0}^{\infty}$ once and for all at time 0.

Knowing that firm 2 has chosen $\{q_{2t+1}\}_{t=0}^{\infty}$, the follower firm 1 goes second and chooses $\{q_{1t+1}\}_{t=0}^{\infty}$ once and for all at time 0.

In choosing $\vec{q}_2$, firm 2 takes into account that firm 1 will base its choice of $\vec{q}_1$ on firm 2's choice of $\vec{q}_2$.

60.2.2 Abstract Statement of the Leader's and Follower's Problems

We can express firm 1's problem as

$$\max_{\vec{q}_1} \Pi_1(\vec{q}_1; \vec{q}_2)$$

where the appearance behind the semi-colon indicates that $\vec{q}_2$ is given.

Firm 1's problem induces a best response mapping

$$\vec{q}_1 = B(\vec{q}_2)$$

(Here B maps a sequence into a sequence)

The Stackelberg leader's problem is

$$\max_{\vec{q}_2} \Pi_2(B(\vec{q}_2), \vec{q}_2)$$

whose maximizer is a sequence $\vec{q}_2$ that depends on the initial conditions q_{10}, q_{20} and the parameters of the model a_0, a_1, γ.

This formulation captures key features of the model

- Both firms make once-and-for-all choices at time 0.
- This is true even though both firms are choosing sequences of quantities that are indexed by **time**.
- The Stackelberg leader chooses first **within time** 0, knowing that the Stackelberg follower will choose second **within time** 0.

While our abstract formulation reveals the timing protocol and equilibrium concept well, it obscures details that must be addressed when we want to compute and interpret a Stackelberg plan and the follower's best response to it.

To gain insights about these things, we study them in more detail.

60.2.3 Firms' Problems

Firm 1 acts as if firm 2's sequence $\{q_{2t+1}\}_{t=0}^{\infty}$ is given and beyond its control.

Firm 2 knows that firm 1 chooses second and takes this into account in choosing $\{q_{2t+1}\}_{t=0}^{\infty}$.

In the spirit of *working backwards*, we study firm 1's problem first, taking $\{q_{2t+1}\}_{t=0}^{\infty}$ as given.

We can formulate firm 1's optimum problem in terms of the Lagrangian

$$L = \sum_{t=0}^{\infty} \beta^t \{a_0 q_{1t} - a_1 q_{1t}^2 - a_1 q_{1t} q_{2t} - \gamma v_{1t}^2 + \lambda_t [q_{1t} + v_{1t} - q_{1t+1}]\}$$

Firm 1 seeks a maximum with respect to $\{q_{1t+1}, v_{1t}\}_{t=0}^{\infty}$ and a minimum with respect to $\{\lambda_t\}_{t=0}^{\infty}$.

We approach this problem using methods described in Ljungqvist and Sargent RMT5 chapter 2, appendix A and Macroeconomic Theory, 2nd edition, chapter IX.

First-order conditions for this problem are

$$\begin{aligned}
\frac{\partial L}{\partial q_{1t}} &= a_0 - 2a_1 q_{1t} - a_1 q_{2t} + \lambda_t - \beta^{-1}\lambda_{t-1} = 0, \quad t \geq 1 \\
\frac{\partial L}{\partial v_{1t}} &= -2\gamma v_{1t} + \lambda_t = 0, \quad t \geq 0
\end{aligned}$$

These first-order conditions and the constraint $q_{1t+1} = q_{1t} + v_{1t}$ can be rearranged to take the form

$$\begin{aligned}
v_{1t} &= \beta v_{1t+1} + \frac{\beta a_0}{2\gamma} - \frac{\beta a_1}{\gamma} q_{1t+1} - \frac{\beta a_1}{2\gamma} q_{2t+1} \\
q_{t+1} &= q_{1t} + v_{1t}
\end{aligned}$$

We can substitute the second equation into the first equation to obtain

$$(q_{1t+1} - q_{1t}) = \beta(q_{1t+2} - q_{1t+1}) + c_0 - c_1 q_{1t+1} - c_2 q_{2t+1}$$

where $c_0 = \frac{\beta a_0}{2\gamma}, c_1 = \frac{\beta a_1}{\gamma}, c_2 = \frac{\beta a_1}{2\gamma}$.

This equation can in turn be rearranged to become the second-order difference equation

$$q_{1t} + (1 + \beta + c_1)q_{1t+1} - \beta q_{1t+2} = c_0 - c_2 q_{2t+1} \tag{1}$$

Equation (1) is a second-order difference equation in the sequence $\vec{q}_1$ whose solution we want.

It satisfies **two boundary conditions:**

- an initial condition that $q_{1,0}$, which is given
- a terminal condition requiring that $\lim_{T \to +\infty} \beta^T q_{1t}^2 < +\infty$

Using the lag operators described in chapter IX of *Macroeconomic Theory, Second edition (1987)*, difference equation (1) can be written as

$$\beta(1 - \frac{1 + \beta + c_1}{\beta} L + \beta^{-1} L^2) q_{1t+2} = -c_0 + c_2 q_{2t+1}$$

The polynomial in the lag operator on the left side can be **factored** as

$$(1 - \frac{1 + \beta + c_1}{\beta} L + \beta^{-1} L^2) = (1 - \delta_1 L)(1 - \delta_2 L) \tag{2}$$

where $0 < \delta_1 < 1 < \frac{1}{\sqrt{\beta}} < \delta_2$.

Because $\delta_2 > \frac{1}{\sqrt{\beta}}$ the operator $(1 - \delta_2 L)$ contributes an **unstable** component if solved **backwards** but a **stable** component if solved **forwards**.

Mechanically, write

$$(1 - \delta_2 L) = -\delta_2 L (1 - \delta_2^{-1} L^{-1})$$

and compute the following inverse operator

$$\left[-\delta_2 L (1 - \delta_2^{-1} L^{-1})\right]^{-1} = -\delta_2 (1 - \delta_2{}^{-1})^{-1} L^{-1}$$

Operating on both sides of equation (2) with β^{-1} times this inverse operator gives the follower's decision rule for setting q_{1t+1} in the **feedback-feedforward** form

$$q_{1t+1} = \delta_1 q_{1t} - c_0 \delta_2^{-1} \beta^{-1} \frac{1}{1 - \delta_2^{-1}} + c_2 \delta_2^{-1} \beta^{-1} \sum_{j=0}^{\infty} \delta_2^j q_{2t+j+1}, \quad t \geq 0 \tag{3}$$

The problem of the Stackelberg leader firm 2 is to choose the sequence $\{q_{2t+1}\}_{t=0}^{\infty}$ to maximize its discounted profits

$$\sum_{t=0}^{\infty} \beta^t \{(a_0 - a_1(q_{1t} + q_{2t}))q_{2t} - \gamma(q_{2t+1} - q_{2t})^2\}$$

subject to the sequence of constraints (3) for $t \geq 0$.

We can put a sequence $\{\theta_t\}_{t=0}^{\infty}$ of Lagrange multipliers on the sequence of equations (3) and formulate the following Lagrangian for the Stackelberg leader firm 2's problem

$$\begin{aligned}\tilde{L} &= \sum_{t=0}^{\infty} \beta^t \{(a_0 - a_1(q_{1t} + q_{2t}))q_{2t} - \gamma(q_{2t+1} - q_{2t})^2\} \\ &+ \sum_{t=0}^{\infty} \beta^t \theta_t \{\delta_1 q_{1t} - c_0 \delta_2^{-1} \beta^{-1} \frac{1}{1 - \delta_2^{-1}} + c_2 \delta_2^{-1} \beta^{-1} \sum_{j=0}^{\infty} \delta_2^{-j} q_{2t+j+1} - q_{1t+1}\end{aligned} \tag{4}$$

subject to initial conditions for q_{1t}, q_{2t} at $t = 0$.

Comments: We have formulated the Stackelberg problem in a space of sequences.

The max-min problem associated with Lagrangian (4) is unpleasant because the time t component of firm 1's payoff function depends on the entire future of its choices of $\{q_{1t+j}\}_{j=0}^{\infty}$.

This renders a direct attack on the problem cumbersome.

Therefore, below, we will formulate the Stackelberg leader's problem recursively.

We'll put our little duopoly model into a broader class of models with the same conceptual structure.

60.3 The Stackelberg Problem

We formulate a class of linear-quadratic Stackelberg leader-follower problems of which our duopoly model is an instance.

We use the optimal linear regulator (a.k.a. the linear-quadratic dynamic programming problem described in LQ Dynamic Programming problems) to represent a Stackelberg leader's problem recursively.

Let z_t be an $n_z \times 1$ vector of **natural state variables**.

Let x_t be an $n_x \times 1$ vector of endogenous forward-looking variables that are physically free to jump at t.

In our duopoly example $x_t = v_{1t}$, the time t decision of the Stackelberg **follower**.

Let u_t be a vector of decisions chosen by the Stackelberg leader at t.

The z_t vector is inherited physically from the past.

But x_t is a decision made by the Stackelberg follower at time t that is the follower's best response to the choice of an entire sequence of decisions made by the Stackelberg leader at time $t = 0$.

Let

$$y_t = \begin{bmatrix} z_t \\ x_t \end{bmatrix}$$

Represent the Stackelberg leader's one-period loss function as

$$r(y, u) = y' R y + u' Q u$$

Subject to an initial condition for z_0, but not for x_0, the Stackelberg leader wants to maximize

$$-\sum_{t=0}^{\infty} \beta^t r(y_t, u_t) \tag{5}$$

The Stackelberg leader faces the model

$$\begin{bmatrix} I & 0 \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} z_{t+1} \\ x_{t+1} \end{bmatrix} = \begin{bmatrix} \hat{A}_{11} & \hat{A}_{12} \\ \hat{A}_{21} & \hat{A}_{22} \end{bmatrix} \begin{bmatrix} z_t \\ x_t \end{bmatrix} + \hat{B} u_t \tag{6}$$

We assume that the matrix $\begin{bmatrix} I & 0 \\ G_{21} & G_{22} \end{bmatrix}$ on the left side of equation (6) is invertible, so that we can multiply both sides by its inverse to obtain

$$\begin{bmatrix} z_{t+1} \\ x_{t+1} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} z_t \\ x_t \end{bmatrix} + B u_t \tag{7}$$

or

$$y_{t+1} = A y_t + B u_t \tag{8}$$

60.3.1 Interpretation of the Second Block of Equations

The Stackelberg follower's best response mapping is summarized by the second block of equations of (7).

In particular, these equations are the first-order conditions of the Stackelberg follower's optimization problem (i.e., its Euler equations).

These Euler equations summarize the forward-looking aspect of the follower's behavior and express how its time t decision depends on the leader's actions at times $s \geq t$.

When combined with a stability condition to be imposed below, the Euler equations summarize the follower's best response to the sequence of actions by the leader.

The Stackelberg leader maximizes (5) by choosing sequences $\{u_t, x_t, z_{t+1}\}_{t=0}^{\infty}$ subject to (8) and an initial condition for z_0.

Note that we have an initial condition for z_0 but not for x_0.

x_0 is among the variables to be chosen at time 0 by the Stackelberg leader.

The Stackelberg leader uses its understanding of the responses restricted by (8) to manipulate the follower's decisions.

60.3.2 More Mechanical Details

For any vector a_t, define $\vec{a}_t = [a_t, a_{t+1} ...]$.

Define a feasible set of $(\vec{y}_1, \vec{u}_0)$ sequences

$$\Omega(y_0) = \{(\vec{y}_1, \vec{u}_0) : y_{t+1} = A y_t + B u_t, \forall t \geq 0\}$$

Please remember that the follower's Euler equation is embedded in the system of dynamic equations $y_{t+1} = A y_t + B u_t$.

Note that in the definition of $\Omega(y_0)$, y_0 is taken as given.

Although it is taken as given in $\Omega(y_0)$, eventually, the x_0 component of y_0 will be chosen by the Stackelberg leader.

60.3.3 Two Subproblems

Once again we use backward induction.

We express the Stackelberg problem in terms of **two subproblems**.

Subproblem 1 is solved by a **continuation Stackelberg leader** at each date $t \geq 0$.

Subproblem 2 is solved the **Stackelberg leader** at $t = 0$.

The two subproblems are designed

- to respect the protocol in which the follower chooses $\vec{q}_1$ after seeing $\vec{q}_2$ chosen by the leader
- to make the leader choose $\vec{q}_2$ while respecting that $\vec{q}_1$ will be the follower's best response to $\vec{q}_2$
- to represent the leader's problem recursively by artfully choosing the state variables confronting and the control variables available to the leader

Subproblem 1

$$v(y_0) = \max_{(\vec{y}_1, \vec{u}_0) \in \Omega(y_0)} -\sum_{t=0}^{\infty} \beta^t r(y_t, u_t)$$

Subproblem 2

$$w(z_0) = \max_{x_0} v(y_0)$$

Subproblem 1 takes the vector of forward-looking variables x_0 as given.

Subproblem 2 optimizes over x_0.

The value function $w(z_0)$ tells the value of the Stackelberg plan as a function of the vector of natural state variables at time 0, z_0.

60.3.4 Two Bellman Equations

We now describe Bellman equations for $v(y)$ and $w(z_0)$.

Subproblem 1

The value function $v(y)$ in subproblem 1 satisfies the Bellman equation

$$v(y) = \max_{u, y^*} \{-r(y, u) + \beta v(y^*)\} \tag{9}$$

where the maximization is subject to

$$y^* = Ay + Bu$$

and y^* denotes next period's value.

Substituting $v(y) = -y'Py$ into Bellman equation (9) gives

$$-y'Py = \max_{u,y^*} \{-y'Ry - u'Qu - \beta y^{*\prime} P y^*\}$$

which as in lecture linear regulator gives rise to the algebraic matrix Riccati equation

$$P = R + \beta A'PA - \beta^2 A'PB(Q + \beta B'PB)^{-1}B'PA$$

and the optimal decision rule coefficient vector

$$F = \beta(Q + \beta B'PB)^{-1}B'PA$$

where the optimal decision rule is

$$u_t = -Fy_t$$

Subproblem 2

We find an optimal x_0 by equating to zero the gradient of $v(y_0)$ with respect to x_0:

$$-2P_{21}z_0 - 2P_{22}x_0 = 0,$$

which implies that

$$x_0 = -P_{22}^{-1}P_{21}z_0$$

60.4 Stackelberg Plan

Now let's map our duopoly model into the above setup.

We we'll formulate a state space system

$$y_t = \begin{bmatrix} z_t \\ x_t \end{bmatrix}$$

where in this instance $x_t = v_{1t}$, the time t decision of the follower firm 1.

60.4.1 Calculations to Prepare Duopoly Model

Now we'll proceed to cast our duopoly model within the framework of the more general linear-quadratic structure described above.

That will allow us to compute a Stackelberg plan simply by enlisting a Riccati equation to solve a linear-quadratic dynamic program.

As emphasized above, firm 1 acts as if firm 2's decisions $\{q_{2t+1}, v_{2t}\}_{t=0}^{\infty}$ are given and beyond its control.

60.4.2 Firm 1's Problem

We again formulate firm 1's optimum problem in terms of the Lagrangian

$$L = \sum_{t=0}^{\infty} \beta^t \{a_0 q_{1t} - a_1 q_{1t}^2 - a_1 q_{1t} q_{2t} - \gamma v_{1t}^2 + \lambda_t [q_{1t} + v_{1t} - q_{1t+1}]\}$$

Firm 1 seeks a maximum with respect to $\{q_{1t+1}, v_{1t}\}_{t=0}^{\infty}$ and a minimum with respect to $\{\lambda_t\}_{t=0}^{\infty}$.

First-order conditions for this problem are

$$\begin{aligned}
\frac{\partial L}{\partial q_{1t}} &= a_0 - 2a_1 q_{1t} - a_1 q_{2t} + \lambda_t - \beta^{-1}\lambda_{t-1} = 0, \quad t \geq 1 \\
\frac{\partial L}{\partial v_{1t}} &= -2\gamma v_{1t} + \lambda_t = 0, \quad t \geq 0
\end{aligned}$$

These first-order order conditions and the constraint $q_{1t+1} = q_{1t} + v_{1t}$ can be rearranged to take the form

$$\begin{aligned}
v_{1t} &= \beta v_{1t+1} + \frac{\beta a_0}{2\gamma} - \frac{\beta a_1}{\gamma} q_{1t+1} - \frac{\beta a_1}{2\gamma} q_{2t+1} \\
q_{t+1} &= q_{1t} + v_{1t}
\end{aligned}$$

We use these two equations as components of the following linear system that confronts a Stackelberg continuation leader at time t

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\beta a_0}{2\gamma} & -\frac{\beta a_1}{2\gamma} & -\frac{\beta a_1}{\gamma} & \beta \end{bmatrix} \begin{bmatrix} 1 \\ q_{2t+1} \\ q_{1t+1} \\ v_{1t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \\ v_{1t} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} v_{2t}$$

Time t revenues of firm 2 are $\pi_{2t} = a_0 q_{2t} - a_1 q_{2t}^2 - a_1 q_{1t} q_{2t}$ which evidently equal

$$z_t' R_1 z_t \equiv \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \end{bmatrix}' \begin{bmatrix} 0 & \frac{a_0}{2} & 0 \\ \frac{a_0}{2} & -a_1 & -\frac{a_1}{2} \\ 0 & -\frac{a_1}{2} & 0 \end{bmatrix} \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \end{bmatrix}$$

If we set $Q = \gamma$, then firm 2's period t profits can then be written

$$y_t' R y_t - Q v_{2t}^2$$

where

$$y_t = \begin{bmatrix} z_t \\ x_t \end{bmatrix}$$

with $x_t = v_{1t}$ and

$$R = \begin{bmatrix} R_1 & 0 \\ 0 & 0 \end{bmatrix}$$

We'll report results of implementing this code soon.

But first we want to represent the Stackelberg leader's optimal choices recursively.

It is important to do this for several reasons:

- properly to interpret a representation of the Stackelberg leaders's choice as a sequence of history-dependent functions
- to formulate a recursive version of the follower's choice problem

First let's get a recursive representation of the Stackelberg leader's choice of $\vec{q}_2$ for our duopoly model.

60.5 Recursive Representation of Stackelberg Plan

In order to attain an appropriate representation of the Stackelberg leader's history-dependent plan, we will employ what amounts to a version of the **Big K, little k** device often used in macroeconomics by distinguishing z_t, which depends partly on decisions x_t of the followers, from another vector $\check{z}_t$, which does not.

We will use $\check{z}_t$ and its history $\check{z}^t = [\check{z}_t, \check{z}_{t-1}, ..., \check{z}_0]$ to describe the sequence of the Stackelberg leader's decisions that the Stackelberg follower takes as given.

Thus, we let $\check{y}_t' = \begin{bmatrix} \check{z}_t' & \check{x}_t' \end{bmatrix}$ with initial condition $\check{z}_0 = z_0$ given.

That we distinguish $\check{z}_t$ from z_t is part and parcel of the **Big K, little k** device in this instance.

We have demonstrated that a Stackelberg plan for $\{u_t\}_{t=0}^{\infty}$ has a recursive representation

$$\begin{aligned} \check{x}_0 &= -P_{22}^{-1} P_{21} z_0 \\ u_t &= -F \check{y}_t, \quad t \geq 0 \\ \check{y}_{t+1} &= (A - BF) \check{y}_t, \quad t \geq 0 \end{aligned}$$

From this representation we can deduce the sequence of functions $\sigma = \{\sigma_t(\check{z}^t)\}_{t=0}^{\infty}$ that comprise a Stackelberg plan.

For convenience, let $\check{A} \equiv A - BF$ and partition $\check{A}$ conformably to the partition $y_t = \begin{bmatrix} \check{z}_t \\ \check{x}_t \end{bmatrix}$ as

$$\begin{bmatrix} \check{A}_{11} & \check{A}_{12} \\ \check{A}_{21} & \check{A}_{22} \end{bmatrix}$$

Let $H_0^0 \equiv -P_{22}^{-1} P_{21}$ so that $\check{x}_0 = H_0^0 \check{z}_0$.

Then iterations on $\check{y}_{t+1} = \check{A}\check{y}_t$ starting from initial condition $\check{y}_0 = \begin{bmatrix} \check{z}_0 \\ H_0^0 \check{z}_0 \end{bmatrix}$ imply that for $t \geq 1$

$$x_t = \sum_{j=1}^{t} H_j^t \check{z}_{t-j}$$

where

$$\begin{aligned} H_1^t &= \check{A}_{21} \\ H_2^t &= \check{A}_{22}\check{A}_{21} \\ &\vdots \quad \vdots \\ H_{t-1}^t &= \check{A}_{22}^{t-2}\check{A}_{21} \\ H_t^t &= \check{A}_{22}^{t-1}(\check{A}_{21} + \check{A}_{22}H_0^0) \end{aligned}$$

An optimal decision rule for the Stackelberg's choice of u_t is

$$u_t = -F\check{y}_t \equiv -\begin{bmatrix} F_z & F_x \end{bmatrix} \begin{bmatrix} \check{z}_t \\ x_t \end{bmatrix}$$

or

$$u_t = -F_z\check{z}_t - F_x \sum_{j=1}^{t} H_j^t z_{t-j} = \sigma_t(\check{z}^t) \tag{10}$$

Representation (10) confirms that whenever $F_x \neq 0$, the typical situation, the time t component σ_t of a Stackelberg plan is **history dependent**, meaning that the Stackelberg leader's choice u_t depends not just on $\check{z}_t$ but on components of $\check{z}^{t-1}$.

60.5.1 Comments and Interpretations

After all, at the end of the day, it will turn out that because we set $\check{z}_0 = z_0$, it will be true that $z_t = \check{z}_t$ for all $t \geq 0$.

Then why did we distinguish $\check{z}_t$ from z_t?

The answer is that if we want to present to the Stackelberg **follower** a history-dependent representation of the Stackelberg **leader's** sequence $\vec{q}_2$, we must use representation (10) cast in terms of the history $\check{z}^t$ and **not** a corresponding representation cast in terms of z^t.

60.5.2 Dynamic Programming and Time Consistency of follower's Problem

Given the sequence $\vec{q}_2$ chosen by the Stackelberg leader in our duopoly model, it turns out that the Stackelberg **follower's** problem is recursive in the *natural* state variables that confront a follower at any time $t \geq 0$.

This means that the follower's plan is time consistent.

To verify these claims, we'll formulate a recursive version of a follower's problem that builds on our recursive representation of the Stackelberg leader's plan and our use of the **Big K, little k** idea.

60.5.3 Recursive Formulation of a Follower's Problem

We now use what amounts to another "Big K, little k" trick (see rational expectations equilibrium) to formulate a recursive version of a follower's problem cast in terms of an ordinary Bellman equation.

Firm 1, the follower, faces $\{q_{2t}\}_{t=0}^{\infty}$ as a given quantity sequence chosen by the leader and believes that its output price at t satisfies

$$p_t = a_0 - a_1(q_{1t} + q_{2t}), \quad t \geq 0$$

Our challenge is to represent $\{q_{2t}\}_{t=0}^{\infty}$ as a given sequence.

To do so, recall that under the Stackelberg plan, firm 2 sets output according to the q_{2t} component of

$$y_{t+1} = \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \\ x_t \end{bmatrix}$$

which is governed by

$$y_{t+1} = (A - BF)y_t$$

To obtain a recursive representation of a $\{q_{2t}\}$ sequence that is exogenous to firm 1, we define a state $\tilde{y}_t$

$$\tilde{y}_t = \begin{bmatrix} 1 \\ q_{2t} \\ \tilde{q}_{1t} \\ \tilde{x}_t \end{bmatrix}$$

that evolves according to

$$\tilde{y}_{t+1} = (A - BF)\tilde{y}_t$$

subject to the initial condition $\tilde{q}_{10} = q_{10}$ and $\tilde{x}_0 = x_0$ where $x_0 = -P_{22}^{-1}P_{21}$ as stated above.

Firm 1's state vector is

$$X_t = \begin{bmatrix} \tilde{y}_t \\ q_{1t} \end{bmatrix}$$

It follows that the follower firm 1 faces law of motion

$$\begin{bmatrix} \tilde{y}_{t+1} \\ q_{1t+1} \end{bmatrix} = \begin{bmatrix} A - BF & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \tilde{y}_t \\ q_{1t} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} x_t \tag{11}$$

This specfification assures that from the point of the view of a firm 1, q_{2t} is an exogenous process.

Here

- $\tilde{q}_{1t}, \tilde{x}_t$ play the role of **Big K**.
- q_{1t}, x_t play the role of **little k**.

The time t component of firm 1's objective is

$$\tilde{X}_t' \tilde{R} x_t - x_t^2 \tilde{Q} = \begin{bmatrix} 1 \\ q_{2t} \\ \tilde{q}_{1t} \\ \tilde{x}_t \\ q_{1t} \end{bmatrix}' \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{a_0}{2} \\ 0 & 0 & 0 & 0 & -\frac{a_1}{2} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{a_0}{2} & -\frac{a_1}{2} & 0 & 0 & -a_1 \end{bmatrix} \begin{bmatrix} 1 \\ q_{2t} \\ \tilde{q}_{1t} \\ \tilde{x}_t \\ q_{1t} \end{bmatrix} - \gamma x_t^2$$

Firm 1's optimal decision rule is

$$x_t = -\tilde{F} X_t$$

and it's state evolves according to

$$\tilde{X}_{t+1} = (\tilde{A} - \tilde{B}\tilde{F}) X_t$$

under its optimal decision rule.

Later we shall compute $\tilde{F}$ and verify that when we set

$$X_0 = \begin{bmatrix} 1 \\ q_{20} \\ q_{10} \\ x_0 \\ q_{10} \end{bmatrix}$$

we recover

$$x_0 = -\tilde{F} \tilde{X}_0$$

which will verify that we have properly set up a recursive representation of the follower's problem facing the Stackelberg leader's $\vec{q}_2$.

60.5.4 Time Consistency of Follower's Plan

Since the follower can solve its problem using dynamic programming its problem is recursive in what for it are the **natural state variables**, namely

$$\begin{bmatrix} 1 \\ q_{2t} \\ \tilde{q}_{10} \\ \tilde{x}_0 \end{bmatrix}$$

It follows that the follower's plan is time consistent.

60.6 Computing the Stackelberg Plan

Here is our code to compute a Stackelberg plan via a linear-quadratic dynamic program as outlined above

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
        precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using QuantEcon, Plots, LinearAlgebra, Statistics, Parameters, Random
        gr(fmt = :png);
```

We define named tuples and default values for the model and solver settings, and instantiate one copy of each

```
In [3]: model = @with_kw (a0 = 10,
                          a1 = 2,
                          β = 0.96,
                          γ = 120.,
                          n = 300)

        # things like tolerances, etc.
        settings = @with_kw (tol0 = 1e-8,
                             tol1 = 1e-16,
                             tol2 = 1e-2)

        defaultModel = model();
        defaultSettings = settings();
```

Now we can compute the actual policy using the LQ routine from QuantEcon.jl

```
In [4]: @unpack a0, a1, β, γ, n = defaultModel
        @unpack tol0, tol1, tol2 = defaultSettings

        βs = [β^x for x = 0:n-1]
        Alhs = I + zeros(4, 4);
        Alhs[4, :] = [β * a0 / (2 * γ), -β * a1 / (2 * γ), -β * a1 / γ, β] # Euler
        equation
        coefficients
        Arhs = I + zeros(4, 4);
        Arhs[3, 4] = 1.;
        Alhsinv = inv(Alhs);
```

```
A = Alhsinv * Arhs;
B = Alhsinv * [0, 1, 0, 0,];
R = [0 -a0/2 0 0; -a0/2 a1 a1/2 0; 0 a1/2 0 0; 0 0 0 0];
Q = γ;
lq = QuantEcon.LQ(Q, R, A, B, bet=β);
P, F, d = stationary_values(lq)

P22 = P[4:end, 4:end];
P21 = P[4:end, 1:3];
P22inv = inv(P22);
H_0_0 = -P22inv * P21;

# simulate forward
π_leader = zeros(n);
z0 = [1, 1, 1];
x0 = H_0_0 * z0;
y0 = vcat(z0, x0);

Random.seed!(1) # for reproducibility
yt, ut = compute_sequence(lq, y0, n);
π_matrix = R + F' * Q * F;

for t in 1:n
    π_leader[t] = -(yt[:, t]' * π_matrix * yt[:, t]);
end

println("Computed policy for Stackelberg leader: $F")
```

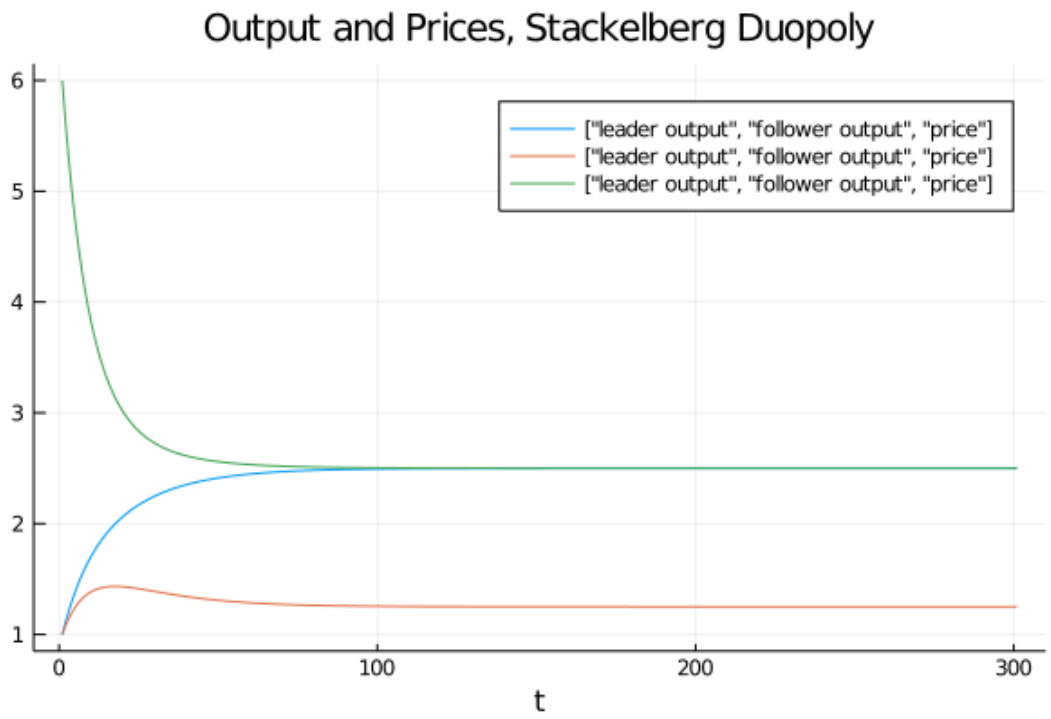
```
Computed policy for Stackelberg leader: [-1.5800445387726552 0.294613127470314
0.6748093760774969 6.539705936147513]
```

60.6.1 Implied Time Series for Price and Quantities

The following code plots the price and quantities

In [5]:
```
q_leader = yt[2, 1:end];
q_follower = yt[3, 1:end];
q = q_leader + q_follower;
p = a0 .- a1*q;

plot(1:n+1, [q_leader, q_follower, p],
    title = "Output and Prices, Stackelberg Duopoly",
    labels = ["leader output", "follower output", "price"],
    xlabel = "t")
```

Out[5]:



60.6.2 Value of Stackelberg Leader

We'll compute the present value earned by the Stackelberg leader.

We'll compute it two ways (they give identical answers – just a check on coding and thinking)

In [6]:
```
v_leader_forward = sum(βs .* π_leader);
v_leader_direct = -yt[:, 1]' * P * yt[:, 1];

println("v_leader_forward (forward sim) is $v_leader_forward")
println("v_leader_direct is $v_leader_direct")
```

```
   v_leader_forward (forward sim) is 150.0316212532548
v_leader_direct is 150.03237147548847
```

In [7]:
```
# manually check whether P is an approximate fixed point
P_next = (R + F' * Q * F + β * (A - B * F)' * P * (A - B * F));
all(P - P_next .< tol0)
```

Out[7]:
```
true
```

In [8]:
```
# manually checks whether two different ways of computing the
# value function give approximately the same answer
v_expanded = -((y0' * R * y0 + ut[:, 1]' * Q * ut[:, 1] +
           β * (y0' * (A - B * F)' * P * (A - B * F) * y0)));
(v_leader_direct - v_expanded < tol0)[1, 1]
```

Out[8]:
```
true
```

60.7 Exhibiting Time Inconsistency of Stackelberg Plan

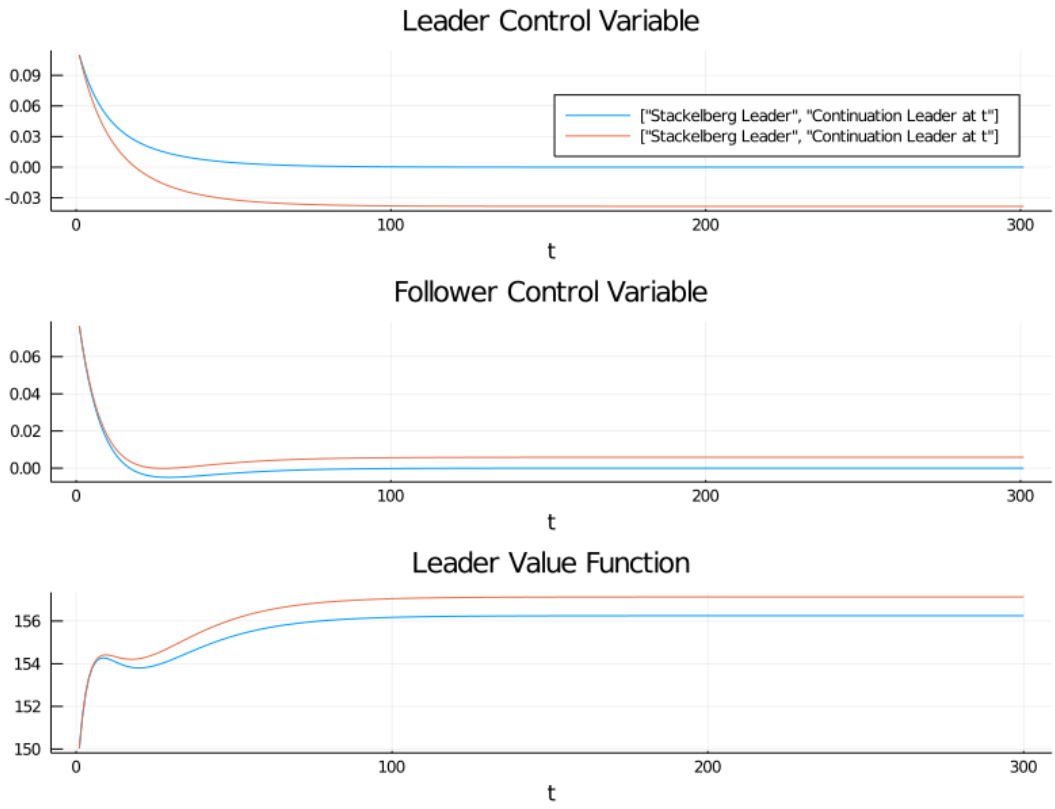
In the code below we compare two values

- the continuation value $-y_t P y_t$ earned by a continuation Stackelberg leader who inherits state y_t at t
- the value of a **reborn Stackelberg leader** who inherits state z_t at t and sets $x_t = -P_{22}^{-1} P_{21}$

The difference between these two values is a tell-tale time of the time inconsistency of the Stackelberg plan

In [9]:
```
# Compute value function over time with reset at time t
vt_leader = zeros(n);
vt_reset_leader = similar(vt_leader);

yt_reset = copy(yt)
yt_reset[end, :] = (H_0_0 * yt[1:3, :])

for t in 1:n
    vt_leader[t] = -yt[:, t]' * P * yt[:, t]
    vt_reset_leader[t] = -yt_reset[:, t]' * P * yt_reset[:, t]
end

p1 = plot(1:n+1, [(-F * yt)', (-F * yt_reset)'], labels = ["Stackelberg
↪Leader",
"Continuation Leader at t"],
        title = "Leader Control Variable", xlabel = "t");
p2 = plot(1:n+1, [yt[4, :], yt_reset[4, :]], title = "Follower Control
↪Variable", xlabel
= "t", legend = false);
p3 = plot(1:n, [vt_leader, vt_reset_leader], legend = false,
            xlabel = "t", title = "Leader Value Function");
plot(p1, p2, p3, layout = (3, 1), size = (800, 600))
```

Out[9]:



60.8 Recursive Formulation of the Follower's Problem

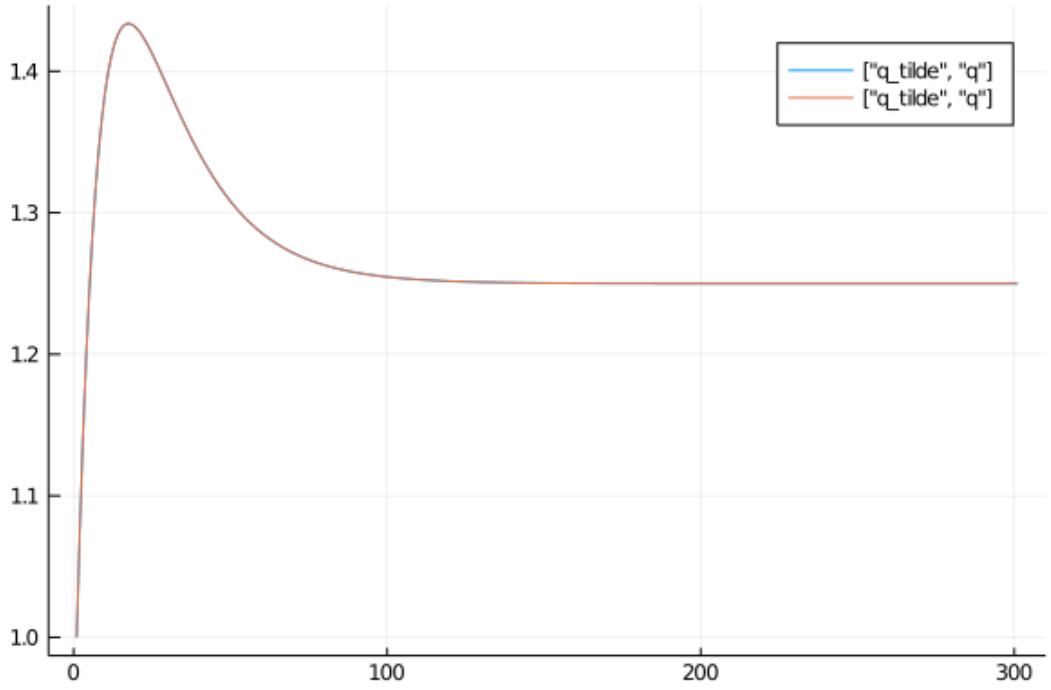
We now formulate and compute the recursive version of the follower's problem.

We check that the recursive **Big K , little k** formulation of the follower's problem produces the same output path $\vec{q}_1$ that we computed when we solved the Stackelberg problem

In [10]:
```
Ã = I + zeros(5, 5);
Ã[1:4, 1:4] .= A - B * F;

R = [0 0 0 0 -a0/2; 0 0 0 0 a1/2; 0 0 0 0 0; 0 0 0 0 0; -a0/2 a1/2 0 0 a1];

Q = Q;

B = [0, 0, 0, 0, 1];


lq_tilde = QuantEcon.LQ(Q, R, Ã, B, bet=β);

P, F, d = stationary_values(lq_tilde);
y0_tilde = vcat(y0, y0[3]);
yt_tilde = compute_sequence(lq_tilde, y0_tilde, n)[1];
```

In [11]:
```
# checks that the recursive formulation of the follower's problem gives
# the same solution as the original Stackelberg problem
plot(1:n+1, [yt_tilde[5, :], yt_tilde[3, :]], labels = ["q_tilde", "q"])
```

Out[11]:



Note: Variables with `_tilde` are obtained from solving the follower's problem – those without are from the Stackelberg problem.

```
In [12]: # maximum absolute difference in quantities over time between the first
  ↪and second
         solution methods
         max(abs(yt_tilde[5] - yt_tilde[3]))
```

```
Out[12]: 0.0
```

```
In [13]: # x0 == x0_tilde
         yt[:, 1][end] - (yt_tilde[:, 2] - yt_tilde[:, 1])[end] < tol0
```

```
Out[13]: true
```

60.8.1 Explanation of Alignment

If we inspect the coefficients in the decision rule $-\tilde{F}$, we can spot the reason that the follower chooses to set $x_t = \tilde{x}_t$ when it sets $x_t = -\tilde{F} X_t$ in the recursive formulation of the follower problem.

Can you spot what features of $\tilde{F}$ imply this?

Hint: remember the components of X_t

```
In [14]: F # policy function in the follower's problem
```

```
Out[14]: 1×5 Array{Float64,2}:
          2.5489e-17  -3.18612e-18  -0.103187  -1.0  0.103187
```

In [15]:
```
P # value function in the Stackelberg problem
```

Out[15]:
```
4×4 Array{Float64,2}:
   963.541  -194.605   -511.622   -5258.23
  -194.605    37.3536    81.9771    784.765
  -511.622    81.9771   247.343    2517.05
 -5258.23    784.765   2517.05    25556.2
```

In [16]:
```
P̃ # value function in the follower's problem
```

Out[16]:
```
5×5 Array{Float64,2}:
 -18.1991     2.58003     15.6049     151.23      -5.0
   2.58003   -0.969466    -5.26008    -50.9764     1.0
  15.6049    -5.26008    -32.2759    -312.792    -12.3824
 151.23     -50.9764    -312.792    -3031.33    -120.0
  -5.0        1.0        -12.3824    -120.0       14.3824
```

In [17]:
```
# manually check that P is an approximate fixed point
all((P  - ((R + F' * Q * F) + β * (A - B * F)' * P * (A - B * F)) .< tol0))
```

Out[17]:
```
true
```

In [18]:
```
# compute `P_guess` using `F_tilde_star`
F̃_star = -[0, 0, 0, 1, 0]';
P_guess = zeros(5, 5);

for i in 1:1000
    P_guess = ((R̃ + F̃_star' * Q̃ * F̃_star) +
               β * (Ã - B̃ * F̃_star)' * P_guess
               * (Ã - B̃ * F̃_star));
end
```

In [19]:
```
# value function in the follower's problem
-(y0_tilde' * P̃ * y0_tilde)[1, 1]
```

Out[19]:
```
112.65590740578102
```

In [20]:
```
# value function using P_guess
-(y0_tilde' * P_guess * y0_tilde)[1, 1]
```

Out[20]:
```
112.65590740578097
```

In [21]:
```
# c policy using policy iteration algorithm
F_iter = (β * inv(Q + β * B̃' * P_guess * B̃)
      * B̃' * P_guess * Ã);
P_iter = zeros(5, 5);
dist_vec = zeros(5, 5);
```

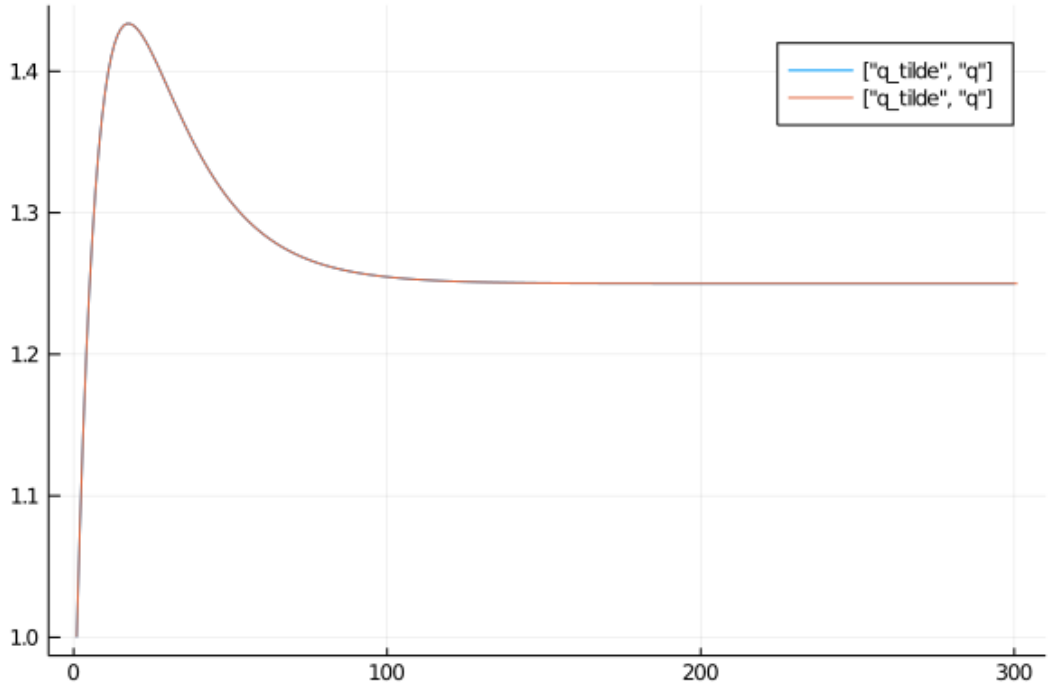
```
    for i in 1:100
        # compute P_iter
        dist_vec = similar(P_iter)
        for j in 1:1000
            P_iter = (R̃ + F_iter' * Q * F_iter) + β *
                      (Ã - B̃ * F_iter)' * P_iter *
                      (Ã - B̃ * F_iter);

            # update F_iter
            F_iter = β * inv(Q + β * B̃' * P_iter * B̃) *
                        B̃' * P_iter * Ã;

            dist_vec = P_iter - ((R̃ + F_iter' * Q * F_iter) +
                    β * (Ã - B̃ * F_iter)' * P_iter *
                    (Ã - B̃ * F_iter));
        end
    end

    if maximum(abs.(dist_vec)) < 1e-8
       dist_vec2 = F_iter - (β * inv(Q + β * B̃' * P_iter * B̃) * B̃' * P_iter * Ã)
        if maximum(abs.(dist_vec2)) < 1e-8
            @show F_iter
        else
           println("The policy didn't converge: try increasing the number
↪of outer loop
    iterations")
        end
    else
        println("The policy didn't converge: try increasing the number of
↪inner loop
    iterations")
    end
```

```
F_iter = [0.0 -1.474514954580286e-17 -0.1031865014522383 -1.0000000000000007
0.10318650145223823]
```

Out[21]:
```
1×5 Adjoint{Float64,Array{Float64,1}}:
 0.0  -1.47451e-17  -0.103187  -1.0  0.103187
```

In [22]:
```
yt_tilde_star = zeros(n, 5);
yt_tilde_star[1, :] = y0_tilde;

for t in 1:n-1
    yt_tilde_star[t+1, :] = (Ã - B̃ * F̃_star) * yt_tilde_star[t, :];
end

plot([yt_tilde_star[:, 5], yt_tilde[3, :]], labels = ["q_tilde", "q"])
```

Out[22]:




```
In [23]: maximum(abs.(yt_tilde_star[:, 5] - yt_tilde[3, 1:end-1]))
```

```
Out[23]: 0.0
```

60.9 Markov Perfect Equilibrium

The **state** vector is

$$z_t = \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \end{bmatrix}$$

and the state transition dynamics are

$$z_{t+1} = Az_t + B_1 v_{1t} + B_2 v_{2t}$$

where A is a 3×3 identity matrix and

$$B_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

The Markov perfect decision rules are

$$v_{1t} = -F_1 z_t, \quad v_{2t} = -F_2 z_t$$

and in the Markov perfect equilibrium the state evolves according to

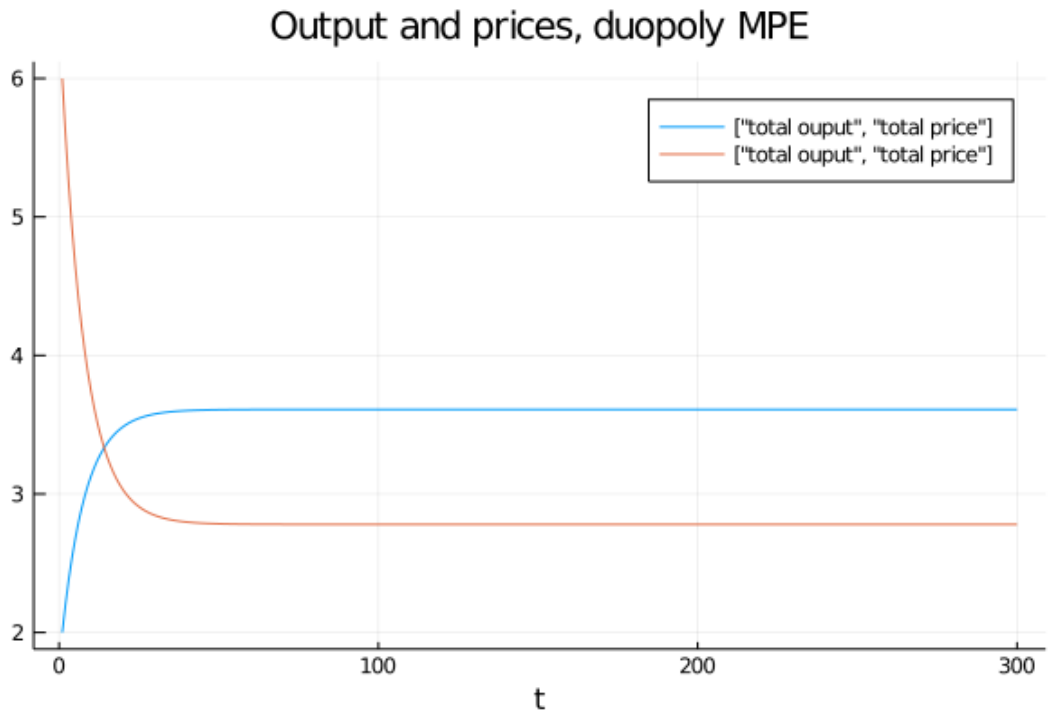
$$z_{t+1} = (A - B_1 F_1 - B_2 F_2) z_t$$

In [24]:
```
# in LQ form
A = I + zeros(3, 3);
B1 = [0, 0, 1];
B2 = [0, 1, 0];
R1 = [0 0 -a0/2; 0 0 a1/2; -a0/2 a1/2 a1];
R2 = [0 -a0/2 0; -a0/2 a1 a1/2; 0 a1/2 0];
Q1 = Q2 = γ;
S1 = S2 = W1 = W2 = M1 = M2 = 0.;

# solve using nnash from QE
F1, F2, P1, P2 = nnash(A, B1, B2, R1, R2, Q1, Q2,
                       S1, S2, W1, W2, M1, M2,
                       beta = β,
                       tol = tol1);

# simulate forward
AF = A - B1 * F1 - B2 * F2;
z = zeros(3, n);
z[:, 1] .= 1;
for t in 1:n-1
    z[:, t+1] = AF * z[:, t]
end

println("Policy for F1 is $F1")
println("Policy for F2 is $F2")
```

```
Policy for F1 is [-0.22701362843207126 0.03129874118441059 0.09447112842804818]
Policy for F2 is [-0.22701362843207126 0.09447112842804818 0.03129874118441059]
```

In [25]:
```
q1 = z[2, :];
q2 = z[3, :];
q = q1 + q2; # total output, MPE
p = a0 .- a1 * q; # total price, MPE
plot([q, p], labels = ["total ouput", "total price"], title = "Output and
↪prices,
duopoly MPE", xlabel = "t")
```

Out[25]:



In [26]:
```
# computes the maximum difference in quantities across firms
maximum(abs.(q1 - q2))
```

Out[26]:
```
8.881784197001252e-16
```

In [27]:
```
# compute values
u1 = -F1 * z;
u2 = -F2 * z;
π_1 = (p .* q1)' - γ * u1.^2;
π_2 = (p .* q2)' - γ * u2.^2;

v1_forward = π_1 * βs;
v2_forward = π_2 * βs;

v1_direct = -z[:, 1]' * P1 * z[:, 1];
v2_direct = -z[:, 1]' * P2 * z[:, 1];

println("Firm 1: Direct is $v1_direct, Forward is $(v1_forward[1])");
println("Firm 2: Direct is $v2_direct, Forward is $(v2_forward[1])");
```

```
Firm 1: Direct is 133.3295555721595, Forward is 133.33033197956638
Firm 2: Direct is 133.32955557215945, Forward is 133.33033197956638
```

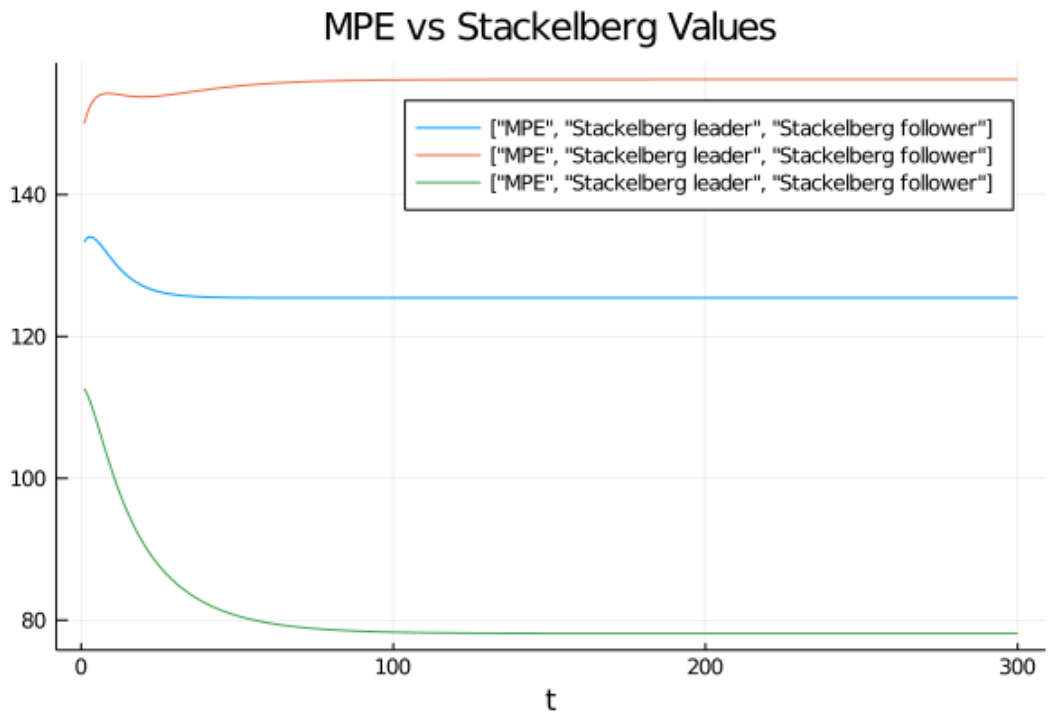
In [28]:
```
# sanity check
Λ_1 = A - B2 * F2;
lq1 = QuantEcon.LQ(Q1, R1, Λ_1, B1, bet = β);
P1_ih, F1_ih, d = stationary_values(lq1);

v2_direct_alt = -z[:, 1]' * P1_ih * z[:, 1] + d;
all(abs.(v2_direct - v2_direct_alt) < tol2)
```

Out[28]:
```
true
```

60.10 MPE vs. Stackelberg

In [29]:
```
vt_MPE = zeros(n);
vt_follower = zeros(n);

for t in 1:n
    vt_MPE[t] = -z[:, t]' * P1 * z[:, t];
    vt_follower[t] = -yt_tilde[:, t]' * P * yt_tilde[:, t];
end

plot([vt_MPE, vt_leader, vt_follower], labels = ["MPE", "Stackelberg
↪leader",
            "Stackelberg follower"], title = "MPE vs Stackelberg Values",
            xlabel = "t")
```

Out[29]:



In [30]:
```
# display values
println("vt_leader(y0) = $(vt_leader[1])");
println("vt_follower(y0) = $(vt_follower[1])")
println("vt_MPE(y0) = $(vt_MPE[1])");
```

```
  vt_leader(y0) = 150.03237147548847
vt_follower(y0) = 112.65590740578102
vt_MPE(y0) = 133.3295555721595
```

In [31]:
```
# total difference in value b/t Stackelberg and MPE
vt_leader[1] + vt_follower[1] - 2*vt_MPE[1]
```

Out[31]: -3.9708322630494877

Chapter 61

Optimal Taxation in an LQ Economy

61.1 Contents

61.2 Overview

In this lecture we study optimal fiscal policy in a linear quadratic setting.

We slightly modify a well-known model of Robert Lucas and Nancy Stokey [72] so that convenient formulas for solving linear-quadratic models can be applied to simplify the calculations.

The economy consists of a representative household and a benevolent government.

The government finances an exogenous stream of government purchases with state-contingent loans and a linear tax on labor income.

A linear tax is sometimes called a flat-rate tax.

The household maximizes utility by choosing paths for consumption and labor, taking prices and the government's tax rate and borrowing plans as given.

Maximum attainable utility for the household depends on the government's tax and borrowing plans.

The *Ramsey problem* [88] is to choose tax and borrowing plans that maximize the household's welfare, taking the household's optimizing behavior as given.

There is a large number of competitive equilibria indexed by different government fiscal policies.

The Ramsey planner chooses the best competitive equilibrium.

We want to study the dynamics of tax rates, tax revenues, government debt under a Ramsey

plan.

Because the Lucas and Stokey model features state-contingent government debt, the government debt dynamics differ substantially from those in a model of Robert Barro [8].

The treatment given here closely follows this manuscript, prepared by Thomas J. Sargent and Francois R. Velde.

We cover only the key features of the problem in this lecture, leaving you to refer to that source for additional results and intuition.

61.2.1 Model Features

- Linear quadratic (LQ) model
- Representative household
- Stochastic dynamic programming over an infinite horizon
- Distortionary taxation

61.2.2 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

61.3 The Ramsey Problem

We begin by outlining the key assumptions regarding technology, households and the government sector.

61.3.1 Technology

Labor can be converted one-for-one into a single, non-storable consumption good.

In the usual spirit of the LQ model, the amount of labor supplied in each period is unrestricted.

This is unrealistic, but helpful when it comes to solving the model.

Realistic labor supply can be induced by suitable parameter values.

61.3.2 Households

Consider a representative household who chooses a path $\{\ell_t, c_t\}$ for labor and consumption to maximize

$$-\mathbb{E}\frac{1}{2}\sum_{t=0}^{\infty}\beta^t\left[(c_t - b_t)^2 + \ell_t^2\right] \tag{1}$$

subject to the budget constraint

$$\mathbb{E}\sum_{t=0}^{\infty}\beta^t p_t^0\left[d_t+(1-\tau_t)\ell_t+s_t-c_t\right]=0 \tag{2}$$

Here

- β is a discount factor in $(0,1)$
- p_t^0 is a scaled Arrow-Debreu price at time 0 of history contingent goods at time $t+j$
- b_t is a stochastic preference parameter
- d_t is an endowment process
- τ_t is a flat tax rate on labor income
- s_t is a promised time-t coupon payment on debt issued by the government

The scaled Arrow-Debreu price p_t^0 is related to the unscaled Arrow-Debreu price as follows.

If we let $\pi_t^0(x^t)$ denote the probability (density) of a history $x^t=[x_t,x_{t-1},\ldots,x_0]$ of the state x^t, then the Arrow-Debreu time 0 price of a claim on one unit of consumption at date t, history x^t would be

$$\frac{\beta^t p_t^0}{\pi_t^0(x^t)}$$

Thus, our scaled Arrow-Debreu price is the ordinary Arrow-Debreu price multiplied by the discount factor β^t and divided by an appropriate probability.

The budget constraint (2) requires that the present value of consumption be restricted to equal the present value of endowments, labor income and coupon payments on bond holdings.

61.3.3 Government

The government imposes a linear tax on labor income, fully committing to a stochastic path of tax rates at time zero.

The government also issues state-contingent debt.

Given government tax and borrowing plans, we can construct a competitive equilibrium with distorting government taxes.

Among all such competitive equilibria, the Ramsey plan is the one that maximizes the welfare of the representative consumer.

61.3.4 Exogenous Variables

Endowments, government expenditure, the preference shock process b_t, and promised coupon payments on initial government debt s_t are all exogenous, and given by

- $d_t=S_d x_t$
- $g_t=S_g x_t$
- $b_t=S_b x_t$
- $s_t=S_s x_t$

The matrices S_d,S_g,S_b,S_s are primitives and $\{x_t\}$ is an exogenous stochastic process taking values in $\mathbb{R}^k$.

We consider two specifications for $\{x_t\}$.

1. Discrete case: $\{x_t\}$ is a discrete state Markov chain with transition matrix P.
2. VAR case: $\{x_t\}$ obeys $x_{t+1} = Ax_t + Cw_{t+1}$ where $\{w_t\}$ is independent zero mean Gaussian with identify covariance matrix.

61.3.5 Feasibility

The period-by-period feasibility restriction for this economy is

$$c_t + g_t = d_t + \ell_t \tag{3}$$

A labor-consumption process $\{\ell_t, c_t\}$ is called *feasible* if (3) holds for all t.

61.3.6 Government budget constraint

Where p_t^0 is again a scaled Arrow-Debreu price, the time zero government budget constraint is

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t p_t^0 (s_t + g_t - \tau_t \ell_t) = 0 \tag{4}$$

61.3.7 Equilibrium

An *equilibrium* is a feasible allocation $\{\ell_t, c_t\}$, a sequence of prices $\{p_t^0\}$, and a tax system $\{\tau_t\}$ such that

1. The allocation $\{\ell_t, c_t\}$ is optimal for the household given $\{p_t^0\}$ and $\{\tau_t\}$.
2. The government's budget constraint (4) is satisfied.

The *Ramsey problem* is to choose the equilibrium $\{\ell_t, c_t, \tau_t, p_t^0\}$ that maximizes the household's welfare.

If $\{\ell_t, c_t, \tau_t, p_t^0\}$ solves the Ramsey problem, then $\{\tau_t\}$ is called the *Ramsey plan*.

The solution procedure we adopt is

1. Use the first-order conditions from the household problem to pin down prices and allocations given $\{\tau_t\}$.
2. Use these expressions to rewrite the government budget constraint (4) in terms of exogenous variables and allocations.
3. Maximize the household's objective function (1) subject to the constraint constructed in step 2 and the feasibility constraint (3).

The solution to this maximization problem pins down all quantities of interest.

61.3.8 Solution

Step one is to obtain the first-conditions for the household's problem, taking taxes and prices as given.

Letting μ be the Lagrange multiplier on (2), the first-order conditions are $p_t^0 = (c_t - b_t)/\mu$ and $\ell_t = (c_t - b_t)(1 - \tau_t)$.

Rearranging and normalizing at $\mu = b_0 - c_0$, we can write these conditions as

$$p_t^0 = \frac{b_t - c_t}{b_0 - c_0} \quad \text{and} \quad \tau_t = 1 - \frac{\ell_t}{b_t - c_t} \tag{5}$$

Substituting (5) into the government's budget constraint (4) yields

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t \left[(b_t - c_t)(s_t + g_t - \ell_t) + \ell_t^2 \right] = 0 \tag{6}$$

The Ramsey problem now amounts to maximizing (1) subject to (6) and (3).

The associated Lagrangian is

$$\mathcal{L} = \mathbb{E} \sum_{t=0}^{\infty} \beta^t \left\{ -\frac{1}{2} \left[(c_t - b_t)^2 + \ell_t^2 \right] + \lambda \left[(b_t - c_t)(\ell_t - s_t - g_t) - \ell_t^2 \right] + \mu_t [d_t + \ell_t - c_t - g_t] \right\} \tag{7}$$

The first order conditions associated with c_t and ℓ_t are

$$-(c_t - b_t) + \lambda[-\ell_t + (g_t + s_t)] = \mu_t$$

and

$$\ell_t - \lambda[(b_t - c_t) - 2\ell_t] = \mu_t$$

Combining these last two equalities with (3) and working through the algebra, one can show that

$$\ell_t = \bar{\ell}_t - \nu m_t \quad \text{and} \quad c_t = \bar{c}_t - \nu m_t \tag{8}$$

where

- $\nu := \lambda/(1 + 2\lambda)$
- $\bar{\ell}_t := (b_t - d_t + g_t)/2$
- $\bar{c}_t := (b_t + d_t - g_t)/2$
- $m_t := (b_t - d_t - s_t)/2$

Apart from ν, all of these quantities are expressed in terms of exogenous variables.

To solve for ν, we can use the government's budget constraint again.

The term inside the brackets in (6) is $(b_t - c_t)(s_t + g_t) - (b_t - c_t)\ell_t + \ell_t^2$.

Using (8), the definitions above and the fact that $\bar{\ell} = b - \bar{c}$, this term can be rewritten as

$$(b_t - \bar{c}_t)(g_t + s_t) + 2m_t^2(\nu^2 - \nu)$$

Reinserting into (6), we get

$$\mathbb{E}\left\{\sum_{t=0}^{\infty} \beta^t (b_t - \bar{c}_t)(g_t + s_t)\right\} + (\nu^2 - \nu)\mathbb{E}\left\{\sum_{t=0}^{\infty} \beta^t 2m_t^2\right\} = 0 \tag{9}$$

Although it might not be clear yet, we are nearly there because:

- The two expectations terms in (9) can be solved for in terms of model primitives.
- This in turn allows us to solve for the Lagrange multiplier ν.
- With ν in hand, we can go back and solve for the allocations via (8).
- Once we have the allocations, prices and the tax system can be derived from (5).

61.3.9 Computing the Quadratic Term

Let's consider how to obtain the term ν in (9).

If we can compute the two expected geometric sums

$$b_0 := \mathbb{E}\left\{\sum_{t=0}^{\infty} \beta^t (b_t - \bar{c}_t)(g_t + s_t)\right\} \quad \text{and} \quad a_0 := \mathbb{E}\left\{\sum_{t=0}^{\infty} \beta^t 2m_t^2\right\} \tag{10}$$

then the problem reduces to solving

$$b_0 + a_0(\nu^2 - \nu) = 0$$

for ν.

Provided that $4b_0 < a_0$, there is a unique solution $\nu \in (0, 1/2)$, and a unique corresponding $\lambda > 0$.

Let's work out how to compute mathematical expectations in (10).

For the first one, the random variable $(b_t - \bar{c}_t)(g_t + s_t)$ inside the summation can be expressed as

$$\frac{1}{2} x_t'(S_b - S_d + S_g)'(S_g + S_s)x_t$$

For the second expectation in (10), the random variable $2m_t^2$ can be written as

$$\frac{1}{2} x_t'(S_b - S_d - S_s)'(S_b - S_d - S_s)x_t$$

It follows that both objects of interest are special cases of the expression

$$q(x_0) = \mathbb{E}\sum_{t=0}^{\infty} \beta^t x_t' H x_t \tag{11}$$

where H is a matrix conformable to x_t and x_t' is the transpose of column vector x_t.

Suppose first that $\{x_t\}$ is the Gaussian VAR described above.

In this case, the formula for computing $q(x_0)$ is known to be $q(x_0) = x_0' Q x_0 + v$, where

- Q is the solution to $Q = H + \beta A' Q A$, and
- $v = \text{trace}\,(C' Q C)\beta/(1-\beta)$

The first equation is known as a discrete Lyapunov equation, and can be solved using this function.

61.3.10 Finite state Markov case

Next suppose that $\{x_t\}$ is the discrete Markov process described above.

Suppose further that each x_t takes values in the state space $\{x^1, \ldots, x^N\} \subset \mathbb{R}^k$.

Let $h \colon \mathbb{R}^k \to \mathbb{R}$ be a given function, and suppose that we wish to evaluate

$$q(x_0) = \mathbb{E} \sum_{t=0}^{\infty} \beta^t h(x_t) \quad \text{given} \quad x_0 = x^j$$

For example, in the discussion above, $h(x_t) = x_t' H x_t$.

It is legitimate to pass the expectation through the sum, leading to

$$q(x_0) = \sum_{t=0}^{\infty} \beta^t (P^t h)[j] \tag{12}$$

Here

- P^t is the t-th power of the transition matrix P
- h is, with some abuse of notation, the vector $(h(x^1), \ldots, h(x^N))$
- $(P^t h)[j]$ indicates the j-th element of $P^t h$

It can be show that (12) is in fact equal to the j-th element of the vector $(I - \beta P)^{-1} h$.

This last fact is applied in the calculations below.

61.3.11 Other Variables

We are interested in tracking several other variables besides the ones described above.

To prepare the way for this, we define

$$p_{t+j}^t = \frac{b_{t+j} - c_{t+j}}{b_t - c_t}$$

as the scaled Arrow-Debreu time t price of a history contingent claim on one unit of consumption at time $t + j$.

These are prices that would prevail at time t if market were reopened at time t.

These prices are constituents of the present value of government obligations outstanding at time t, which can be expressed as

$$B_t := \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j p_{t+j}^t (\tau_{t+j} \ell_{t+j} - g_{t+j}) \tag{13}$$

Using our expression for prices and the Ramsey plan, we can also write B_t as

$$B_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{(b_{t+j} - c_{t+j})(\ell_{t+j} - g_{t+j}) - \ell_{t+j}^2}{b_t - c_t}$$

This version is more convenient for computation.

Using the equation

$$p_{t+j}^t = p_{t+1}^t p_{t+j}^{t+1}$$

it is possible to verity that (13) implies that

$$B_t = (\tau_t \ell_t - g_t) + E_t \sum_{j=1}^{\infty} p_{t+j}^t (\tau_{t+j} \ell_{t+j} - g_{t+j})$$

and

$$B_t = (\tau_t \ell_t - g_t) + \beta E_t p_{t+1}^t B_{t+1} \tag{14}$$

Define

$$R_t^{-1} := \mathbb{E}_t \beta^j p_{t+1}^t \tag{15}$$

R_t is the gross 1-period risk-free rate for loans between t and $t+1$.

61.3.12 A Martingale

We now want to study the following two objects, namely,

$$\pi_{t+1} := B_{t+1} - R_t [B_t - (\tau_t \ell_t - g_t)]$$

and the cumulation of π_t

$$\Pi_t := \sum_{s=0}^{t} \pi_t$$

The term π_{t+1} is the difference between two quantities:

- B_{t+1}, the value of government debt at the start of period $t+1$.
- $R_t[B_t + g_t - \tau_t]$, which is what the government would have owed at the beginning of period $t+1$ if it had simply borrowed at the one-period risk-free rate rather than selling state-contingent securities.

Thus, π_{t+1} is the excess payout on the actual portfolio of state contingent government debt relative to an alternative portfolio sufficient to finance $B_t + g_t - \tau_t \ell_t$ and consisting entirely of risk-free one-period bonds.

Use expressions (14) and (15) to obtain

$$\pi_{t+1} = B_{t+1} - \frac{1}{\beta E_t p_{t+1}^t} \left[\beta E_t p_{t+1}^t B_{t+1}\right]$$

or

$$\pi_{t+1} = B_{t+1} - \tilde{E}_t B_{t+1} \tag{16}$$

where $\tilde{E}_t$ is the conditional mathematical expectation taken with respect to a one-step transition density that has been formed by multiplying the original transition density with the likelihood ratio

$$m_{t+1}^t = \frac{p_{t+1}^t}{E_t p_{t+1}^t}$$

It follows from equation (16) that

$$\tilde{E}_t \pi_{t+1} = \tilde{E}_t B_{t+1} - \tilde{E}_t B_{t+1} = 0$$

which asserts that $\{\pi_{t+1}\}$ is a martingale difference sequence under the distorted probability measure, and that $\{\Pi_t\}$ is a martingale under the distorted probability measure.

In the tax-smoothing model of Robert Barro [8], government debt is a random walk.

In the current model, government debt $\{B_t\}$ is not a random walk, but the `excess payoff` $\{\Pi_t\}$ on it is.

61.4 Implementation

The following code provides functions for

1. Solving for the Ramsey plan given a specification of the economy.
2. Simulating the dynamics of the major variables.

Description and clarifications are given below

In [3]:
```
using QuantEcon, Plots, LinearAlgebra, Parameters
gr(fmt = :png);

abstract type AbstractStochProcess end

struct ContStochProcess{TF <: AbstractFloat} <: AbstractStochProcess
    A::Matrix{TF}
    C::Matrix{TF}
end
```

```
struct DiscreteStochProcess{TF <: AbstractFloat} <: AbstractStochProcess
    P::Matrix{TF}
    x_vals::Matrix{TF}
end

struct Economy{TF <: AbstractFloat, SP <: AbstractStochProcess}
    β::TF
    Sg::Matrix{TF}
    Sd::Matrix{TF}
    Sb::Matrix{TF}
    Ss::Matrix{TF}
    proc::SP
end

function compute_exog_sequences(econ, x)
    # compute exogenous variable sequences
    Sg, Sd, Sb, Ss = econ.Sg, econ.Sd, econ.Sb, econ.Ss
    g, d, b, s = [dropdims(S * x, dims = 1) for S in (Sg, Sd, Sb, Ss)]

    #= solve for Lagrange multiplier in the govt budget constraint
    In fact we solve for ν = λ / (1 + 2*λ).  Here ν is the
    solution to a quadratic equation a(ν^2 - ν) + b = 0 where
   a and b are expected discounted sums of quadratic forms of the state. =#
    Sm = Sb - Sd - Ss

    return g, d, b, s, Sm
end


function compute_allocation(econ, Sm, ν, x, b)
    Sg, Sd, Sb, Ss = econ.Sg, econ.Sd, econ.Sb, econ.Ss

    # solve for the allocation given ν and x
    Sc = 0.5 .* (Sb + Sd - Sg - ν .* Sm)
    Sl = 0.5 .* (Sb - Sd + Sg - ν .* Sm)
    c = dropdims(Sc * x, dims = 1)
    l = dropdims(Sl * x, dims = 1)
    p = dropdims((Sb - Sc) * x, dims = 1)  # Price without normalization
    τ = 1 .- l ./ (b .- c)
    rvn = l .* τ

    return Sc, Sl, c, l, p, τ, rvn
end


function compute_ν(a0, b0)
    disc = a0^2 - 4a0 * b0

    if disc ≥ 0
        ν = 0.5 *(a0 - sqrt(disc)) / a0
    else
        println("There is no Ramsey equilibrium for these parameters.")
        error("Government spending (economy.g) too low")
    end

    # Test that the Lagrange multiplier has the right sign
```

```
        if ν * (0.5 - ν) < 0
            print("Negative multiplier on the government budget constraint.")
            error("Government spending (economy.g) too low")
        end

        return ν
    end


    function compute_Π(B, R, rvn, g, ξ)
        π = B[2:end] - R[1:end-1] .* B[1:end-1] - rvn[1:end-1] + g[1:end-1]
        Π = cumsum(π .* ξ)
        return π, Π
    end


    function compute_paths(econ::Economy{<:AbstractFloat, <:
↪DiscreteStochProcess}, T)
        # simplify notation
        @unpack β, Sg, Sd, Sb, Ss = econ
        @unpack P, x_vals = econ.proc

        mc = MarkovChain(P)
        state = simulate(mc, T, init=1)
        x = x_vals[:, state]

        # Compute exogenous sequence
        g, d, b, s, Sm = compute_exog_sequences(econ, x)

        # compute a0, b0
        ns = size(P, 1)
        F = I - β.*P
        a0 = (F \ ((Sm * x_vals)'.^2))[1] ./ 2
        H = ((Sb - Sd + Sg) * x_vals) .* ((Sg - Ss)*x_vals)
        b0 = (F \ H')[1] ./ 2

        # compute lagrange multiplier
        ν = compute_ν(a0, b0)

        # Solve for the allocation given ν and x
        Sc, Sl, c, l, p, τ, rvn = compute_allocation(econ, Sm, ν, x, b)

        # compute remaining variables
        H = ((Sb - Sc) * x_vals) .* ((Sl - Sg) * x_vals) - (Sl * x_vals).^2
        temp = dropdims(F * H', dims = 2)
        B = temp[state] ./ p
        H = dropdims(P[state, :] * ((Sb - Sc) * x_vals)', dims = 2)
        R = p ./ (β .* H)
        temp = dropdims(P[state, :] *((Sb - Sc) * x_vals)', dims = 2)
        ξ = p[2:end] ./ temp[1:end-1]

        # compute π
        π, Π = compute_Π(B, R, rvn, g, ξ)

        return (g = g, d = d, b = b, s = s, c = c,
                l = l, p = p, τ = τ, rvn = rvn, B = B,
                R = R, π = π, Π = Π, ξ = ξ)
    end
```

```
function compute_paths(econ::Economy{<:AbstractFloat, <:ContStochProcess},
↪T)
    # simplify notation
    @unpack β, Sg, Sd, Sb, Ss = econ
    @unpack A, C = econ.proc

    # generate an initial condition x0 satisfying x0 = A x0
    nx, nx = size(A)
    x0 = nullspace(I - A)
    x0 = x0[end] < 0 ? -x0 : x0
    x0 = x0 ./ x0[end]
    x0 = dropdims(x0, dims = 2)

    # generate a time series x of length T starting from x0
    nx, nw = size(C)
    x = zeros(nx, T)
    w = randn(nw, T)
    x[:, 1] = x0
    for t in 2:T
        x[:, t] = A *x[:, t-1] + C * w[:, t]
    end

    # compute exogenous sequence
    g, d, b, s, Sm = compute_exog_sequences(econ, x)

    # compute a0 and b0
    H = Sm'Sm
    a0 = 0.5 * var_quadratic_sum(A, C, H, β, x0)
    H = (Sb - Sd + Sg)'*(Sg + Ss)
    b0 = 0.5 * var_quadratic_sum(A, C, H, β, x0)

    # compute lagrange multiplier
    ν = compute_ν(a0, b0)

    # solve for the allocation given ν and x
    Sc, Sl, c, l, p, τ, rvn = compute_allocation(econ, Sm, ν, x, b)

    # compute remaining variables
    H = Sl'Sl - (Sb - Sc)' *(Sl - Sg)
    L = zeros(T)
    for t in eachindex(L)
        L[t] = var_quadratic_sum(A, C, H, β, x[:, t])
    end
    B = L ./ p
    Rinv = dropdims(β .* (Sb- Sc)*A*x, dims = 1) ./ p
    R = 1 ./ Rinv
    AF1 = (Sb - Sc) * x[:, 2:end]
    AF2 = (Sb - Sc) * A * x[:, 1:end-1]
    ξ =  AF1 ./ AF2
    ξ = dropdims(ξ, dims = 1)

    # compute 𝜋
    π, Π = compute_Π(B, R, rvn, g, ξ)

    return (g = g, d = d, b = b, s = s,
            c = c, l = l, p = p, τ = τ,
            rvn = rvn, B = B, R = R,
```

```
                π = π, Π = Π, ξ = ξ)
end

function gen_fig_1(path)
    T = length(path.c)

    plt_1 = plot(path.rvn, lw=2, label = "tau_t l_t")
    plot!(plt_1, path.g, lw=2, label= "g_t")
    plot!(plt_1, path.c, lw=2, label= "c_t")
    plot!(xlabel="Time", grid=true)

    plt_2 = plot(path.rvn, lw=2, label="tau_t l_t")
    plot!(plt_2, path.g, lw=2, label="g_t")
    plot!(plt_2, path.B[2:end], lw=2, label="B_(t+1)")
    plot!(xlabel="Time", grid=true)

    plt_3 = plot(path.R, lw=2, label="R_(t-1)")
    plot!(plt_3, xlabel="Time", grid=true)

    plt_4 = plot(path.rvn, lw=2, label="tau_t l_t")
    plot!(plt_4, path.g, lw=2, label="g_t")
    plot!(plt_4, path.π, lw=2, label="pi_t")
    plot!(plt_4, xlabel="Time", grid=true)

    plot(plt_1, plt_2, plt_3, plt_4, layout=(2,2), size = (800,600))
end

function gen_fig_2(path)

    T = length(path.c)

    paths = [path.ξ, path.Π]
    labels = ["xi_t", "Pi_t"]
    plt_1 = plot()
    plt_2 = plot()
    plots = [plt_1, plt_2]

    for (plot, path, label) in zip(plots, paths, labels)
        plot!(plot, 2:T, path, lw=2, label=label, xlabel="Time", grid=true)
    end
    plot(plt_1, plt_2, layout=(2,1), size = (600,500))
end
```

```
Out[3]: gen_fig_2 (generic function with 1 method)
```

61.4.1 Comments on the Code

The function `var_quadratic_sum` From `QuantEcon.jl` is for computing the value of (11) when the exogenous process $\{x_t\}$ is of the VAR type described above.

This code defines two Types: `Economy` and `Path`.

The first is used to collect all the parameters and primitives of a given LQ economy, while the second collects output of the computations.

61.5 Examples

Let's look at two examples of usage.

61.5.1 The Continuous Case

Our first example adopts the VAR specification described above.

Regarding the primitives, we set

- $\beta = 1/1.05$
- $b_t = 2.135$ and $s_t = d_t = 0$ for all t

Government spending evolves according to

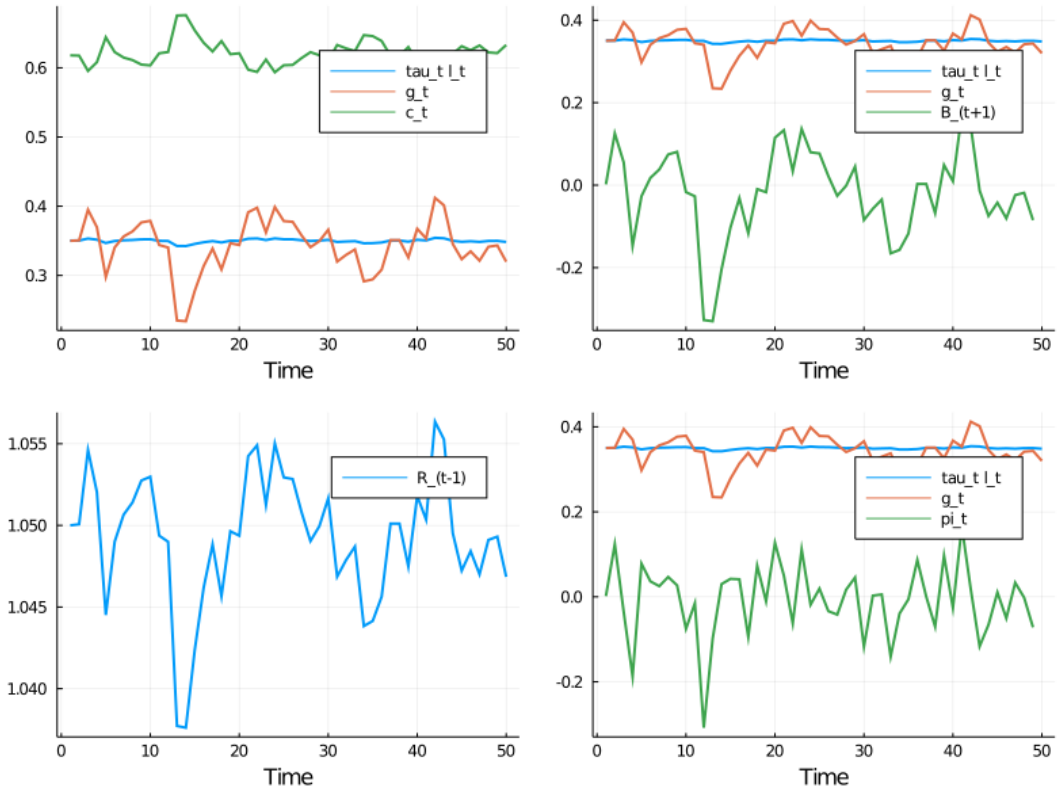
$$g_{t+1} - \mu_g = \rho(g_t - \mu_g) + C_g w_{g,t+1}$$

with $\rho = 0.7$, $\mu_g = 0.35$ and $C_g = \mu_g\sqrt{1-\rho^2}/10$.

Here's the code

In [4]:
```
# for reproducible results
using Random
Random.seed!(42)

# parameters
β = 1 / 1.05
ρ, mg = .7, .35
A = [ρ mg*(1 - ρ); 0.0 1.0]
C = [sqrt(1 - ρ^2) * mg / 10 0.0; 0 0]
Sg = [1.0 0.0]
Sd = [0.0 0.0]
Sb = [0 2.135]
Ss = [0.0 0.0]
proc = ContStochProcess(A, C)

econ = Economy(β, Sg, Sd, Sb, Ss, proc)
T = 50
path = compute_paths(econ, T)

gen_fig_1(path)
```

Out[4]:

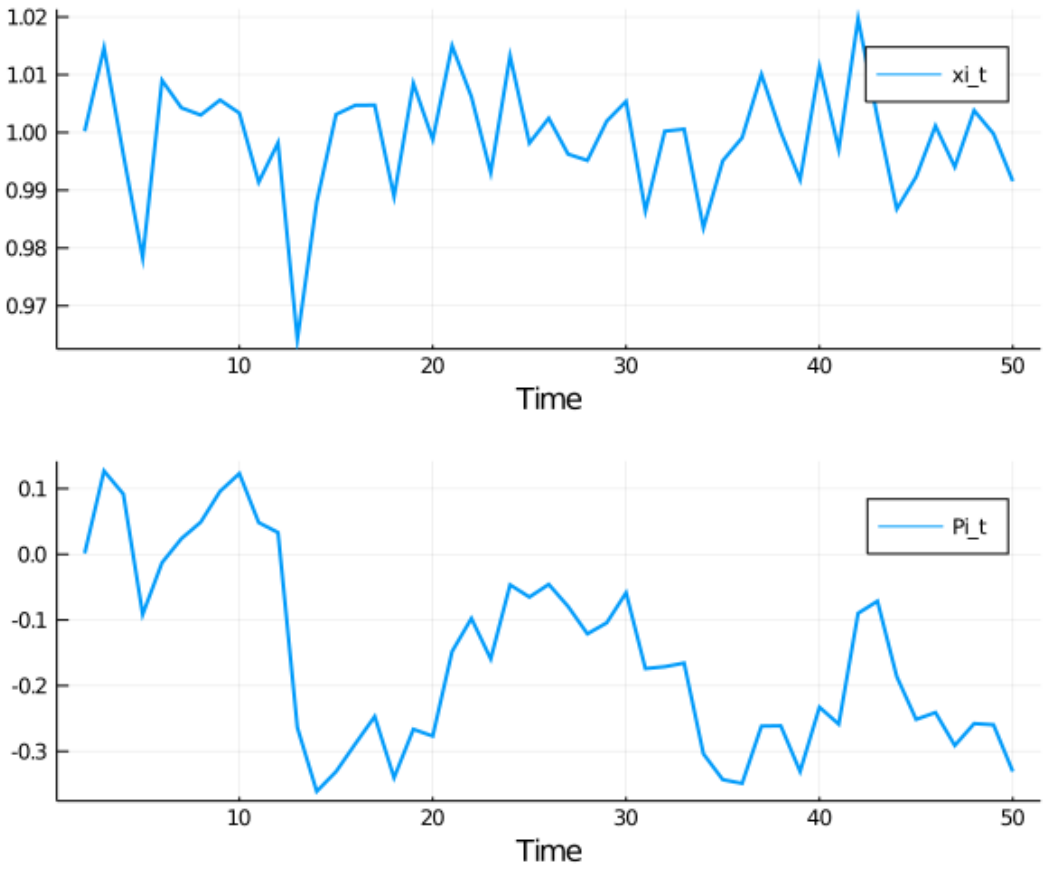


The legends on the figures indicate the variables being tracked.

Most obvious from the figure is tax smoothing in the sense that tax revenue is much less variable than government expenditure

```
In [5]: gen_fig_2(path)
```

```
Out[5]:
```



See the original manuscript for comments and interpretation

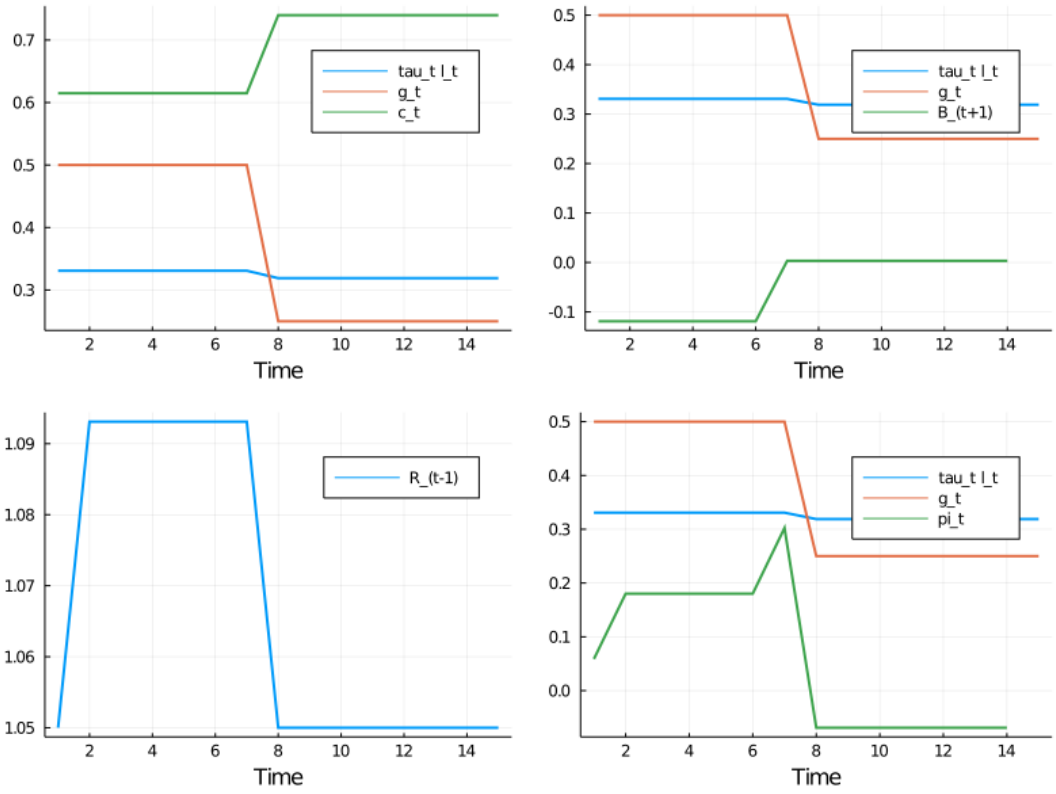
61.5.2 The Discrete Case

Our second example adopts a discrete Markov specification for the exogenous process

In [6]:
```
# Parameters
β = 1 / 1.05
P = [0.8 0.2 0.0
    0.0 0.5 0.5
    0.0 0.0 1.0]

# Possible states of the world
# Each column is a state of the world. The rows are [g d b s 1]
x_vals = [0.5 0.5 0.25;
        0.0 0.0  0.0;
        2.2 2.2  2.2;
        0.0 0.0  0.0;
        1.0 1.0  1.0]
Sg = [1.0 0.0 0.0 0.0 0.0]
Sd = [0.0 1.0 0.0 0.0 0.0]
Sb = [0.0 0.0 1.0 0.0 0.0]
Ss = [0.0 0.0 0.0 1.0 0.0]
proc = DiscreteStochProcess(P, x_vals)

econ = Economy(β, Sg, Sd, Sb, Ss, proc)
T = 15
```

```
path = compute_paths(econ, T)

gen_fig_1(path)
```

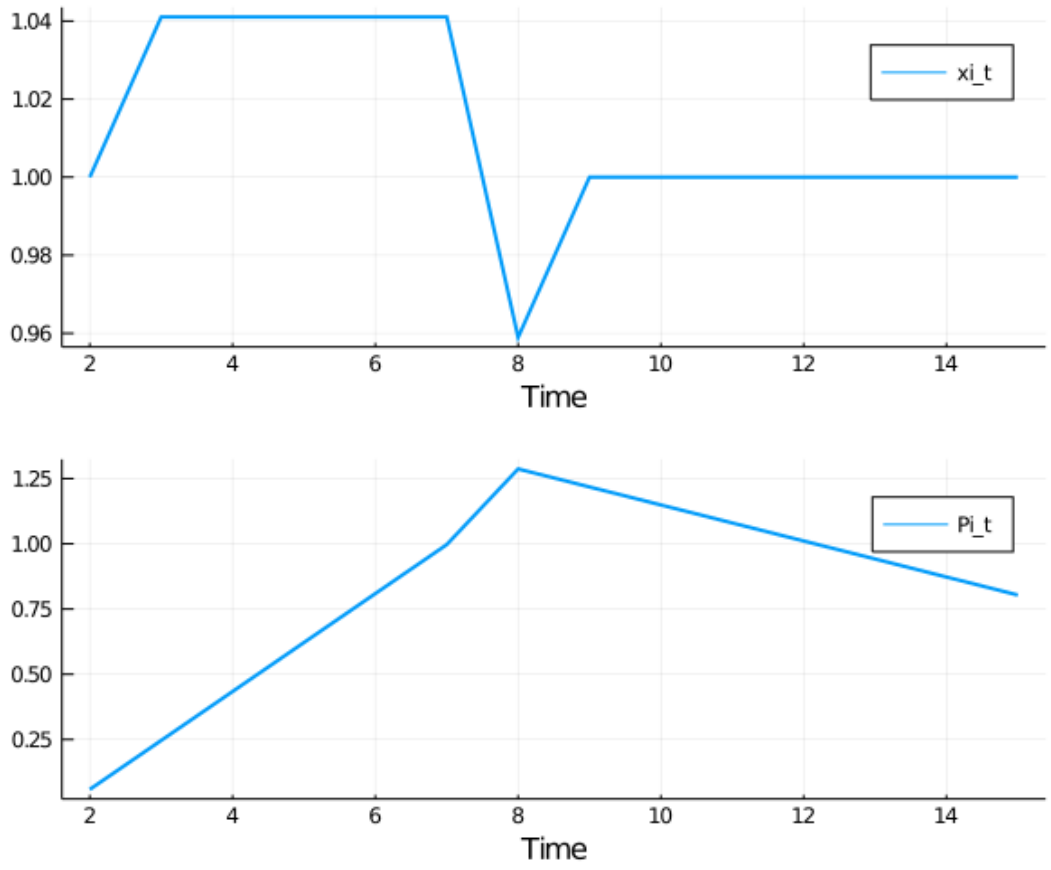
Out[6]:



The call `gen_fig_2(path)` generates

In [7]:
```
gen_fig_2(path)
```

Out[7]:



See the original manuscript for comments and interpretation

61.6 Exercises

61.6.1 Exercise 1

Modify the VAR example given above, setting

$$g_{t+1} - \mu_g = \rho(g_{t-3} - \mu_g) + C_g w_{g,t+1}$$

with $\rho = 0.95$ and $C_g = 0.7\sqrt{1-\rho^2}$.

Produce the corresponding figures.

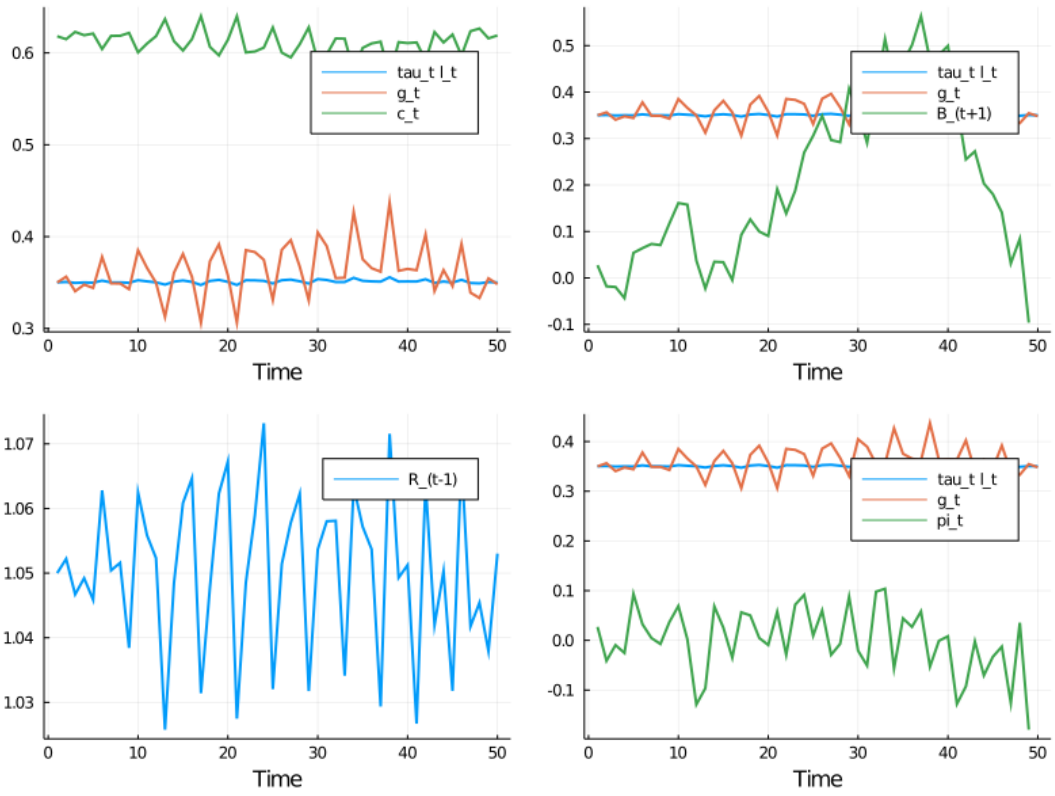
61.7 Solutions

```
In [8]: # parameters
        β = 1 / 1.05
        ρ, mg = .95, .35
        A = [0. 0. 0. ρ  mg*(1-ρ);
             1. 0. 0. 0.       0.;
             0. 1. 0. 0.       0.;
             0. 0. 1. 0.       0.;
```

```
      0. 0. 0. 0.       1.]
C = zeros(5, 5)
C[1, 1] = sqrt(1 - ρ^2) * mg / 8
Sg = [1. 0. 0. 0. 0.]
Sd = [0. 0. 0. 0. 0.]
Sb = [0. 0. 0. 0. 2.135]
Ss = [0. 0. 0. 0. 0.]
proc = ContStochProcess(A, C)
econ = Economy(β, Sg, Sd, Sb, Ss, proc)

T = 50
path = compute_paths(econ, T)
```

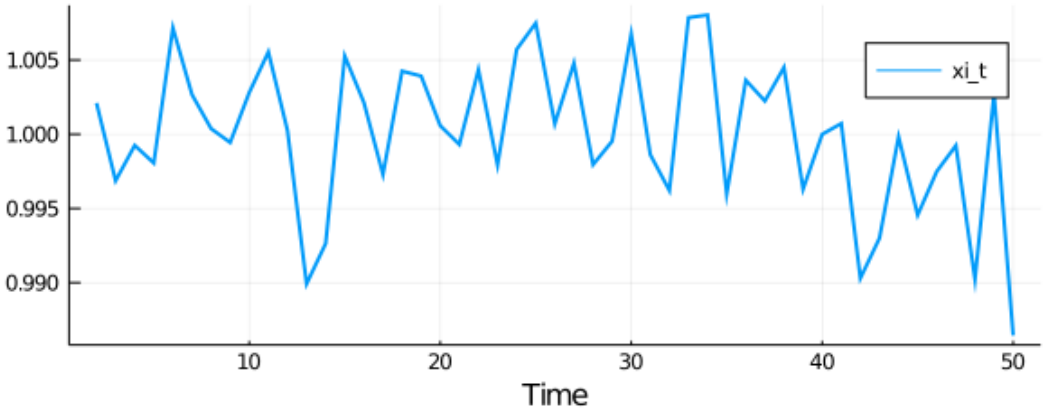
In [9]:
```
gen_fig_1(path)
```

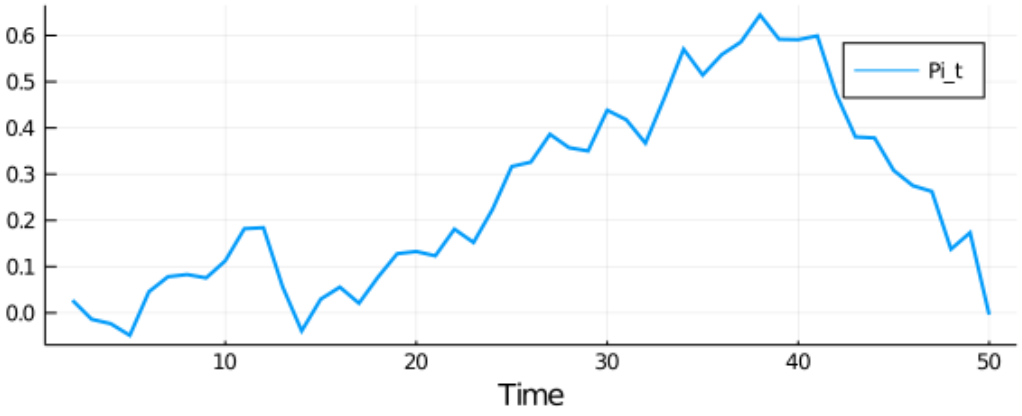
Out[9]:



In [10]:
```
gen_fig_2(path)
```

Out[10]:


1.005
1.000
0.995
0.990
10
20
30
40
50
Time
xi_t


0.6
0.5
0.4
0.3
0.2
0.1
0.0
10
20
30
40
50
Time
Pi_t

Chapter 62

Optimal Taxation with State-Contingent Debt

62.1 Contents

62.2 Overview

This lecture describes a celebrated model of optimal fiscal policy by Robert E. Lucas, Jr., and Nancy Stokey [72].

The model revisits classic issues about how to pay for a war.

Here a *war* means a more or less temporary surge in an exogenous government expenditure process.

The model features

- a government that must finance an exogenous stream of government expenditures with either
  - a flat rate tax on labor, or
  - purchases and sales from a full array of Arrow state-contingent securities
- a representative household that values consumption and leisure
- a linear production function mapping labor into a single good
- a Ramsey planner who at time $t = 0$ chooses a plan for taxes and trades of Arrow securities for all $t \geq 0$

After first presenting the model in a space of sequences, we shall represent it recursively in terms of two Bellman equations formulated along lines that we encountered in Dynamic Stackelberg models.

As in Dynamic Stackelberg models, to apply dynamic programming we shall define the state vector artfully.

In particular, we shall include forward-looking variables that summarize optimal responses of private agents to a Ramsey plan.

See Optimal taxation for an analysis within a linear-quadratic setting.

62.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
        using QuantEcon, NLsolve, NLopt, Interpolations
```

62.3 A Competitive Equilibrium with Distorting Taxes

For $t \geq 0$, a history $s^t = [s_t, s_{t-1}, \ldots, s_0]$ of an exogenous state s_t has joint probability density $\pi_t(s^t)$.

We begin by assuming that government purchases $g_t(s^t)$ at time $t \geq 0$ depend on s^t.

Let $c_t(s^t)$, $\ell_t(s^t)$, and $n_t(s^t)$ denote consumption, leisure, and labor supply, respectively, at history s^t and date t.

A representative household is endowed with one unit of time that can be divided between leisure ℓ_t and labor n_t:

$$n_t(s^t) + \ell_t(s^t) = 1 \tag{1}$$

Output equals $n_t(s^t)$ and can be divided between $c_t(s^t)$ and $g_t(s^t)$

$$c_t(s^t) + g_t(s^t) = n_t(s^t) \tag{2}$$

A representative household's preferences over $\{c_t(s^t), \ell_t(s^t)\}_{t=0}^{\infty}$ are ordered by

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t) u[c_t(s^t), \ell_t(s^t)] \tag{3}$$

where the utility function u is increasing, strictly concave, and three times continuously differentiable in both arguments.

The technology pins down a pre-tax wage rate to unity for all t, s^t.

The government imposes a flat-rate tax $\tau_t(s^t)$ on labor income at time t, history s^t.

There are complete markets in one-period Arrow securities.

One unit of an Arrow security issued at time t at history s^t and promising to pay one unit of time $t+1$ consumption in state s_{t+1} costs $p_{t+1}(s_{t+1}|s^t)$.

The government issues one-period Arrow securities each period.

The government has a sequence of budget constraints whose time $t \geq 0$ component is

$$g_t(s^t) = \tau_t(s^t) n_t(s^t) + \sum_{s_{t+1}} p_{t+1}(s_{t+1}|s^t) b_{t+1}(s_{t+1}|s^t) - b_t(s_t|s^{t-1}) \tag{4}$$

where

- $p_{t+1}(s_{t+1}|s^t)$ is a competitive equilibrium price of one unit of consumption at date $t+1$ in state s_{t+1} at date t and history s^t
- $b_t(s_t|s^{t-1})$ is government debt falling due at time t, history s^t.

Government debt $b_0(s_0)$ is an exogenous initial condition.

The representative household has a sequence of budget constraints whose time $t \geq 0$ component is

$$c_t(s^t) + \sum_{s_{t+1}} p_t(s_{t+1}|s^t) b_{t+1}(s_{t+1}|s^t) = [1 - \tau_t(s^t)]\, n_t(s^t) + b_t(s_t|s^{t-1}) \quad \forall t \geq 0. \tag{5}$$

A **government policy** is an exogenous sequence $\{g(s_t)\}_{t=0}^{\infty}$, a tax rate sequence $\{\tau_t(s^t)\}_{t=0}^{\infty}$, and a government debt sequence $\{b_{t+1}(s^{t+1})\}_{t=0}^{\infty}$.

A **feasible allocation** is a consumption-labor supply plan $\{c_t(s^t), n_t(s^t)\}_{t=0}^{\infty}$ that satisfies (2) at all t, s^t.

A **price system** is a sequence of Arrow security prices $\{p_{t+1}(s_{t+1}|s^t)\}_{t=0}^{\infty}$.

The household faces the price system as a price-taker and takes the government policy as given.

The household chooses $\{c_t(s^t), \ell_t(s^t)\}_{t=0}^{\infty}$ to maximize (3) subject to (5) and (1) for all t, s^t.

A **competitive equilibrium with distorting taxes** is a feasible allocation, a price system, and a government policy such that

- Given the price system and the government policy, the allocation solves the household's optimization problem.
- Given the allocation, government policy, and price system, the government's budget constraint is satisfied for all t, s^t.

Note: There are many competitive equilibria with distorting taxes.

They are indexed by different government policies.

The **Ramsey problem** or **optimal taxation problem** is to choose a competitive equilibrium with distorting taxes that maximizes (3).

62.3.1 Arrow-Debreu Version of Price System

We find it convenient sometimes to work with the Arrow-Debreu price system that is implied by a sequence of Arrow securities prices.

Let $q_t^0(s^t)$ be the price at time 0, measured in time 0 consumption goods, of one unit of consumption at time t, history s^t.

The following recursion relates Arrow-Debreu prices $\{q_t^0(s^t)\}_{t=0}^{\infty}$ to Arrow securities prices $\{p_{t+1}(s_{t+1}|s^t)\}_{t=0}^{\infty}$

$$q_{t+1}^0(s^{t+1}) = p_{t+1}(s_{t+1}|s^t) q_t^0(s^t) \quad s.t. \quad q_0^0(s^0) = 1 \tag{6}$$

Arrow-Debreu prices are useful when we want to compress a sequence of budget constraints into a single intertemporal budget constraint, as we shall find it convenient to do below.

62.3.2 Primal Approach

We apply a popular approach to solving a Ramsey problem, called the *primal approach*.

The idea is to use first-order conditions for household optimization to eliminate taxes and prices in favor of quantities, then pose an optimization problem cast entirely in terms of quantities.

After Ramsey quantities have been found, taxes and prices can then be unwound from the allocation.

The primal approach uses four steps:

1. Obtain first-order conditions of the household's problem and solve them for $\{q_t^0(s^t), \tau_t(s^t)\}_{t=0}^\infty$ as functions of the allocation $\{c_t(s^t), n_t(s^t)\}_{t=0}^\infty$.

2. Substitute these expressions for taxes and prices in terms of the allocation into the household's present-value budget constraint.

   - This intertemporal constraint involves only the allocation and is regarded as an *implementability constraint*.

3. Find the allocation that maximizes the utility of the representative household (3) subject to the feasibility constraints (1) and (2) and the implementability condition derived in step 2.

   - This optimal allocation is called the **Ramsey allocation**.

4. Use the Ramsey allocation together with the formulas from step 1 to find taxes and prices.

62.3.3 The Implementability Constraint

By sequential substitution of one one-period budget constraint (5) into another, we can obtain the household's present-value budget constraint:

$$\sum_{t=0}^\infty \sum_{s^t} q_t^0(s^t) c_t(s^t) = \sum_{t=0}^\infty \sum_{s^t} q_t^0(s^t)[1-\tau_t(s^t)] n_t(s^t) + b_0 \tag{7}$$

$\{q_t^0(s^t)\}_{t=1}^\infty$ can be interpreted as a time 0 Arrow-Debreu price system.

To approach the Ramsey problem, we study the household's optimization problem.

First-order conditions for the household's problem for $\ell_t(s^t)$ and $b_t(s_{t+1}|s^t)$, respectively, imply

$$(1-\tau_t(s^t)) = \frac{u_l(s^t)}{u_c(s^t)} \tag{8}$$

and

$$p_{t+1}(s_{t+1}|s^t) = \beta\pi(s_{t+1}|s^t)\left(\frac{u_c(s^{t+1})}{u_c(s^t)}\right) \tag{9}$$

where $\pi(s_{t+1}|s^t)$ is the probability distribution of s_{t+1} conditional on history s^t.

Equation (9) implies that the Arrow-Debreu price system satisfies

$$q_t^0(s^t) = \beta^t \pi_t(s^t)\frac{u_c(s^t)}{u_c(s^0)} \tag{10}$$

Using the first-order conditions (8) and (9) to eliminate taxes and prices from (7), we derive the *implementability condition*

$$\sum_{t=0}^{\infty}\sum_{s^t}\beta^t\pi_t(s^t)[u_c(s^t)c_t(s^t) - u_\ell(s^t)n_t(s^t)] - u_c(s^0)b_0 = 0. \tag{11}$$

The **Ramsey problem** is to choose a feasible allocation that maximizes

$$\sum_{t=0}^{\infty}\sum_{s^t}\beta^t\pi_t(s^t)u[c_t(s^t), 1-n_t(s^t)] \tag{12}$$

subject to (11).

62.3.4 Solution Details

First define a "pseudo utility function"

$$V\left[c_t(s^t), n_t(s^t), \Phi\right] = u[c_t(s^t), 1-n_t(s^t)] + \Phi\left[u_c(s^t)c_t(s^t) - u_\ell(s^t)n_t(s^t)\right] \tag{13}$$

where Φ is a Lagrange multiplier on the implementability condition (7).

Next form the Lagrangian

$$J = \sum_{t=0}^{\infty}\sum_{s^t}\beta^t\pi_t(s^t)\Big\{V[c_t(s^t), n_t(s^t), \Phi] + \theta_t(s^t)\Big[n_t(s^t) - c_t(s^t) - g_t(s_t)\Big]\Big\} - \Phi u_c(0)b_0 \tag{14}$$

where $\{\theta_t(s^t); \forall s^t\}_{t\geq 0}$ is a sequence of Lagrange multipliers on the feasible conditions (2).

Given an initial government debt b_0, we want to maximize J with respect to $\{c_t(s^t), n_t(s^t); \forall s^t\}_{t\geq 0}$ and to minimize with respect to $\{\theta(s^t); \forall s^t\}_{t\geq 0}$.

The first-order conditions for the Ramsey problem for periods $t \geq 1$ and $t = 0$, respectively, are

$$\begin{aligned} c_t(s^t)&: (1+\Phi)u_c(s^t) + \Phi\left[u_{cc}(s^t)c_t(s^t) - u_{\ell c}(s^t)n_t(s^t)\right] - \theta_t(s^t) = 0, \quad t \geq 1 \\ n_t(s^t)&: -(1+\Phi)u_\ell(s^t) - \Phi\left[u_{c\ell}(s^t)c_t(s^t) - u_{\ell\ell}(s^t)n_t(s^t)\right] + \theta_t(s^t) = 0, \quad t \geq 1 \end{aligned} \tag{15}$$

and

$$\begin{aligned} c_0(s^0,b_0)\colon\ & (1+\Phi)u_c(s^0,b_0)+\Phi\left[u_{cc}(s^0,b_0)c_0(s^0,b_0)-u_{\ell c}(s^0,b_0)n_0(s^0,b_0)\right]-\theta_0(s^0,b_0)\\ & -\Phi u_{cc}(s^0,b_0)b_0=0\\ n_0(s^0,b_0)\colon\ & -(1+\Phi)u_\ell(s^0,b_0)-\Phi\left[u_{c\ell}(s^0,b_0)c_0(s^0,b_0)-u_{\ell\ell}(s^0,b_0)n_0(s^0,b_0)\right]+\theta_0(s^0,b_0)\\ & +\Phi u_{c\ell}(s^0,b_0)b_0=0 \end{aligned} \tag{16}$$

Please note how these first-order conditions differ between $t=0$ and $t\geq 1$.

It is instructive to use first-order conditions (15) for $t\geq 1$ to eliminate the multipliers $\theta_t(s^t)$.

For convenience, we suppress the time subscript and the index s^t and obtain

$$\begin{aligned} &(1+\Phi)u_c(c,1-c-g)+\Phi\left[cu_{cc}(c,1-c-g)-(c+g)u_{\ell c}(c,1-c-g)\right]\\ &\quad=(1+\Phi)u_\ell(c,1-c-g)+\Phi\left[cu_{c\ell}(c,1-c-g)-(c+g)u_{\ell\ell}(c,1-c-g)\right] \end{aligned} \tag{17}$$

where we have imposed conditions (1) and (2).

Equation (17) is one equation that can be solved to express the unknown c as a function of the exogenous variable g.

We also know that time $t=0$ quantities c_0 and n_0 satisfy

$$\begin{aligned} &(1+\Phi)u_c(c,1-c-g)+\Phi\left[cu_{cc}(c,1-c-g)-(c+g)u_{\ell c}(c,1-c-g)\right]\\ &\quad=(1+\Phi)u_\ell(c,1-c-g)+\Phi\left[cu_{c\ell}(c,1-c-g)-(c+g)u_{\ell\ell}(c,1-c-g)\right]+\Phi(u_{cc}-u_{c,\ell})b_0 \end{aligned} \tag{18}$$

Notice that a counterpart to b_0 does *not* appear in (17), so c does not depend on it for $t\geq 1$.

But things are different for time $t=0$.

An analogous argument for the $t=0$ equations (16) leads to one equation that can be solved for c_0 as a function of the pair $(g(s_0),b_0)$.

These outcomes mean that the following statement would be true even when government purchases are history-dependent functions $g_t(s^t)$ of the history of s^t.

Proposition: If government purchases are equal after two histories s^t and $\tilde{s}^\tau$ for $t,\tau\geq 0$, i.e., if

$$g_t(s^t)=g^\tau(\tilde{s}^\tau)=g$$

then it follows from (17) that the Ramsey choices of consumption and leisure, $(c_t(s^t),\ell_t(s^t))$ and $(c_j(\tilde{s}^\tau),\ell_j(\tilde{s}^\tau))$, are identical.

The proposition asserts that the optimal allocation is a function of the currently realized quantity of government purchases g only and does *not* depend on the specific history that preceded that realization of g.

62.3.5 The Ramsey Allocation for a Given Φ

Temporarily take Φ as given.

We shall compute $c_0(s^0,b_0)$ and $n_0(s^0,b_0)$ from the first-order conditions (16).

Evidently, for $t \geq 1$, c and n depend on the time t realization of g only.

But for $t = 0$, c and n depend on both g_0 and the government's initial debt b_0.

Thus, while b_0 influences c_0 and n_0, there appears no analogous variable b_t that influences c_t and n_t for $t \geq 1$.

The absence of b_t as a determinant of the Ramsey allocation for $t \geq 1$ and its presence for $t = 0$ is a symptom of the *time-inconsistency* of a Ramsey plan.

Φ has to take a value that assures that the household and the government's budget constraints are both satisfied at a candidate Ramsey allocation and price system associated with that Φ.

62.3.6 Further Specialization

At this point, it is useful to specialize the model in the following ways.

We assume that s is governed by a finite state Markov chain with states $s \in [1, \ldots, S]$ and transition matrix Π, where

$$\Pi(s'|s) = \text{Prob}(s_{t+1} = s'|s_t = s)$$

Also, assume that government purchases g are an exact time-invariant function $g(s)$ of s.

We maintain these assumptions throughout the remainder of this lecture.

62.3.7 Determining Φ

We complete the Ramsey plan by computing the Lagrange multiplier Φ on the implementability constraint (11).

Government budget balance restricts Φ via the following line of reasoning.

The household's first-order conditions imply

$$(1 - \tau_t(s^t)) = \frac{u_l(s^t)}{u_c(s^t)} \tag{19}$$

and the implied one-period Arrow securities prices

$$p_{t+1}(s_{t+1}|s^t) = \beta \Pi(s_{t+1}|s_t) \frac{u_c(s^{t+1})}{u_c(s^t)} \tag{20}$$

Substituting from (19), (20), and the feasibility condition (2) into the recursive version (5) of the household budget constraint gives

$$\begin{aligned} u_c(s^t)[n_t(s^t) - g_t(s^t)] + \beta \sum_{s_{t+1}} \Pi(s_{t+1}|s_t) u_c(s^{t+1}) b_{t+1}(s_{t+1}|s^t) = \\ u_l(s^t) n_t(s^t) + u_c(s^t) b_t(s_t|s^{t-1}) \end{aligned} \tag{21}$$

Define $x_t(s^t) = u_c(s^t) b_t(s_t|s^{t-1})$.

Notice that $x_t(s^t)$ appears on the right side of (21) while β times the conditional expectation of $x_{t+1}(s^{t+1})$ appears on the left side.

Hence the equation shares much of the structure of a simple asset pricing equation with x_t being analogous to the price of the asset at time t.

We learned earlier that for a Ramsey allocation $c_t(s^t), n_t(s^t)$ and $b_t(s_t|s^{t-1})$, and therefore also $x_t(s^t)$, are each functions of s_t only, being independent of the history s^{t-1} for $t \geq 1$.

That means that we can express equation (21) as

$$u_c(s)[n(s) - g(s)] + \beta \sum_{s'} \Pi(s'|s)x'(s') = u_l(s)n(s) + x(s) \tag{22}$$

where s' denotes a next period value of s and $x'(s')$ denotes a next period value of x.

Equation (22) is easy to solve for $x(s)$ for $s = 1, \ldots, S$.

If we let $\vec{n}, \vec{g}, \vec{x}$ denote $S \times 1$ vectors whose ith elements are the respective n, g, and x values when $s = i$, and let Π be the transition matrix for the Markov state s, then we can express (22) as the matrix equation

$$\vec{u}_c(\vec{n} - \vec{g}) + \beta\Pi\vec{x} = \vec{u}_l\vec{n} + \vec{x} \tag{23}$$

This is a system of S linear equations in the $S \times 1$ vector x, whose solution is

$$\vec{x} = (I - \beta\Pi)^{-1}[\vec{u}_c(\vec{n} - \vec{g}) - \vec{u}_l\vec{n}] \tag{24}$$

In these equations, by $\vec{u}_c\vec{n}$, for example, we mean element-by-element multiplication of the two vectors.

After solving for $\vec{x}$, we can find $b(s_t|s^{t-1})$ in Markov state $s_t = s$ from $b(s) = \frac{x(s)}{u_c(s)}$ or the matrix equation

$$\vec{b} = \frac{\vec{x}}{\vec{u}_c} \tag{25}$$

where division here means element-by-element division of the respective components of the $S \times 1$ vectors $\vec{x}$ and $\vec{u}_c$.

Here is a computational algorithm:

1. Start with a guess for the value for Φ, then use the first-order conditions and the feasibility conditions to compute $c(s_t), n(s_t)$ for $s \in [1, \ldots, S]$ and $c_0(s_0, b_0)$ and $n_0(s_0, b_0)$, given Φ

- these are $2(S+1)$ equations in $2(S+1)$ unknowns

1. Solve the S equations (24) for the S elements of $\vec{x}$

- these depend on Φ

1. Find a Φ that satisfies

$$u_{c,0}b_0 = u_{c,0}(n_0 - g_0) - u_{l,0}n_0 + \beta \sum_{s=1}^{S} \Pi(s|s_0)x(s) \tag{26}$$

by gradually raising Φ if the left side of (26) exceeds the right side and lowering Φ if the left side is less than the right side.

1. After computing a Ramsey allocation, recover the flat tax rate on labor from (8) and the implied one-period Arrow securities prices from (9).

In summary, when g_t is a time invariant function of a Markov state s_t, a Ramsey plan can be constructed by solving $3S + 3$ equations in S components each of $\vec{c}$, $\vec{n}$, and $\vec{x}$ together with n_0, c_0, and Φ.

62.3.8 Time Inconsistency

Let $\{\tau_t(s^t)\}_{t=0}^{\infty}, \{b_{t+1}(s_{t+1}|s^t)\}_{t=0}^{\infty}$ be a time 0, state s_0 Ramsey plan.

Then $\{\tau_j(s^j)\}_{j=t}^{\infty}, \{b_{j+1}(s_{j+1}|s^j)\}_{j=t}^{\infty}$ is a time t, history s^t continuation of a time 0, state s_0 Ramsey plan.

A time t, history s^t Ramsey plan is a Ramsey plan that starts from initial conditions $s^t, b_t(s_t|s^{t-1})$.

A time t, history s^t continuation of a time 0, state 0 Ramsey plan is *not* a time t, history s^t Ramsey plan.

The means that a Ramsey plan is *not time consistent*.

Another way to say the same thing is that a Ramsey plan is *time inconsistent*.

The reason is that a continuation Ramsey plan takes $u_{ct}b_t(s_t|s^{t-1})$ as given, not $b_t(s_t|s^{t-1})$.

We shall discuss this more below.

62.3.9 Specification with CRRA Utility

In our calculations below and in a subsequent lecture based on an extension of the Lucas-Stokey model by Aiyagari, Marcet, Sargent, and Seppälä (2002) [2], we shall modify the one-period utility function assumed above.

(We adopted the preceding utility specification because it was the one used in the original [72] paper)

We will modify their specification by instead assuming that the representative agent has utility function

$$u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma}$$

where $\sigma > 0$, $\gamma > 0$.

We continue to assume that

$$c_t + g_t = n_t$$

We eliminate leisure from the model.

We also eliminate Lucas and Stokey's restriction that $\ell_t + n_t \leq 1$.

We replace these two things with the assumption that labor $n_t \in [0, +\infty]$.

With these adjustments, the analysis of Lucas and Stokey prevails once we make the following replacements

$$
\begin{aligned}
u_\ell(c,\ell) &\sim -u_n(c,n) \\
u_c(c,\ell) &\sim u_c(c,n) \\
u_{\ell,\ell}(c,\ell) &\sim u_{nn}(c,n) \\
u_{c,c}(c,\ell) &\sim u_{c,c}(c,n) \\
u_{c,\ell}(c,\ell) &\sim 0
\end{aligned}
$$

With these understandings, equations (17) and (18) simplify in the case of the CRRA utility function.

They become

$$
(1+\Phi)[u_c(c) + u_n(c+g)] + \Phi[cu_{cc}(c) + (c+g)u_{nn}(c+g)] = 0 \tag{27}
$$

and

$$
(1+\Phi)[u_c(c_0) + u_n(c_0+g_0)] + \Phi[c_0u_{cc}(c_0) + (c_0+g_0)u_{nn}(c_0+g_0)] - \Phi u_{cc}(c_0)b_0 = 0 \tag{28}
$$

In equation (27), it is understood that c and g are each functions of the Markov state s.

In addition, the time $t = 0$ budget constraint is satisfied at c_0 and initial government debt b_0:

$$
b_0 + g_0 = \tau_0(c_0 + g_0) + \frac{\bar{b}}{R_0} \tag{29}
$$

where R_0 is the gross interest rate for the Markov state s_0 that is assumed to prevail at time $t = 0$ and τ_0 is the time $t = 0$ tax rate.

In equation (29), it is understood that

$$
\begin{aligned}
\tau_0 &= 1 - \frac{u_{l,0}}{u_{c,0}} \\
R_0 &= \beta \sum_{s=1}^{S} \Pi(s|s_0) \frac{u_c(s)}{u_{c,0}}
\end{aligned}
$$

62.3.10 Sequence Implementation

The above steps are implemented in a type called SequentialAllocation

```
In [3]: using QuantEcon, NLsolve, NLopt, LinearAlgebra, Interpolations
        import QuantEcon: simulate
```

```
  mutable struct Model{TF <: AbstractFloat,
                       TM <: AbstractMatrix{TF},
                       TV <: AbstractVector{TF}}
      β::TF
      Π::TM
      G::TV
      Θ::TV
      transfers::Bool
      U::Function
      Uc::Function
      Ucc::Function
      Un::Function
      Unn::Function
      n_less_than_one::Bool
  end

  struct SequentialAllocation{TP <: Model,
                              TI <: Integer,
                              TV <: AbstractVector}
      model::TP
      mc::MarkovChain
      S::TI
      cFB::TV
      nFB::TV
      ΞFB::TV
      zFB::TV
  end

function SequentialAllocation(model)
    β, Π, G, Θ = model.β, model.Π, model.G, model.Θ
    mc = MarkovChain(Π)
    S = size(Π, 1)   # Number of states
    # now find the first best allocation
    cFB, nFB, ΞFB, zFB = find_first_best(model, S, 1)

    return SequentialAllocation(model, mc, S, cFB, nFB, ΞFB, zFB)
end

function find_first_best(model, S, version)
    if version != 1 && version != 2
        throw(ArgumentError("version must be 1 or 2"))
    end
    β, Θ, Uc, Un, G, Π =
        model.β, model.Θ, model.Uc, model.Un, model.G, model.Π
    function res!(out, z)
        c = z[1:S]
        n = z[S+1:end]
        out[1:S] = Θ .* Uc(c, n) + Un(c, n)
        out[S+1:end] = Θ .* n - c - G
    end
    res = nlsolve(res!, 0.5 * ones(2 * S))

    if converged(res) == false
        error("Could not find first best")
    end

    if version == 1
```

```
            cFB = res.zero[1:S]
            nFB = res.zero[S+1:end]
            ΞFB = Uc(cFB, nFB)          # Multiplier on the resource constraint
            zFB = vcat(cFB, nFB, ΞFB)
            return cFB, nFB, ΞFB, zFB
        elseif version == 2
            cFB = res.zero[1:S]
            nFB = res.zero[S+1:end]
            IFB = Uc(cFB, nFB) .* cFB + Un(cFB, nFB) .* nFB
            xFB = \(I - β * Π, IFB)
            zFB = [vcat(cFB[s], xFB[s], xFB) for s in 1:S]
            return cFB, nFB, IFB, xFB, zFB
        end
    end

    function time1_allocation(pas::SequentialAllocation, μ)
        model, S = pas.model, pas.S
        Θ, β, Π, G, Uc, Ucc, Un, Unn =
            model.Θ, model.β, model.Π, model.G,
            model.Uc, model.Ucc, model.Un, model.Unn
        function FOC!(out, z)
            c = z[1:S]
            n = z[S+1:2S]
            Ξ = z[2S+1:end]
           out[1:S] = Uc(c, n) .- μ * (Ucc(c, n) .* c .+ Uc(c, n)) .- Ξ # FOC c
           out[S+1:2S] = Un(c, n) .- μ * (Unn(c, n) .* n .+ Un(c, n)) + Θ .* Ξ
↪# FOC n
            out[2S+1:end] = Θ .* n - c - G # Resource constraint
            return out
        end
        # Find the root of the FOC
        res = nlsolve(FOC!, pas.zFB)
        if res.f_converged == false
            error("Could not find LS allocation.")
        end
        z = res.zero
        c, n, Ξ = z[1:S], z[S+1:2S], z[2S+1:end]
        # Now compute x
        Inv  = Uc(c, n) .* c +  Un(c, n) .* n
        x = \(I - β * model.Π, Inv)
        return c, n, x, Ξ
    end

    function time0_allocation(pas::SequentialAllocation, B_, s_0)
        model = pas.model
        Π, Θ, G, β = model.Π, model.Θ, model.G, model.β
        Uc, Ucc, Un, Unn =
            model.Uc, model.Ucc, model.Un, model.Unn

        # First order conditions of planner's problem
        function FOC!(out, z)
            μ, c, n, Ξ = z[1], z[2], z[3], z[4]
            xprime = time1_allocation(pas, μ)[3]
            out .= vcat(
                Uc(c, n) .* (c - B_) .+ Un(c, n) .* n + β * dot(Π[s_0, :],
↪xprime),
                Uc(c, n) .- μ * (Ucc(c, n) .* (c - B_) + Uc(c, n)) - Ξ,
                Un(c, n) .- μ * (Unn(c, n) .* n .+ Un(c, n)) + Θ[s_0] .* Ξ,
```

```
            (Θ .* n .- c - G)[s_0]
            )
    end

    # Find root
    res = nlsolve(FOC!, [0.0, pas.cFB[s_0], pas.nFB[s_0], pas.ΞFB[s_0]])
    if res.f_converged == false
        error("Could not find time 0 LS allocation.")
    end
    return (res.zero...,)
end

function time1_value(pas::SequentialAllocation, μ)
    model = pas.model
    c, n, x, Ξ = time1_allocation(pas, μ)
    U_val = model.U.(c, n)
    V = \(I - model.β*model.Π, U_val)
    return c, n, x, V
end

function T(model, c, n)
    Uc, Un = model.Uc.(c, n), model.Un.(c, n)
    return 1 .+ Un ./ (model.Θ .* Uc)
end

function simulate(pas::SequentialAllocation, B_, s_0, T, sHist = nothing)

    model = pas.model
    Π, β, Uc = model.Π, model.β, model.Uc

    if isnothing(sHist)
        sHist = QuantEcon.simulate(pas.mc, T, init=s_0)
    end
    cHist = zeros(T)
    nHist = similar(cHist)
    Bhist = similar(cHist)
    THist = similar(cHist)
    μHist = similar(cHist)
    RHist = zeros(T-1)
    # time 0
    μ, cHist[1], nHist[1], _  = time0_allocation(pas, B_, s_0)
    THist[1] = T(pas.model, cHist[1], nHist[1])[s_0]
    Bhist[1] = B_
    μHist[1] = μ
    # time 1 onward
    for t in 2:T
        c, n, x, Ξ = time1_allocation(pas,μ)
        u_c = Uc(c,n)
        s = sHist[t]
        THist[t] = T(pas.model, c, n)[s]
        Eu_c = dot(Π[sHist[t-1],:], u_c)
        cHist[t], nHist[t], Bhist[t] = c[s], n[s], x[s] / u_c[s]
        RHist[t-1] = Uc(cHist[t-1], nHist[t-1]) / (β * Eu_c)
        μHist[t] = μ
    end
    return cHist, nHist, Bhist, THist, sHist, μHist, RHist
end
```

```
  mutable struct BellmanEquation{TP <: Model,
                                 TI <: Integer,
                                 TV <: AbstractVector,
                                 TM <: AbstractMatrix{TV},
                                 TVV <: AbstractVector{TV}}
      model::TP
      S::TI
      xbar::TV
      time_0::Bool
      z0::TM
      cFB::TV
      nFB::TV
      xFB::TV
      zFB::TVV
  end

function BellmanEquation(model, xgrid, policies0)
    S = size(model.Π, 1) # Number of states
    xbar = collect(extrema(xgrid))
    time_0 = false
    cf, nf, xprimef = policies0
    z0 = [vcat(cf[s](x), nf[s](x), [xprimef[s, sprime](x)
             for sprime in 1:S])
             for x in xgrid, s in 1:S]
    cFB, nFB, IFB, xFB, zFB = find_first_best(model, S, 2)
    return BellmanEquation(model, S, xbar, time_0, z0, cFB, nFB, xFB, zFB)
end

function get_policies_time1(T, i_x, x, s, Vf)
    model, S = T.model, T.S
    β, Θ, G, Π = model.β, model.Θ, model.G, model.Π
    U, Uc, Un = model.U, model.Uc, model.Un

    function objf(z, grad)
        c, xprime = z[1], z[2:end]
        n = c + G[s]
        Vprime = [Vf[sprime](xprime[sprime]) for sprime in 1:S]
        return -(U(c, n) + β * dot(Π[s, :], Vprime))
    end
    function cons(z, grad)
        c, xprime = z[1], z[2:end]
        n = c+G[s]
        return x - Uc(c, n) * c - Un(c, n) * n - β * dot(Π[s, :], xprime)
    end
    lb = vcat(0, T.xbar[1] * ones(S))
    ub = vcat(1 - G[s], T.xbar[2] * ones(S))
    opt = Opt(:LN_COBYLA, length(T.z0[i_x, s])-1)
    min_objective!(opt, objf)
    equality_constraint!(opt, cons)
    lower_bounds!(opt, lb)
    upper_bounds!(opt, ub)
    maxeval!(opt, 300)
    maxtime!(opt, 10)
    init = vcat(T.z0[i_x, s][1], T.z0[i_x, s][3:end])
    for (i, val) in enumerate(init)
        if val > ub[i]
            init[i] = ub[i]
        elseif val < lb[i]
```

```
            init[i] = lb[i]
        end
    end
    (minf, minx, ret) = optimize(opt, init)
    T.z0[i_x, s] = vcat(minx[1], minx[1] + G[s], minx[2:end])
    return vcat(-minf, T.z0[i_x, s])
end

function get_policies_time0(T, B_, s0, Vf)
    model, S = T.model, T.S
    β, Θ, G, Π = model.β, model.Θ, model.G, model.Π
    U, Uc, Un = model.U, model.Uc, model.Un
    function objf(z, grad)
        c, xprime = z[1], z[2:end]
        n = c + G[s0]
        Vprime = [Vf[sprime](xprime[sprime]) for sprime in 1:S]
        return -(U(c, n) + β * dot(Π[s0, :], Vprime))
    end
    function cons(z, grad)
        c, xprime = z[1], z[2:end]
        n = c + G[s0]
      return -Uc(c, n) * (c - B_) - Un(c, n) * n - β * dot(Π[s0, :], xprime)
    end
    lb = vcat(0, T.xbar[1] * ones(S))
    ub = vcat(1-G[s0], T.xbar[2] * ones(S))
    opt = Opt(:LN_COBYLA, length(T.zFB[s0])-1)
    min_objective!(opt, objf)
    equality_constraint!(opt, cons)
    lower_bounds!(opt, lb)
    upper_bounds!(opt, ub)
    maxeval!(opt, 300)
    maxtime!(opt, 10)
    init = vcat(T.zFB[s0][1], T.zFB[s0][3:end])
    for (i, val) in enumerate(init)
        if val > ub[i]
            init[i] = ub[i]
        elseif val < lb[i]
            init[i] = lb[i]
        end
    end
    (minf, minx, ret) = optimize(opt, init)
    return vcat(-minf, vcat(minx[1], minx[1]+G[s0], minx[2:end]))
end
```

```
Out[3]: get_policies_time0 (generic function with 1 method)
```

62.4 Recursive Formulation of the Ramsey problem

$x_t(s^t) = u_c(s^t) b_t(s_t|s^{t-1})$ in equation (21) appears to be a purely "forward-looking" variable.

But $x_t(s^t)$ is a also a natural candidate for a state variable in a recursive formulation of the Ramsey problem.

62.4.1 Intertemporal Delegation

To express a Ramsey plan recursively, we imagine that a time 0 Ramsey planner is followed by a sequence of continuation Ramsey planners at times $t = 1, 2, ...$

A "continuation Ramsey planner" has a different objective function and faces different constraints than a Ramsey planner.

A key step in representing a Ramsey plan recursively is to regard the marginal utility scaled government debts $x_t(s^t) = u_c(s^t)b_t(s_t|s^{t-1})$ as predetermined quantities that continuation Ramsey planners at times $t \geq 1$ are obligated to attain.

Continuation Ramsey planners do this by choosing continuation policies that induce the representative household to make choices that imply that $u_c(s^t)b_t(s_t|s^{t-1}) = x_t(s^t)$.

A time $t \geq 1$ continuation Ramsey planner delivers x_t by choosing a suitable n_t, c_t pair and a list of s_{t+1}-contingent continuation quantities x_{t+1} to bequeath to a time $t+1$ continuation Ramsey planner.

A time $t \geq 1$ continuation Ramsey planner faces x_t, s_t as state variables.

But the time 0 Ramsey planner faces b_0, not x_0, as a state variable.

Furthermore, the Ramsey planner cares about $(c_0(s_0), \ell_0(s_0))$, while continuation Ramsey planners do not.

The time 0 Ramsey planner hands x_1 as a function of s_1 to a time 1 continuation Ramsey planner.

These lines of delegated authorities and responsibilities across time express the continuation Ramsey planners' obligations to implement their parts of the original Ramsey plan, designed once-and-for-all at time 0.

62.4.2 Two Bellman Equations

After s_t has been realized at time $t \geq 1$, the state variables confronting the time t **continuation Ramsey planner** are (x_t, s_t).

- Let $V(x, s)$ be the value of a **continuation Ramsey plan** at $x_t = x, s_t = s$ for $t \geq 1$.
- Let $W(b, s)$ be the value of a **Ramsey plan** at time 0 at $b_0 = b$ and $s_0 = s$.

We work backwards by presenting a Bellman equation for $V(x, s)$ first, then a Bellman equation for $W(b, s)$.

62.4.3 The Continuation Ramsey Problem

The Bellman equation for a time $t \geq 1$ continuation Ramsey planner is

$$V(x, s) = \max_{n, \{x'(s')\}} u(n - g(s), 1 - n) + \beta \sum_{s' \in S} \Pi(s'|s) V(x', s') \tag{30}$$

where maximization over n and the S elements of $x'(s')$ is subject to the single implementability constraint for $t \geq 1$

$$x = u_c(n - g(s)) - u_l n + \beta \sum_{s' \in S} \Pi(s'|s) x'(s') \tag{31}$$

Here u_c and u_l are today's values of the marginal utilities.

For each given value of x, s, the continuation Ramsey planner chooses n and an $x'(s')$ for each $s' \in S$.

Associated with a value function $V(x,s)$ that solves Bellman equation (30) are $S+1$ time-invariant policy functions

$$\begin{aligned} n_t &= f(x_t, s_t), \quad t \geq 1 \\ x_{t+1}(s_{t+1}) &= h(s_{t+1}; x_t, s_t),\ s_{t+1} \in S,\ t \geq 1 \end{aligned} \tag{32}$$

62.4.4 The Ramsey Problem

The Bellman equation for the time 0 Ramsey planner is

$$W(b_0, s_0) = \max_{n_0, \{x'(s_1)\}} u(n_0 - g_0, 1 - n_0) + \beta \sum_{s_1 \in S} \Pi(s_1|s_0) V(x'(s_1), s_1) \tag{33}$$

where maximization over n_0 and the S elements of $x'(s_1)$ is subject to the time 0 implementability constraint

$$u_{c,0} b_0 = u_{c,0}(n_0 - g_0) - u_{l,0} n_0 + \beta \sum_{s_1 \in S} \Pi(s_1|s_0) x'(s_1) \tag{34}$$

coming from restriction (26).

Associated with a value function $W(b_0, n_0)$ that solves Bellman equation (33) are $S+1$ time 0 policy functions

$$\begin{aligned} n_0 &= f_0(b_0, s_0) \\ x_1(s_1) &= h_0(s_1; b_0, s_0) \end{aligned} \tag{35}$$

Notice the appearance of state variables (b_0, s_0) in the time 0 policy functions for the Ramsey planner as compared to (x_t, s_t) in the policy functions (32) for the time $t \geq 1$ continuation Ramsey planners.

The value function $V(x_t, s_t)$ of the time t continuation Ramsey planner equals $E_t \sum_{\tau=t}^{\infty} \beta^{\tau - t} u(c_t, l_t)$, where the consumption and leisure processes are evaluated along the original time 0 Ramsey plan.

62.4.5 First-Order Conditions

Attach a Lagrange multiplier $\Phi_1(x,s)$ to constraint (31) and a Lagrange multiplier Φ_0 to constraint (26).

Time $t \geq 1$: the first-order conditions for the time $t \geq 1$ constrained maximization problem on the right side of the continuation Ramsey planner's Bellman equation (30) are

$$\beta \Pi(s'|s) V_x(x', s') - \beta \Pi(s'|s) \Phi_1 = 0 \tag{36}$$

for $x'(s')$ and

$$(1+\Phi_1)(u_c-u_l)+\Phi_1\left[n(u_{ll}-u_{lc})+(n-g(s))(u_{cc}-u_{lc})\right]=0 \tag{37}$$

for n.

Given Φ_1, equation (37) is one equation to be solved for n as a function of s (or of $g(s)$).

Equation (36) implies $V_x(x',s')=\Phi_1$, while an envelope condition is $V_x(x,s)=\Phi_1$, so it follows that

$$V_x(x',s')=V_x(x,s)=\Phi_1(x,s) \tag{38}$$

Time $t=0$: For the time 0 problem on the right side of the Ramsey planner's Bellman equation (33), first-order conditions are

$$V_x(x(s_1),s_1)=\Phi_0 \tag{39}$$

for $x(s_1),s_1\in S$, and

$$\begin{aligned}(1+\Phi_0)(u_{c,0}-u_{n,0})+\Phi_0\left[n_0(u_{ll,0}-u_{lc,0})+(n_0-g(s_0))(u_{cc,0}-u_{cl,0})\right]\\ -\Phi_0(u_{cc,0}-u_{cl,0})b_0=0\end{aligned} \tag{40}$$

Notice similarities and differences between the first-order conditions for $t\geq 1$ and for $t=0$.

An additional term is present in (40) except in three special cases

- $b_0=0$, or
- u_c is constant (i.e., preferences are quasi-linear in consumption), or
- initial government assets are sufficiently large to finance all government purchases with interest earnings from those assets, so that $\Phi_0=0$

Except in these special cases, the allocation and the labor tax rate as functions of s_t differ between dates $t=0$ and subsequent dates $t\geq 1$.

Naturally, the first-order conditions in this recursive formulation of the Ramsey problem agree with the first-order conditions derived when we first formulated the Ramsey plan in the space of sequences.

62.4.6 State Variable Degeneracy

Equations (39) and (40) imply that $\Phi_0=\Phi_1$ and that

$$V_x(x_t,s_t)=\Phi_0 \tag{41}$$

for all $t\geq 1$.

When V is concave in x, this implies *state-variable degeneracy* along a Ramsey plan in the sense that for $t\geq 1$, x_t will be a time-invariant function of s_t.

Given Φ_0, this function mapping s_t into x_t can be expressed as a vector $\vec{x}$ that solves equation (34) for n and c as functions of g that are associated with $\Phi=\Phi_0$.

62.4.7 Manifestations of Time Inconsistency

While the marginal utility adjusted level of government debt x_t is a key state variable for the continuation Ramsey planners at $t \geq 1$, it is not a state variable at time 0.

The time 0 Ramsey planner faces b_0, not $x_0 = u_{c,0} b_0$, as a state variable.

The discrepancy in state variables faced by the time 0 Ramsey planner and the time $t \geq 1$ continuation Ramsey planners captures the differing obligations and incentives faced by the time 0 Ramsey planner and the time $t \geq 1$ continuation Ramsey planners.

- The time 0 Ramsey planner is obligated to honor government debt b_0 measured in time 0 consumption goods.
- The time 0 Ramsey planner can manipulate the *value* of government debt as measured by $u_{c,0} b_0$.
- In contrast, time $t \geq 1$ continuation Ramsey planners are obligated *not* to alter values of debt, as measured by $u_{c,t} b_t$, that they inherit from a preceding Ramsey planner or continuation Ramsey planner.

When government expenditures g_t are a time invariant function of a Markov state s_t, a Ramsey plan and associated Ramsey allocation feature marginal utilities of consumption $u_c(s_t)$ that, given Φ, for $t \geq 1$ depend only on s_t, but that for $t = 0$ depend on b_0 as well.

This means that $u_c(s_t)$ will be a time invariant function of s_t for $t \geq 1$, but except when $b_0 = 0$, a different function for $t = 0$.

This in turn means that prices of one period Arrow securities $p_{t+1}(s_{t+1}|s_t) = p(s_{t+1}|s_t)$ will be the *same* time invariant functions of (s_{t+1}, s_t) for $t \geq 1$, but a different function $p_0(s_1|s_0)$ for $t = 0$, except when $b_0 = 0$.

The differences between these time 0 and time $t \geq 1$ objects reflect the Ramsey planner's incentive to manipulate Arrow security prices and, through them, the value of initial government debt b_0.

62.4.8 Recursive Implementation

The above steps are implemented in a type called RecursiveAllocation

```
In [4]: struct RecursiveAllocation{TP <: Model, TI <: Integer,
                                   TVg <: AbstractVector, TVv <: AbstractVector,
                                   TVp <: AbstractArray}
            model::TP
            mc::MarkovChain
            S::TI
            T::BellmanEquation
            μgrid::TVg
            xgrid::TVg
            Vf::TVv
            policies::TVp
        end


        function RecursiveAllocation(model, μgrid)
            mc = MarkovChain(model.Π)
            G = model.G
            S = size(model.Π, 1) # Number of states
```

```
    # Now find the first best allocation
    Vf, policies, T, xgrid = solve_time1_bellman(model, μgrid)
    T.time_0 = true      # Bellman equation now solves time 0 problem
    return RecursiveAllocation(model, mc, S, T, μgrid, xgrid, Vf, policies)
end

function solve_time1_bellman(model, μgrid)
    μgrid0 = μgrid
    S = size(model.Π, 1)
    # First get initial fit
    PP = SequentialAllocation(model)
    c = zeros(length(μgrid), 2)
    n = similar(c)
    x = similar(c)
    V = similar(c)
    for (i, μ) in enumerate(μgrid0)
        c[i, :], n[i, :], x[i, :], V[i, :] = time1_value(PP, μ)
    end
    Vf = Vector{AbstractInterpolation}(undef, 2)
    cf = similar(Vf)
    nf = similar(Vf)
    xprimef = similar(Vf, 2, S)
    for s in 1:2
        cf[s] = LinearInterpolation(x[:, s][end:-1:1], c[:, s][end:-1:1])
        nf[s] = LinearInterpolation(x[:, s][end:-1:1], n[:, s][end:-1:1])
        Vf[s] = LinearInterpolation(x[:, s][end:-1:1], V[:, s][end:-1:1])
        for sprime in 1:S
           xprimef[s, sprime] = LinearInterpolation(x[:, s][end:-1:1], x[:,
s][end:-1:1])
        end
    end
    policies = [cf, nf, xprimef]
    # Create xgrid
    xbar = [maximum(minimum(x, dims = 1)), minimum(maximum(x, dims = 1))]
    xgrid = range(xbar[1],  xbar[2], length = length(μgrid0))
    # Now iterate on bellman equation
    T = BellmanEquation(model, xgrid, policies)
    diff = 1.0
    while diff > 1e-6
        if T.time_0 == false
            Vfnew, policies =
                fit_policy_function(PP,
                (i_x, x, s) -> get_policies_time1(T, i_x, x, s, Vf), xgrid)
        elseif T.time_0 == true
            Vfnew, policies =
                fit_policy_function(PP,
                (i_x, B_, s0) -> get_policies_time0(T, i_x, B_, s0, Vf),
↪xgrid)
        else
            error("T.time_0 is $(T.time_0), which is invalid")
        end
        diff = 0.0
        for s in 1:S
            diff = max(diff, maximum(abs,
(Vf[s].(xgrid)-Vfnew[s].(xgrid))./Vf[s].(xgrid)))
        end
        print("diff = $diff \n")
        Vf = Vfnew
```

```
        end
        # Store value function policies and Bellman Equations
        return Vf, policies, T, xgrid
    end

    function fit_policy_function(PP, PF, xgrid)
        S = PP.S
        Vf = Vector{AbstractInterpolation}(undef, S)
        cf = similar(Vf)
        nf = similar(Vf)
        xprimef = similar(Vf, S, S)
        for s in 1:S
            PFvec = zeros(length(xgrid), 3+S)
            for (i_x, x) in enumerate(xgrid)
                PFvec[i_x, :] = PF(i_x, x, s)
            end
            Vf[s] = LinearInterpolation(xgrid, PFvec[:, 1])
            cf[s] = LinearInterpolation(xgrid, PFvec[:, 2])
            nf[s] = LinearInterpolation(xgrid, PFvec[:, 3])
            for sprime in 1:S
                xprimef[s, sprime] = LinearInterpolation(xgrid, PFvec[:,
↪3+sprime])
            end
        end
        return Vf, [cf, nf, xprimef]
    end

    function time0_allocation(pab::RecursiveAllocation, B_, s0)
        xgrid = pab.xgrid
        if pab.T.time_0 == false
            z0 = get_policies_time1(pab.T, i_x, x, s, pab.Vf)
        elseif pab.T.time_0 == true
            z0 = get_policies_time0(pab.T, B_, s0, pab.Vf)
        else
            error("T.time_0 is $(T.time_0), which is invalid")
        end
        c0, n0, xprime0 = z0[2], z0[3], z0[4:end]
        return c0, n0, xprime0
    end

    function simulate(pab::RecursiveAllocation, B_, s_0, T,
                      sHist = QuantEcon.simulate(mc, s_0, T))
        model, S, policies = pab.model, pab.S, pab.policies
        β, Π, Uc = model.β, model.Π, model.Uc
        cf, nf, xprimef = policies[1], policies[2], policies[3]
        cHist = zeros(T)
        nHist = similar(cHist)
        Bhist = similar(cHist)
        THist = similar(cHist)
        μHist = similar(cHist)
        RHist = zeros(T - 1)
        # time 0
        cHist[1], nHist[1], xprime = time0_allocation(pab, B_, s_0)
        THist[1] = T(pab.model, cHist[1], nHist[1])[s_0]
        Bhist[1] = B_
        μHist[1] = 0.0
        # time 1 onward
        for t in 2:T
```

```
        s, x = sHist[t], xprime[sHist[t]]
        n = nf[s](x)
        c = [cf[shat](x) for shat in 1:S]
        xprime = [xprimef[s, sprime](x) for sprime in 1:S]
        THist[t] = T(pab.model, c, n)[s]
        u_c = Uc(c, n)
        Eu_c = dot(Π[sHist[t-1], :], u_c)
        μHist[t] = pab.Vf[s](x)
        RHist[t-1] = Uc(cHist[t-1], nHist[t-1]) / (β * Eu_c)
        cHist[t], nHist[t], Bhist[t] = c[s], n, x / u_c[s]
    end
    return cHist, nHist, Bhist, THist, sHist, μHist, RHist
end
```

```
Out[4]: simulate (generic function with 7 methods)
```

62.5 Examples

62.5.1 Anticipated One Period War

This example illustrates in a simple setting how a Ramsey planner manages risk.

Government expenditures are known for sure in all periods except one.

- For $t < 3$ and $t > 3$ we assume that $g_t = g_l = 0.1$.
- At $t = 3$ a war occcurs with probability 0.5.
  - If there is war, $g_3 = g_h = 0.2$.
  - If there is no war $g_3 = g_l = 0.1$.

We define the components of the state vector as the following six (t, g) pairs:
$(0, g_l), (1, g_l), (2, g_l), (3, g_l), (3, g_h), (t \geq 4, g_l)$.

We think of these 6 states as corresponding to $s = 1, 2, 3, 4, 5, 6$.

The transition matrix is

$$\Pi = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Government expenditures at each state are

$$g = \begin{pmatrix} 0.1 \\ 0.1 \\ 0.1 \\ 0.1 \\ 0.2 \\ 0.1 \end{pmatrix}.$$

We assume that the representative agent has utility function

$$u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma}$$

and set $\sigma = 2$, $\gamma = 2$, and the discount factor $\beta = 0.9$.

Note: For convenience in terms of matching our code, we have expressed utility as a function of n rather than leisure l.

This utility function is implemented in the type CRRAutility

```
In [5]: function crra_utility(;
            β = 0.9,
            σ = 2.0,
            γ = 2.0,
            Π = 0.5 * ones(2, 2),
            G = [0.1, 0.2],
            Θ = ones(2),
            transfers = false
            )
            function U(c, n)
                if σ == 1.0
                    U = log(c)
                else
                    U = (c.^(1.0 .- σ) .- 1.0) / (1.0 - σ)
                end
                return U .- n.^(1 + γ) / (1 + γ)
            end
            # Derivatives of utility function
            Uc(c,n) =  c.^(-σ)
            Ucc(c,n) = -σ * c.^(-σ - 1.0)
            Un(c,n) = -n.^γ
            Unn(c,n) = -γ * n.^(γ - 1.0)
            n_less_than_one = false
            return Model(β, Π, G, Θ, transfers,
                         U, Uc, Ucc, Un, Unn, n_less_than_one)
        end
```

```
Out[5]: crra_utility (generic function with 1 method)
```

We set initial government debt $b_0 = 1$.

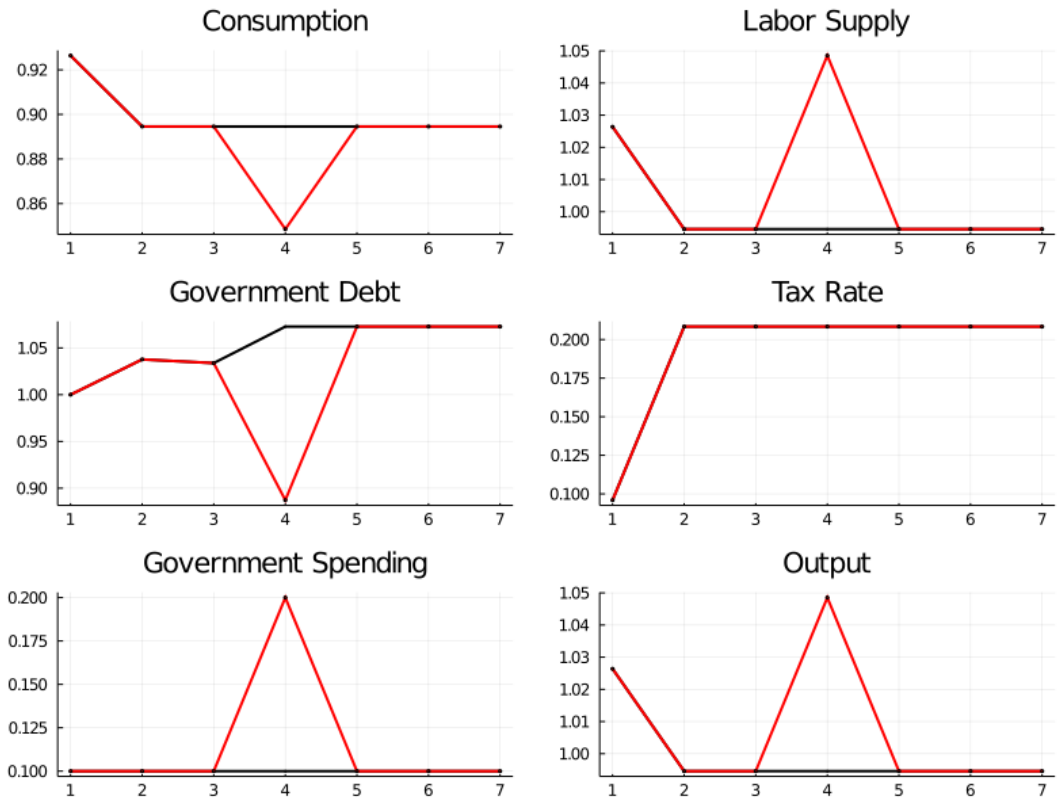
We can now plot the Ramsey tax under both realizations of time $t = 3$ government expenditures

- black when $g_3 = .1$, and
- red when $g_3 = .2$

```
In [6]: using Random
        Random.seed!(42) # For reproducible results.

        M_time_example = crra_utility(G=[0.1, 0.1, 0.1, 0.2, 0.1, 0.1],
                                      Θ=ones(6))           # Θ can in principle be
        ↪random

        M_time_example.Π = [0.0 1.0 0.0 0.0 0.0 0.0;
                            0.0 0.0 1.0 0.0 0.0 0.0;
```

```
                        0.0 0.0 0.0 0.5 0.5 0.0;
                        0.0 0.0 0.0 0.0 0.0 1.0;
                        0.0 0.0 0.0 0.0 0.0 1.0;
                        0.0 0.0 0.0 0.0 0.0 1.0]

    PP_seq_time = SequentialAllocation(M_time_example)  # Solve sequential
↪problem

    sHist_h = [1, 2, 3, 4, 6, 6, 6]
    sHist_l = [1, 2, 3, 5, 6, 6, 6]

    sim_seq_h = simulate(PP_seq_time, 1.0, 1, 7, sHist_h)
    sim_seq_l = simulate(PP_seq_time, 1.0, 1, 7, sHist_l)

    using Plots
    gr(fmt=:png);
    titles = hcat("Consumption",
                  "Labor Supply",
                  "Government Debt",
                  "Tax Rate",
                  "Government Spending",
                  "Output")

    sim_seq_l_plot = [sim_seq_l[1:4]..., M_time_example.G[sHist_l],
                      M_time_example.Θ[sHist_l].*sim_seq_l[2]]
    sim_seq_h_plot = [sim_seq_h[1:4]..., M_time_example.G[sHist_h],
                      M_time_example.Θ[sHist_h].*sim_seq_h[2]]

    plots = plot(layout=(3,2), size=(800,600))
    for i = 1:6
        plot!(plots[i], sim_seq_l_plot[i], color=:black, lw=2,
              marker=:circle, markersize=2, label="")
        plot!(plots[i], sim_seq_h_plot[i], color=:red, lw=2,
              marker=:circle, markersize=2, label="")
        plot!(plots[i], title=titles[i], grid=true)
    end
    plot(plots)
```

Out[6]:



Tax smoothing

- the tax rate is constant for all $t \geq 1$
  - For $t \geq 1, t \neq 3$, this is a consequence of g_t being the same at all those dates
  - For $t = 3$, it is a consequence of the special one-period utility function that we have assumed
  - Under other one-period utility functions, the time $t = 3$ tax rate could be either higher or lower than for dates $t \geq 1, t \neq 3$
- the tax rate is the same at $t = 3$ for both the high g_t outcome and the low g_t outcome

We have assumed that at $t = 0$, the government owes positive debt b_0.

It sets the time $t = 0$ tax rate partly with an eye to reducing the value $u_{c,0} b_0$ of b_0.

It does this by increasing consumption at time $t = 0$ relative to consumption in later periods.

This has the consequence of *raising* the time $t = 0$ value of the gross interest rate for risk-free loans between periods t and $t + 1$, which equals

$$R_t = \frac{u_{c,t}}{\beta \mathbb{E}_t [u_{c,t+1}]}$$

A tax policy that makes time $t = 0$ consumption be higher than time $t = 1$ consumption evidently increases the risk-free rate one-period interest rate, R_t, at $t = 0$.

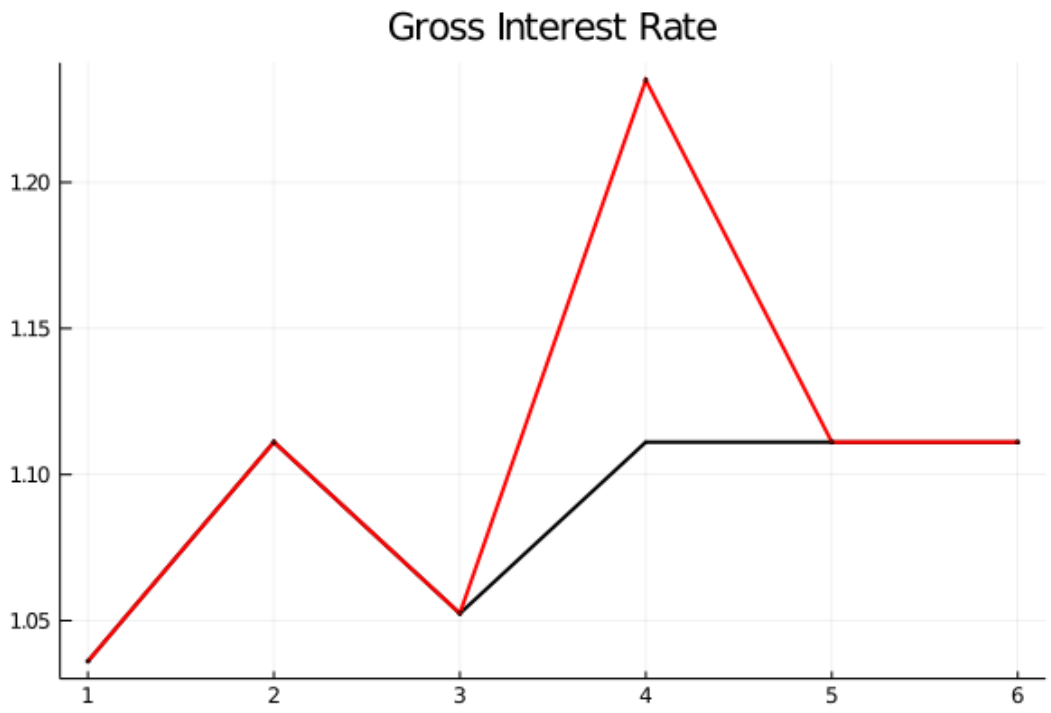
Raising the time $t = 0$ risk-free interest rate makes time $t = 0$ consumption goods cheaper relative to consumption goods at later dates, thereby lowering the value $u_{c,0} b_0$ of initial government debt b_0.

We see this in a figure below that plots the time path for the risk free interest rate under both realizations of the time $t = 3$ government expenditure shock.

The following plot illustrates how the government lowers the interest rate at time 0 by raising consumption

In [7]:
```
plot(sim_seq_l[end], color=:black, lw=2,
        marker=:circle, markersize=2, label="")
plot!(sim_seq_h[end], color=:red, lw=2,
        marker=:circle, markersize=2, label="")
plot!(title="Gross Interest Rate", grid=true)
```

Out[7]:



62.5.2 Government Saving

At time $t = 0$ the government evidently *dissaves* since $b_1 > b_0$.

- This is a consequence of it setting a *lower* tax rate at $t = 0$, implying more consumption at $t = 0$.

At time $t = 1$, the government evidently *saves* since it has set the tax rate sufficiently high to allow it to set $b_2 < b_1$.

- Its motive for doing this is that it anticipates a likely war at $t = 3$.

At time $t = 2$ the government trades state-contingent Arrow securities to hedge against war at $t = 3$.

- It purchases a security that pays off when $g_3 = g_h$.

- It sells a security that pays off when $g_3 = g_l$.
- These purchases are designed in such a way that regardless of whether or not there is a war at $t = 3$, the government will begin period $t = 4$ with the *same* government debt.
- The time $t = 4$ debt level can be serviced with revenues from the constant tax rate set at times $t \geq 1$.

At times $t \geq 4$ the government rolls over its debt, knowing that the tax rate is set at level required to service the interest payments on the debt and government expenditures.

62.5.3 Time 0 Manipulation of Interest Rate

We have seen that when $b_0 > 0$, the Ramsey plan sets the time $t = 0$ tax rate partly with an eye toward raising a risk-free interest rate for one-period loans between times $t = 0$ and $t = 1$.

By raising this interest rate, the plan makes time $t = 0$ goods cheap relative to consumption goods at later times.

By doing this, it lowers the value of time $t = 0$ debt that it has inherited and must finance.

62.5.4 Time 0 and Time-Inconsistency

In the preceding example, the Ramsey tax rate at time 0 differs from its value at time 1.

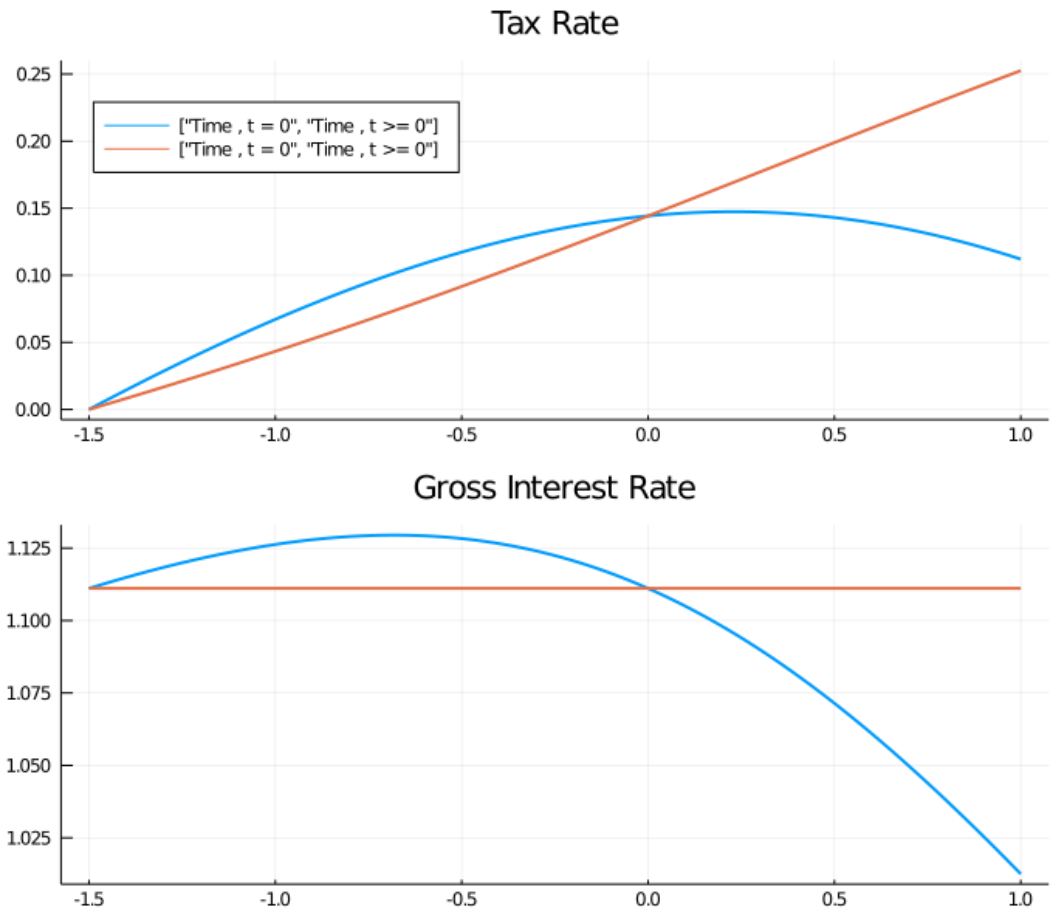
To explore what is going on here, let's simplify things by removing the possibility of war at time $t = 3$.

The Ramsey problem then includes no randomness because $g_t = g_l$ for all t.

The figure below plots the Ramsey tax rates and gross interest rates at time $t = 0$ and time $t \geq 1$ as functions of the initial government debt (using the sequential allocation solution and a CRRA utility function defined above)

```
In [8]: M2 = crra_utility(G=[0.15], Π=ones(1, 1), Θ=[1.0])

        PP_seq_time0 = SequentialAllocation(M2) # solve sequential problem

        B_vec = range(-1.5, 1.0, length = 100)
        taxpolicy = Matrix(hcat([simulate(PP_seq_time0, B_, 1, 2)[4] for B_ in
 ↪B_vec]...)')
       interest_rate = Matrix(hcat([simulate(PP_seq_time0, B_, 1, 3)[end] for B_ in
        B_vec]...)')

        titles = ["Tax Rate" "Gross Interest Rate"]
        labels = [["Time , t = 0", "Time , t >= 0"], ""]
        plots = plot(layout=(2,1), size =(700,600))
        for (i, series) in enumerate((taxpolicy, interest_rate))
            plot!(plots[i], B_vec, series, linewidth=2, label=labels[i])
            plot!(plots[i], title=titles[i], grid=true, legend=:topleft)
        end
        plot(plots)
```

Out[8]:



The figure indicates that if the government enters with positive debt, it sets a tax rate at $t = 0$ that is less than all later tax rates.

By setting a lower tax rate at $t = 0$, the government raises consumption, which reduces the *value* $u_{c,0} b_0$ of its initial debt.

It does this by increasing c_0 and thereby lowering $u_{c,0}$.

Conversely, if $b_0 < 0$, the Ramsey planner sets the tax rate at $t = 0$ higher than in subsequent periods.

A side effect of lowering time $t = 0$ consumption is that it raises the one-period interest rate at time 0 above that of subsequent periods.

There are only two values of initial government debt at which the tax rate is constant for all $t \geq 0$.

The first is $b_0 = 0$

- Here the government can't use the $t = 0$ tax rate to alter the value of the initial debt.

The second occurs when the government enters with sufficiently large assets that the Ramsey planner can achieve first best and sets $\tau_t = 0$ for all t.

It is only for these two values of initial government debt that the Ramsey plan is time-consistent.

Another way of saying this is that, except for these two values of initial government debt, a continuation of a Ramsey plan is not a Ramsey plan.

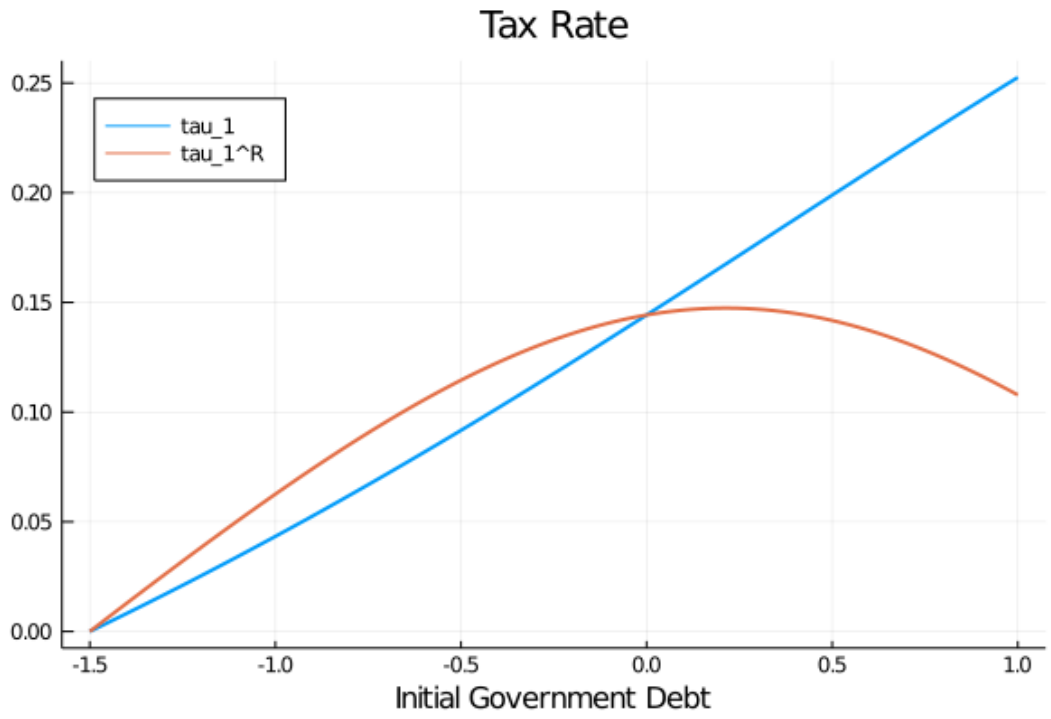
To illustrate this, consider a Ramsey planner who starts with an initial government debt b_1 associated with one of the Ramsey plans computed above.

Call τ_1^R the time $t = 0$ tax rate chosen by the Ramsey planner confronting this value for initial government debt government.

The figure below shows both the tax rate at time 1 chosen by our original Ramsey planner and what a new Ramsey planner would choose for its time $t = 0$ tax rate

```
In [9]: # Compute the debt entered with at time 1
        B1_vec = hcat([simulate(PP_seq_time0, B_, 1, 2)[3][2] for B_ in B_vec]...)'

        # Compute the optimal policy if the government could reset
        tau1_reset = Matrix(hcat([simulate(PP_seq_time0, B1, 1, 1)[4] for B1 in
↪B1_vec]...)')

        plot(B_vec, taxpolicy[:, 2], linewidth=2, label="tau_1")
        plot!(B_vec, tau1_reset, linewidth=2, label="tau_1^R")
        plot!(title="Tax Rate", xlabel="Initial Government Debt", legend=:topleft,
↪grid=true)
```

Out[9]:



The tax rates in the figure are equal for only two values of initial government debt.

62.5.5 Tax Smoothing and non-CRRA Preferences

The complete tax smoothing for $t \geq 1$ in the preceding example is a consequence of our having assumed CRRA preferences.

To see what is driving this outcome, we begin by noting that the Ramsey tax rate for $t \geq 1$ is a time invariant function $\tau(\Phi, g)$ of the Lagrange multiplier on the implementability constraint and government expenditures.

For CRRA preferences, we can exploit the relations $U_{cc}c = -\sigma U_c$ and $U_{nn}n = \gamma U_n$ to derive

$$\frac{(1 + (1-\sigma)\Phi)U_c}{(1 + (1-\gamma)\Phi)U_n} = 1$$

from the first-order conditions.

This equation immediately implies that the tax rate is constant.

For other preferences, the tax rate may not be constant.

For example, let the period utility function be

$$u(c, n) = \log(c) + 0.69 \log(1 - n)$$

We will write a new constructor LogUtility to represent this utility function

In [10]:
```
function log_utility(;β = 0.9,
                      ψ = 0.69,
                      Π = 0.5 * ones(2, 2),
                      G = [0.1, 0.2],
                      Θ = ones(2),
                      transfers = false)
    # Derivatives of utility function
    U(c,n) = log(c) + ψ * log(1 - n)
    Uc(c,n) = 1 ./ c
    Ucc(c,n) = -c.^(-2.0)
    Un(c,n) = -ψ ./ (1.0 .- n)
    Unn(c,n) = -ψ ./ (1.0 .- n).^2.0
    n_less_than_one = true
    return Model(β, Π, G, Θ, transfers,
                 U, Uc, Ucc, Un, Unn, n_less_than_one)
end
```

Out[10]:
```
log_utility (generic function with 1 method)
```

Also suppose that g_t follows a two state i.i.d. process with equal probabilities attached to g_l and g_h.

To compute the tax rate, we will use both the sequential and recursive approaches described above.

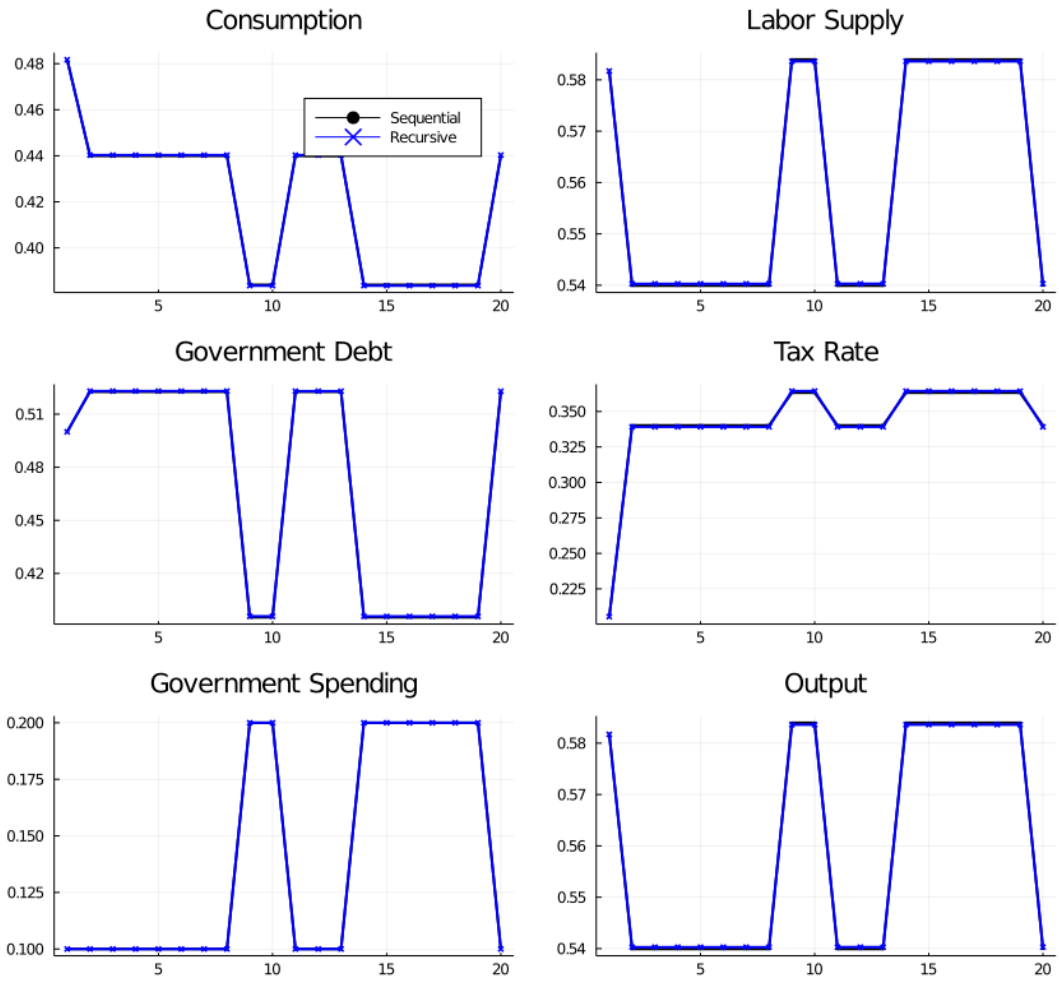
The figure below plots a sample path of the Ramsey tax rate

In [11]:
```
M1 = log_utility()
μ_grid = range(-0.6,  0.0, length = 200)
PP_seq = SequentialAllocation(M1)          # Solve sequential problem
PP_bel = RecursiveAllocation(M1, μ_grid)  # Solve recursive problem

T = 20
sHist = [1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1, 1, 2, 2, 2, 2, 2, 2, 1]
```

```
    # Simulate
    sim_seq = simulate(PP_seq, 0.5, 1, T, sHist)
    sim_bel = simulate(PP_bel, 0.5, 1, T, sHist)

    # Plot policies
    sim_seq_plot = [sim_seq[1:4]..., M1.G[sHist], M1.Θ[sHist].*sim_seq[2]]
    sim_bel_plot = [sim_bel[1:4]..., M1.G[sHist], M1.Θ[sHist].*sim_bel[2]]

    titles = hcat("Consumption",
                  "Labor Supply",
                  "Government Debt",
                  "Tax Rate",
                  "Government Spending",
                  "Output")
    labels = [["Sequential", "Recursive"], ["",""], ["",""], ["",""],
↪["",""], ["",""]]
    plots=plot(layout=(3,2), size=(850,780))

    for i = 1:6
        plot!(plots[i], sim_seq_plot[i], color=:black, lw=2, marker=:circle,
              markersize=2, label=labels[i][1])
        plot!(plots[i], sim_bel_plot[i], color=:blue, lw=2, marker=:xcross,
              markersize=2, label=labels[i][2])
        plot!(plots[i], title=titles[i], grid=true, legend=:topright)
    end
    plot(plots)
```

```
    diff = 0.0003504611535379196
diff = 0.00015763906388123851
diff = 7.124337606645018e-5
diff = 3.2356917242389125e-5
diff = 1.4829540976261937e-5
diff = 6.9104341194283816e-6
diff = 3.323224703213 99e-6
diff = 1.6870560419905608e-6
diff = 9.29342141847281e-7
```

Out[11]:



As should be expected, the recursive and sequential solutions produce almost identical allocations.

Unlike outcomes with CRRA preferences, the tax rate is not perfectly smoothed.

Instead the government raises the tax rate when g_t is high.

62.6 Further Comments

A related lecture describes an extension of the Lucas-Stokey model by Aiyagari, Marcet, Sargent, and Seppälä (2002) [2].

In th AMSS economy, only a risk-free bond is traded.

That lecture compares the recursive representation of the Lucas-Stokey model presented in this lecture with one for an AMSS economy.

By comparing these recursive formulations, we shall glean a sense in which the dimension of the state is lower in the Lucas Stokey model.

Accompanying that difference in dimension will be different dynamics of government debt.

Chapter 63

Optimal Taxation without State-Contingent Debt

63.1 Contents

63.2 Overview

In an earlier lecture we described a model of optimal taxation with state-contingent debt due to Robert E. Lucas, Jr., and Nancy Stokey [72].

Aiyagari, Marcet, Sargent, and Seppälä [2] (hereafter, AMSS) studied optimal taxation in a model without state-contingent debt.

In this lecture, we

- describe assumptions and equilibrium concepts
- solve the model
- implement the model numerically
- conduct some policy experiments
- compare outcomes with those in a corresponding complete-markets model

We begin with an introduction to the model.

63.2.1 Setup

```
In [1]: using InstantiateFromURL
        # optionally add arguments to force installation: instantiate = true,
      ↪precompile = true
        github_project("QuantEcon/quantecon-notebooks-julia", version = "0.8.0")
```

```
In [2]: using LinearAlgebra, Statistics
```

63.3 Competitive Equilibrium with Distorting Taxes

Many but not all features of the economy are identical to those of the Lucas-Stokey economy.

Let's start with things that are identical.

For $t \geq 0$, a history of the state is represented by $s^t = [s_t, s_{t-1}, \ldots, s_0]$.

Government purchases $g(s)$ are an exact time-invariant function of s.

Let $c_t(s^t)$, $\ell_t(s^t)$, and $n_t(s^t)$ denote consumption, leisure, and labor supply, respectively, at history s^t at time t.

Each period a representative household is endowed with one unit of time that can be divided between leisure ℓ_t and labor n_t:

$$n_t(s^t) + \ell_t(s^t) = 1 \tag{1}$$

Output equals $n_t(s^t)$ and can be divided between consumption $c_t(s^t)$ and $g(s_t)$

$$c_t(s^t) + g(s_t) = n_t(s^t) \tag{2}$$

Output is not storable.

The technology pins down a pre-tax wage rate to unity for all t, s^t.

A representative household's preferences over $\{c_t(s^t), \ell_t(s^t)\}_{t=0}^{\infty}$ are ordered by

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t) u[c_t(s^t), \ell_t(s^t)] \tag{3}$$

where

- $\pi_t(s^t)$ is a joint probability distribution over the sequence s^t, and
- the utility function u is increasing, strictly concave, and three times continuously differentiable in both arguments

The government imposes a flat rate tax $\tau_t(s^t)$ on labor income at time t, history s^t.

Lucas and Stokey assumed that there are complete markets in one-period Arrow securities; also see smoothing models.

It is at this point that AMSS [2] modify the Lucas and Stokey economy.

AMSS allow the government to issue only one-period risk-free debt each period.

Ruling out complete markets in this way is a step in the direction of making total tax collections behave more like that prescribed in [8] than they do in [72].

63.3.1 Risk-free One-Period Debt Only

In period t and history s^t, let

- $b_{t+1}(s^t)$ be the amount of the time $t+1$ consumption good that at time t the government promised to pay.
- $R_t(s^t)$ be the gross interest rate on risk-free one-period debt between periods t and $t+1$.
- $T_t(s^t)$ be a nonnegative lump-sum transfer to the representative household Section **??**.

That $b_{t+1}(s^t)$ is the same for all realizations of s_{t+1} captures its *risk-free* character.

The market value at time t of government debt maturing at time $t+1$ equals $b_{t+1}(s^t)$ divided by $R_t(s^t)$.

The government's budget constraint in period t at history s^t is

$$\begin{aligned} b_t(s^{t-1}) &= \tau_t^n(s^t) n_t(s^t) - g_t(s_t) - T_t(s^t) + \frac{b_{t+1}(s^t)}{R_t(s^t)} \\ &\equiv z(s^t) + \frac{b_{t+1}(s^t)}{R_t(s^t)}, \end{aligned} \tag{4}$$

where $z(s^t)$ is the net-of-interest government surplus.

To rule out Ponzi schemes, we assume that the government is subject to a **natural debt limit** (to be discussed in a forthcoming lecture).

The consumption Euler equation for a representative household able to trade only one-period risk-free debt with one-period gross interest rate $R_t(s^t)$ is

$$\frac{1}{R_t(s^t)} = \sum_{s^{t+1}|s^t} \beta \pi_{t+1}(s^{t+1}|s^t) \frac{u_c(s^{t+1})}{u_c(s^t)}$$

Substituting this expression into the government's budget constraint (4) yields:

$$b_t(s^{t-1}) = z(s^t) + \beta \sum_{s^{t+1}|s^t} \pi_{t+1}(s^{t+1}|s^t) \frac{u_c(s^{t+1})}{u_c(s^t)} \, b_{t+1}(s^t) \tag{5}$$

Components of $z(s^t)$ on the right side depend on s^t, but the left side is required to depend on s^{t-1} only.

This is what it means for one-period government debt to be risk-free.

Therefore, the sum on the right side of equation (5) also has to depend only on s^{t-1}.

This requirement will give rise to **measurability constraints** on the Ramsey allocation to be discussed soon.

If we replace $b_{t+1}(s^t)$ on the right side of equation (5) by the right side of next period's budget constraint (associated with a particular realization s_t) we get

$$b_t(s^{t-1}) = z(s^t) + \sum_{s^{t+1}|s^t} \beta \pi_{t+1}(s^{t+1}|s^t) \frac{u_c(s^{t+1})}{u_c(s^t)} \left[z(s^{t+1}) + \frac{b_{t+2}(s^{t+1})}{R_{t+1}(s^{t+1})} \right]$$

After making similar repeated substitutions for all future occurrences of government indebtedness, and by invoking the natural debt limit, we arrive at:

$$b_t(s^{t-1}) = \sum_{j=0}^{\infty} \sum_{s^{t+j}|s^t} \beta^j \pi_{t+j}(s^{t+j}|s^t) \frac{u_c(s^{t+j})}{u_c(s^t)} \, z(s^{t+j}) \tag{6}$$

Now let's

- substitute the resource constraint into the net-of-interest government surplus, and

- use the household's first-order condition $1-\tau_t^n(s^t) = u_\ell(s^t)/u_c(s^t)$ to eliminate the labor tax rate

so that we can express the net-of-interest government surplus $z(s^t)$ as

$$z(s^t) = \left[1 - \frac{u_\ell(s^t)}{u_c(s^t)}\right][c_t(s^t) + g_t(s_t)] - g_t(s_t) - T_t(s^t)\,. \tag{7}$$

If we substitute the appropriate versions of right side of (7) for $z(s^{t+j})$ into equation (6), we obtain a sequence of *implementability constraints* on a Ramsey allocation in an AMSS economy.

Expression (6) at time $t = 0$ and initial state s^0 was also an *implementability constraint* on a Ramsey allocation in a Lucas-Stokey economy:

$$b_0(s^{-1}) = \mathbb{E}_0 \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^j)}{u_c(s^0)}\, z(s^j) \tag{8}$$

Indeed, it was the *only* implementability constraint there.

But now we also have a large number of additional implementability constraints

$$b_t(s^{t-1}) = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^{t+j})}{u_c(s^t)}\, z(s^{t+j}) \tag{9}$$

Equation (9) must hold for each s^t for each $t \geq 1$.

63.3.2 Comparison with Lucas-Stokey Economy

The expression on the right side of (9) in the Lucas-Stokey (1983) economy would equal the present value of a continuation stream of government surpluses evaluated at what would be competitive equilibrium Arrow-Debreu prices at date t.

In the Lucas-Stokey economy, that present value is measurable with respect to s^t.

In the AMSS economy, the restriction that government debt be risk-free imposes that that same present value must be measurable with respect to s^{t-1}.

In a language used in the literature on incomplete markets models, it can be said that the AMSS model requires that at each (t, s^t) what would be the present value of continuation government surpluses in the Lucas-Stokey model must belong to the **marketable subspace** of the AMSS model.

63.3.3 Ramsey Problem Without State-contingent Debt

After we have substituted the resource constraint into the utility function, we can express the Ramsey problem as being to choose an allocation that solves

$$\max_{\{c_t(s^t), b_{t+1}(s^t)\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u\left(c_t(s^t), 1 - c_t(s^t) - g_t(s_t)\right)$$

where the maximization is subject to

$$\mathbb{E}_0 \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^j)}{u_c(s^0)} z(s^j) \geq b_0(s^{-1}) \tag{10}$$

and

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^{t+j})}{u_c(s^t)} z(s^{t+j}) = b_t(s^{t-1}) \quad \forall\, s^t \tag{11}$$

given $b_0(s^{-1})$.

Lagrangian Formulation

Let $\gamma_0(s^0)$ be a nonnegative Lagrange multiplier on constraint (10).

As in the Lucas-Stokey economy, this multiplier is strictly positive when the government must resort to distortionary taxation; otherwise it equals zero.

A consequence of the assumption that there are no markets in state-contingent securities and that a market exists only in a risk-free security is that we have to attach stochastic processes $\{\gamma_t(s^t)\}_{t=1}^{\infty}$ of Lagrange multipliers to the implementability constraints (11).

Depending on how the constraints bind, these multipliers can be positive or negative:

$$\begin{aligned} \gamma_t(s^t) \;&\geq\; (\leq)\; 0 \quad \text{if the constraint binds in this direction} \\ \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^{t+j})}{u_c(s^t)} z(s^{t+j}) \;&\geq\; (\leq)\; b_t(s^{t-1}). \end{aligned}$$

A negative multiplier $\gamma_t(s^t) < 0$ means that if we could relax constraint (11), we would like to *increase* the beginning-of-period indebtedness for that particular realization of history s^t.

That would let us reduce the beginning-of-period indebtedness for some other history Section **??**.

These features flow from the fact that the government cannot use state-contingent debt and therefore cannot allocate its indebtedness efficiently across future states.

63.3.4 Some Calculations

It is helpful to apply two transformations to the Lagrangian.

Multiply constraint (10) by $u_c(s^0)$ and the constraints (11) by $\beta^t u_c(s^t)$.

Then a Lagrangian for the Ramsey problem can be represented as

$$
\begin{aligned}
J &= \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Big\{ u\left(c_t(s^t), 1 - c_t(s^t) - g_t(s_t)\right) \\
&\qquad + \gamma_t(s^t) \Big[\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j u_c(s^{t+j})\, z(s^{t+j}) - u_c(s^t)\, b_t(s^{t-1}) \Big] \Big\} \\
&= \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Big\{ u\left(c_t(s^t), 1 - c_t(s^t) - g_t(s_t)\right) \\
&\qquad + \Psi_t(s^t)\, u_c(s^t)\, z(s^t) - \gamma_t(s^t)\, u_c(s^t)\, b_t(s^{t-1}) \Big\}
\end{aligned} \tag{12}
$$

where

$$
\Psi_t(s^t) = \Psi_{t-1}(s^{t-1}) + \gamma_t(s^t) \quad \text{and} \quad \Psi_{-1}(s^{-1}) = 0 \tag{13}
$$

In (12), the second equality uses the law of iterated expectations and Abel's summation formula (also called *summation by parts*, see this page).

First-order conditions with respect to $c_t(s^t)$ can be expressed as

$$
\begin{aligned}
u_c(s^t) - u_\ell(s^t) + \Psi_t(s^t) \left\{ \left[u_{cc}(s^t) - u_{c\ell}(s^t) \right] z(s^t) + u_c(s^t)\, z_c(s^t) \right\} \\
- \gamma_t(s^t) \left[u_{cc}(s^t) - u_{c\ell}(s^t) \right] b_t(s^{t-1}) = 0
\end{aligned} \tag{14}
$$

and with respect to $b_t(s^t)$ as

$$
\mathbb{E}_t \left[\gamma_{t+1}(s^{t+1})\, u_c(s^{t+1}) \right] = 0 \tag{15}
$$

If we substitute $z(s^t)$ from (7) and its derivative $z_c(s^t)$ into first-order condition (14), we find two differences from the corresponding condition for the optimal allocation in a Lucas-Stokey economy with state-contingent government debt.

1. The term involving $b_t(s^{t-1})$ in first-order condition (14) does not appear in the corresponding expression for the Lucas-Stokey economy.

    - This term reflects the constraint that beginning-of-period government indebtedness must be the same across all realizations of next period's state, a constraint that would not be present if government debt could be state contingent.

2. The Lagrange multiplier $\Psi_t(s^t)$ in first-order condition (14) may change over time in response to realizations of the state, while the multiplier Φ in the Lucas-Stokey economy is time invariant.

We need some code from our an earlier lecture on optimal taxation with state-contingent debt sequential allocation implementation:

In [3]:
```
using QuantEcon, NLsolve, NLopt
import QuantEcon.simulate
```

```
mutable struct Model{TF <: AbstractFloat,
                     TM <: AbstractMatrix{TF},
                     TV <: AbstractVector{TF}}
    β::TF
    Π::TM
    G::TV
    Θ::TV
    transfers::Bool
    U::Function
    Uc::Function
    Ucc::Function
    Un::Function
    Unn::Function
    n_less_than_one::Bool
end


struct SequentialAllocation{TP <: Model,
                            TI <: Integer,
                            TV <: AbstractVector}
    model::TP
    mc::MarkovChain
    S::TI
    cFB::TV
    nFB::TV
    ΞFB::TV
    zFB::TV
end


function SequentialAllocation(model::Model)
    β, Π, G, Θ = model.β, model.Π, model.G, model.Θ
    mc = MarkovChain(Π)
    S = size(Π, 1)   # Number of states
    # Now find the first best allocation
    cFB, nFB, ΞFB, zFB = find_first_best(model, S, 1)

    return SequentialAllocation(model, mc, S, cFB, nFB, ΞFB, zFB)
end


function find_first_best(model::Model, S::Integer, version::Integer)
    if version != 1 && version != 2
        throw(ArgumentError("version must be 1 or 2"))
    end
    β, Θ, Uc, Un, G, Π =
        model.β, model.Θ, model.Uc, model.Un, model.G, model.Π
    function res!(out, z)
        c = z[1:S]
        n = z[S+1:end]
        out[1:S] = Θ .* Uc.(c, n) + Un.(c, n)
        out[S+1:end] = Θ .* n .- c .- G
    end
    res = nlsolve(res!, 0.5 * ones(2 * S))

    if converged(res) == false
        error("Could not find first best")
```

```
        end

        if version == 1
            cFB = res.zero[1:S]
            nFB = res.zero[S+1:end]
            ΞFB = Uc(cFB, nFB)          # Multiplier on the resource constraint
            zFB = vcat(cFB, nFB, ΞFB)
            return cFB, nFB, ΞFB, zFB
        elseif version == 2
            cFB = res.zero[1:S]
            nFB = res.zero[S+1:end]
            IFB = Uc(cFB, nFB) .* cFB + Un(cFB, nFB) .* nFB
            xFB = \(LinearAlgebra.I - β * Π, IFB)
            zFB = [vcat(cFB[s], xFB[s], xFB) for s in 1:S]
            return cFB, nFB, IFB, xFB, zFB
        end
    end


    function time1_allocation(pas::SequentialAllocation, μ::Real)
        model, S = pas.model, pas.S
        Θ, β, Π, G, Uc, Ucc, Un, Unn =
            model.Θ, model.β, model.Π, model.G,
            model.Uc, model.Ucc, model.Un, model.Unn
        function FOC!(out, z::Vector)
            c = z[1:S]
            n = z[S+1:2S]
            Ξ = z[2S+1:end]
            out[1:S] = Uc.(c, n) - μ * (Ucc.(c, n) .* c + Uc.(c, n)) - Ξ # FOC c
            out[S+1:2S] = Un.(c, n) - μ * (Unn(c, n) .* n .+ Un.(c, n)) + Θ .*
↪Ξ # FOC n
            out[2S+1:end] = Θ .* n - c .- G # resource constraint
            return out
        end
        # Find the root of the FOC
        res = nlsolve(FOC!, pas.zFB)
        if res.f_converged == false
            error("Could not find LS allocation.")
        end
        z = res.zero
        c, n, Ξ = z[1:S], z[S+1:2S], z[2S+1:end]
        # Now compute x
        I  = Uc(c, n) .* c +  Un(c, n) .* n
        x = \(LinearAlgebra.I - β * model.Π, I)
        return c, n, x, Ξ
    end


    function time0_allocation(pas::SequentialAllocation,
                              B_::AbstractFloat, s_0::Integer)
        model = pas.model
        Π, Θ, G, β = model.Π, model.Θ, model.G, model.β
        Uc, Ucc, Un, Unn =
            model.Uc, model.Ucc, model.Un, model.Unn

        # First order conditions of planner's problem
        function FOC!(out, z)
            μ, c, n, Ξ = z[1], z[2], z[3], z[4]
```

```
        xprime = time1_allocation(pas, μ)[3]
        out .= vcat(
        Uc(c, n) .* (c - B_) + Un(c, n) .* n + β * dot(Π[s_0, :], xprime),
        Uc(c, n) .- μ * (Ucc(c, n) .* (c - B_) + Uc(c, n)) .- Ξ,
        Un(c, n) .- μ * (Unn(c, n) .* n + Un(c, n)) + Θ[s_0] .* Ξ,
        (Θ .* n .- c .- G)[s_0]
        )
    end

    # Find root
    res = nlsolve(FOC!, [0.0, pas.cFB[s_0], pas.nFB[s_0], pas.ΞFB[s_0]])
    if res.f_converged == false
        error("Could not find time 0 LS allocation.")
    end
    return (res.zero...,)
end


function time1_value(pas::SequentialAllocation, μ::Real)
    model = pas.model
    c, n, x, Ξ = time1_allocation(pas, μ)
    U_val = model.U.(c, n)
    V = \(LinearAlgebra.I - model.β*model.Π, U_val)
    return c, n, x, V
end


function T(model::Model, c::Union{Real,Vector}, n::Union{Real,Vector})
    Uc, Un = model.Uc.(c, n), model.Un.(c, n)
    return 1. .+ Un./(model.Θ .* Uc)
end


function simulate(pas::SequentialAllocation,
                  B_::AbstractFloat, s_0::Integer,
                  T::Integer,
                  sHist::Union{Vector, Nothing}=nothing)

    model = pas.model
    Π, β, Uc = model.Π, model.β, model.Uc

    if isnothing(sHist)
        sHist = QuantEcon.simulate(pas.mc, T, init=s_0)
    end
    cHist = zeros(T)
    nHist = zeros(T)
    Bhist = zeros(T)
    THist = zeros(T)
    μHist = zeros(T)
    RHist = zeros(T-1)
    # time 0
    μ, cHist[1], nHist[1], _  = time0_allocation(pas, B_, s_0)
    THist[1] = T(pas.model, cHist[1], nHist[1])[s_0]
    Bhist[1] = B_
    μHist[1] = μ
    # time 1 onward
    for t in 2:T
        c, n, x, Ξ = time1_allocation(pas,μ)
```

```
            u_c = Uc(c,n)
            s = sHist[t]
            THist[t] = T(pas.model, c, n)[s]
            Eu_c = dot(Π[sHist[t-1],:], u_c)
            cHist[t], nHist[t], Bhist[t] = c[s], n[s], x[s] / u_c[s]
            RHist[t-1] = Uc(cHist[t-1], nHist[t-1]) / (β * Eu_c)
            μHist[t] = μ
        end
        return cHist, nHist, Bhist, THist, sHist, μHist, RHist
    end


    mutable struct BellmanEquation{TP <: Model,
                                   TI <: Integer,
                                   TV <: AbstractVector,
                                   TM <: AbstractMatrix{TV},
                                   TVV <: AbstractVector{TV}}
        model::TP
        S::TI
        xbar::TV
        time_0::Bool
        z0::TM
        cFB::TV
        nFB::TV
        xFB::TV
        zFB::TVV
    end


    function BellmanEquation(model::Model, xgrid::AbstractVector, policies0::
↪Vector)
        S = size(model.Π, 1) # number of states
        xbar = [minimum(xgrid), maximum(xgrid)]
        time_0 = false
        cf, nf, xprimef = policies0
       z0 = [vcat(cf[s](x), nf[s](x), [xprimef[s, sprime](x) for sprime in 1:S])
                            for x in xgrid, s in 1:S]
        cFB, nFB, IFB, xFB, zFB = find_first_best(model, S, 2)
        return BellmanEquation(model, S, xbar, time_0, z0, cFB, nFB, xFB, zFB)
    end


    function get_policies_time1(T::BellmanEquation,
                            i_x::Integer, x::AbstractFloat,
                            s::Integer, Vf::AbstractArray)
        model, S = T.model, T.S
        β, Θ, G, Π = model.β, model.Θ, model.G, model.Π
        U, Uc, Un = model.U, model.Uc, model.Un

        function objf(z::Vector, grad)
            c, xprime = z[1], z[2:end]
            n=c+G[s]
            Vprime = [Vf[sprime](xprime[sprime]) for sprime in 1:S]
            return -(U(c, n) + β * dot(Π[s, :], Vprime))
        end
        function cons(z::Vector, grad)
            c, xprime = z[1], z[2:end]
            n=c+G[s]
```

```
        return x - Uc(c, n) * c - Un(c, n) * n - β * dot(Π[s, :], xprime)
    end
    lb = vcat(0, T.xbar[1] * ones(S))
    ub = vcat(1 - G[s], T.xbar[2] * ones(S))
    opt = Opt(:LN_COBYLA, length(T.z0[i_x, s])-1)
    min_objective!(opt, objf)
    equality_constraint!(opt, cons)
    lower_bounds!(opt, lb)
    upper_bounds!(opt, ub)
    maxeval!(opt, 300)
    maxtime!(opt, 10)
    init = vcat(T.z0[i_x, s][1], T.z0[i_x, s][3:end])
    for (i, val) in enumerate(init)
        if val > ub[i]
            init[i] = ub[i]
        elseif val < lb[i]
            init[i] = lb[i]
        end
    end
    (minf, minx, ret) = optimize(opt, init)
    T.z0[i_x, s] = vcat(minx[1], minx[1] + G[s], minx[2:end])
    return vcat(-minf, T.z0[i_x, s])
end

function get_policies_time0(T::BellmanEquation,
                            B_::AbstractFloat, s0::Integer, Vf::Array)
    model, S = T.model, T.S
    β, Θ, G, Π = model.β, model.Θ, model.G, model.Π
    U, Uc, Un = model.U, model.Uc, model.Un
    function objf(z, grad)
        c, xprime = z[1], z[2:end]
        n = c+G[s0]
        Vprime = [Vf[sprime](xprime[sprime]) for sprime in 1:S]
        return -(U(c, n) + β * dot(Π[s0, :], Vprime))
    end
    function cons(z::Vector, grad)
        c, xprime = z[1], z[2:end]
        n = c + G[s0]
      return -Uc(c, n) * (c - B_) - Un(c, n) * n - β * dot(Π[s0, :], xprime)
    end
    lb = vcat(0, T.xbar[1] * ones(S))
    ub = vcat(1-G[s0], T.xbar[2] * ones(S))
    opt = Opt(:LN_COBYLA, length(T.zFB[s0])-1)
    min_objective!(opt, objf)
    equality_constraint!(opt, cons)
    lower_bounds!(opt, lb)
    upper_bounds!(opt, ub)
    maxeval!(opt, 300)
    maxtime!(opt, 10)
    init = vcat(T.zFB[s0][1], T.zFB[s0][3:end])
    for (i, val) in enumerate(init)
        if val > ub[i]
            init[i] = ub[i]
        elseif val < lb[i]
            init[i] = lb[i]
        end
    end
    (minf, minx, ret) = optimize(opt, init)
```

```
    return vcat(-minf, vcat(minx[1], minx[1]+G[s0], minx[2:end]))
end
```

```
Out[3]: get_policies_time0 (generic function with 1 method)
```

To analyze the AMSS model, we find it useful to adopt a recursive formulation using techniques like those in our lectures on dynamic Stackelberg models and optimal taxation with state-contingent debt.

63.4 Recursive Version of AMSS Model

We now describe a recursive formulation of the AMSS economy.

We have noted that from the point of view of the Ramsey planner, the restriction to one-period risk-free securities

- leaves intact the single implementability constraint on allocations (8) from the Lucas-Stokey economy, but
- adds measurability constraints (6) on functions of tails of allocations at each time and history

We now explore how these constraints alter Bellman equations for a time 0 Ramsey planner and for time $t \geq 1$, history s^t continuation Ramsey planners.

63.4.1 Recasting State Variables

In the AMSS setting, the government faces a sequence of budget constraints

$$\tau_t(s^t) n_t(s^t) + T_t(s^t) + b_{t+1}(s^t)/R_t(s^t) = g_t + b_t(s^{t-1})$$

where $R_t(s^t)$ is the gross risk-free rate of interest between t and $t+1$ at history s^t and $T_t(s^t)$ are nonnegative transfers.

Throughout this lecture, we shall set transfers to zero (for some issues about the limiting behavior of debt, this makes a possibly important difference from AMSS [2], who restricted transfers to be nonnegative).

In this case, the household faces a sequence of budget constraints

$$b_t(s^{t-1}) + (1 - \tau_t(s^t)) n_t(s^t) = c_t(s^t) + b_{t+1}(s^t)/R_t(s^t) \tag{16}$$

The household's first-order conditions are $u_{c,t} = \beta R_t \mathbb{E}_t u_{c,t+1}$ and $(1-\tau_t)u_{c,t} = u_{l,t}$.

Using these to eliminate R_t and τ_t from budget constraint (16) gives

$$b_t(s^{t-1}) + \frac{u_{l,t}(s^t)}{u_{c,t}(s^t)} n_t(s^t) = c_t(s^t) + \frac{\beta(\mathbb{E}_t u_{c,t+1}) b_{t+1}(s^t)}{u_{c,t}(s^t)} \tag{17}$$

or

$$u_{c,t}(s^t) b_t(s^{t-1}) + u_{l,t}(s^t) n_t(s^t) = u_{c,t}(s^t) c_t(s^t) + \beta(\mathbb{E}_t u_{c,t+1}) b_{t+1}(s^t) \tag{18}$$

Now define

$$x_t \equiv \beta b_{t+1}(s^t)\mathbb{E}_t u_{c,t+1} = u_{c,t}(s^t)\frac{b_{t+1}(s^t)}{R_t(s^t)} \tag{19}$$

and represent the household's budget constraint at time t, history s^t as

$$\frac{u_{c,t}x_{t-1}}{\beta \mathbb{E}_{t-1}u_{c,t}} = u_{c,t}c_t - u_{l,t}n_t + x_t \tag{20}$$

for $t \geq 1$.

63.4.2 Measurability Constraints

Write equation (18) as

$$b_t(s^{t-1}) = c_t(s^t) - \frac{u_{l,t}(s^t)}{u_{c,t}(s^t)}n_t(s^t) + \frac{\beta(\mathbb{E}_t u_{c,t+1})b_{t+1}(s^t)}{u_{c,t}} \tag{21}$$

The right side of equation (21) expresses the time t value of government debt in terms of a linear combination of terms whose individual components are measurable with respect to s^t.

The sum of terms on the right side of equation (21) must equal $b_t(s^{t-1})$.

That implies that it is has to be *measurable* with respect to s^{t-1}.

Equations (21) are the *measurablility constraints* that the AMSS model adds to the single time 0 implementation constraint imposed in the Lucas and Stokey model.

63.4.3 Two Bellman Equations

Let $\Pi(s|s_-)$ be a Markov transition matrix whose entries tell probabilities of moving from state s_- to state s in one period.

Let

- $V(x_-, s_-)$ be the continuation value of a continuation Ramsey plan at $x_{t-1} = x_-, s_{t-1} = s_-$ for $t \geq 1$.
- $W(b, s)$ be the value of the Ramsey plan at time 0 at $b_0 = b$ and $s_0 = s$.

We distinguish between two types of planners:

For $t \geq 1$, the value function for a **continuation Ramsey planner** satisfies the Bellman equation

$$V(x_-, s_-) = \max_{\{n(s), x(s)\}} \sum_s \Pi(s|s_-)\left[u(n(s) - g(s), 1 - n(s)) + \beta V(x(s), s)\right] \tag{22}$$

subject to the following collection of implementability constraints, one for each $s \in S$:

$$\frac{u_c(s)x_-}{\beta \sum_{\tilde{s}} \Pi(\tilde{s}|s_-)u_c(\tilde{s})} = u_c(s)(n(s) - g(s)) - u_l(s)n(s) + x(s) \tag{23}$$

A continuation Ramsey planner at $t \geq 1$ takes $(x_{t-1}, s_{t-1}) = (x_-, s_-)$ as given and before s is realized chooses $(n_t(s_t), x_t(s_t)) = (n(s), x(s))$ for $s \in S$.

The **Ramsey planner** takes (b_0, s_0) as given and chooses (n_0, x_0).

The value function $W(b_0, s_0)$ for the time $t = 0$ Ramsey planner satisfies the Bellman equation

$$W(b_0, s_0) = \max_{n_0, x_0} u(n_0 - g_0, 1 - n_0) + \beta V(x_0, s_0) \tag{24}$$

where maximization is subject to

$$u_{c,0} b_0 = u_{c,0}(n_0 - g_0) - u_{l,0} n_0 + x_0 \tag{25}$$

63.4.4 Martingale Supercedes State-Variable Degeneracy

Let $\mu(s|s_-)\Pi(s|s_-)$ be a Lagrange multiplier on constraint (23) for state s.

After forming an appropriate Lagrangian, we find that the continuation Ramsey planner's first-order condition with respect to $x(s)$ is

$$\beta V_x(x(s), s) = \mu(s|s_-) \tag{26}$$

Applying the envelope theorem to Bellman equation (22) gives

$$V_x(x_-, s_-) = \sum_s \Pi(s|s_-)\mu(s|s_-) \frac{u_c(s)}{\beta \sum_{\tilde{s}} \Pi(\tilde{s}|s_-) u_c(\tilde{s})} \tag{27}$$

Equations (26) and (27) imply that

$$V_x(x_-, s_-) = \sum_s \left(\Pi(s|s_-) \frac{u_c(s)}{\sum_{\tilde{s}} \Pi(\tilde{s}|s_-) u_c(\tilde{s})} \right) V_x(x(s), s) \tag{28}$$

Equation (28) states that $V_x(x, s)$ is a *risk-adjusted martingale*.

Saying that $V_x(x, s)$ is a risk-adjusted martingale means that $V_x(x, s)$ is a martingale with respect to the probability distribution over s^t sequences that is generated by the *twisted* transition probability matrix:

$$\breve{\Pi}(s|s_-) \equiv \Pi(s|s_-) \frac{u_c(s)}{\sum_{\tilde{s}} \Pi(\tilde{s}|s_-) u_c(\tilde{s})}$$

Exercise: Please verify that $\breve{\Pi}(s|s_-)$ is a valid Markov transition density, i.e., that its elements are all nonnegative and that for each s_-, the sum over s equals unity.

63.4.5 Absence of State Variable Degeneracy

Along a Ramsey plan, the state variable $x_t = x_t(s^t, b_0)$ becomes a function of the history s^t and initial government debt b_0.

In Lucas-Stokey model, we found that

- a counterpart to $V_x(x,s)$ is time invariant and equal to the Lagrange multiplier on the Lucas-Stokey implementability constraint
- time invariance of $V_x(x,s)$ is the source of a key feature of the Lucas-Stokey model, namely, state variable degeneracy (i.e., x_t is an exact function of s_t)

That $V_x(x,s)$ varies over time according to a twisted martingale means that there is no state-variable degeneracy in the AMSS model.

In the AMSS model, both x and s are needed to describe the state.

This property of the AMSS model transmits a twisted martingale component to consumption, employment, and the tax rate.

63.4.6 Digression on Nonnegative Transfers

Throughout this lecture we have imposed that transfers $T_t = 0$.

AMSS [2] instead imposed a nonnegativity constraint $T_t \geq 0$ on transfers.

They also considered a special case of quasi-linear preferences, $u(c,l) = c + H(l)$.

In this case, $V_x(x,s) \leq 0$ is a non-positive martingale.

By the *martingale convergence theorem* $V_x(x,s)$ converges almost surely.

Furthermore, when the Markov chain $\Pi(s|s_-)$ and the government expenditure function $g(s)$ are such that g_t is perpetually random, $V_x(x,s)$ almost surely converges to zero.

For quasi-linear preferences, the first-order condition with respect to $n(s)$ becomes

$$(1-\mu(s|s_-))(1-u_l(s)) + \mu(s|s_-)n(s)u_{ll}(s) = 0$$

When $\mu(s|s_-) = \beta V_x(x(s),x)$ converges to zero, in the limit $u_l(s) = 1 = u_c(s)$, so that $\tau(x(s),s) = 0$.

Thus, in the limit, if g_t is perpetually random, the government accumulates sufficient assets to finance all expenditures from earnings on those assets, returning any excess revenues to the household as nonnegative lump sum transfers.

63.4.7 Code

The recursive formulation is implemented as follows

```
In [4]: using Dierckx
```

```
        mutable struct BellmanEquation_Recursive{TP <: Model, TI <: Integer, TR <:
↪Real}
            model::TP
            S::TI
            xbar::Array{TR}
            time_0::Bool
            z0::Array{Array}
            cFB::Vector{TR}
            nFB::Vector{TR}
            xFB::Vector{TR}
```

```
        zFB::Vector{Vector{TR}}
    end


    struct RecursiveAllocation{TP <: Model,
                               TI <: Integer,
                               TVg <: AbstractVector,
                               TT <: Tuple}
        model::TP
        mc::MarkovChain
        S::TI
        T::BellmanEquation_Recursive
        μgrid::TVg
        xgrid::TVg
        Vf::Array
        policies::TT
    end


    function RecursiveAllocation(model::Model, μgrid::AbstractArray)
        G = model.G
        S = size(model.Π, 1)             # number of states
        mc = MarkovChain(model.Π)
        # now find the first best allocation
        Vf, policies, T, xgrid = solve_time1_bellman(model, μgrid)
        T.time_0 = true                  # Bellman equation now solves time 0
↪problem
        return RecursiveAllocation(model, mc, S, T, μgrid, xgrid, Vf, policies)
    end


    function solve_time1_bellman(model::Model{TR}, μgrid::AbstractArray) where
↪{TR <: Real}
        Π = model.Π
        S = size(model.Π, 1)

        # First get initial fit from lucas stockey solution.
        # Need to change things to be ex_ante
        PP = SequentialAllocation(model)

        function incomplete_allocation(PP::SequentialAllocation,
                                       μ_::AbstractFloat,
                                       s_::Integer)
            c, n, x, V = time1_value(PP, μ_)
            return c, n, dot(Π[s_, :], x), dot(Π[s_, :], V)
        end

        cf = Array{Function}(undef, S, S)
        nf = Array{Function}(undef, S, S)
        xprimef = Array{Function}(undef, S, S)
        Vf = Vector{Function}(undef, S)
        xgrid = Array{TR}(undef, S, length(μgrid))

        for s_ in 1:S
            c = Array{TR}(undef, length(μgrid), S)
            n = Array{TR}(undef, length(μgrid), S)
            x = Array{TR}(undef, length(μgrid))
            V = Array{TR}(undef, length(μgrid))
```

```
            for (i_μ, μ) in enumerate(μgrid)
                c[i_μ, :], n[i_μ, :], x[i_μ], V[i_μ] =
                    incomplete_allocation(PP, μ, s_)
            end
            xprimes = repeat(x, 1, S)
            xgrid[s_, :] = x
            for sprime = 1:S
                splc = Spline1D(x[end:-1:1], c[:, sprime][end:-1:1], k=3)
                spln = Spline1D(x[end:-1:1], n[:, sprime][end:-1:1], k=3)
                splx = Spline1D(x[end:-1:1], xprimes[:, sprime][end:-1:1], k=3)
                cf[s_, sprime] = y -> splc(y)
                nf[s_, sprime] = y -> spln(y)
                xprimef[s_, sprime] = y -> splx(y)
              # cf[s_, sprime] = LinInterp(x[end:-1:1], c[:, sprime][end:-1:1])
              # nf[s_, sprime] = LinInterp(x[end:-1:1], n[:, sprime][end:-1:1])
                # xprimef[s_, sprime] = LinInterp(x[end:-1:1], xprimes[:,
↪sprime][end:-1:1])
            end
            splV = Spline1D(x[end:-1:1], V[end:-1:1], k=3)
            Vf[s_] = y -> splV(y)
            # Vf[s_] = LinInterp(x[end:-1:1], V[end:-1:1])
        end

        policies = [cf, nf, xprimef]

        # Create xgrid
        xbar = [maximum(minimum(xgrid)), minimum(maximum(xgrid))]
        xgrid = range(xbar[1], xbar[2], length = length(μgrid))

        # Now iterate on Bellman equation
        T = BellmanEquation_Recursive(model, xgrid, policies)
        diff = 1.0
        while diff > 1e-4
            PF = (i_x, x, s) -> get_policies_time1(T, i_x, x, s, Vf, xbar)
            Vfnew, policies = fit_policy_function(T, PF, xgrid)

            diff = 0.0
            for s=1:S
                diff = max(diff, maximum(abs, (Vf[s].(xgrid) - Vfnew[s].
↪(xgrid)) ./
                                               Vf[s].(xgrid)))
            end

            println("diff = $diff")
            Vf = copy(Vfnew)
        end

        return Vf, policies, T, xgrid
    end


    function fit_policy_function(T::BellmanEquation_Recursive,
                                 PF::Function,
                                 xgrid::AbstractVector{TF}) where {TF <:
↪AbstractFloat}
        S = T.S
        # preallocation
        PFvec = Array{TF}(undef, 4S + 1, length(xgrid))
```

```
    cf = Array{Function}(undef, S, S)
    nf = Array{Function}(undef, S, S)
    xprimef = Array{Function}(undef, S, S)
    TTf = Array{Function}(undef, S, S)
    Vf = Vector{Function}(undef, S)
    # fit policy fuctions
    for s_ in 1:S
        for (i_x, x) in enumerate(xgrid)
            PFvec[:, i_x] = PF(i_x, x, s_)
        end
        splV = Spline1D(xgrid, PFvec[1,:], k=3)
        Vf[s_] = y -> splV(y)
        # Vf[s_] = LinInterp(xgrid, PFvec[1, :])
        for sprime=1:S
            splc = Spline1D(xgrid, PFvec[1 + sprime, :], k=3)
            spln = Spline1D(xgrid, PFvec[1 + S + sprime, :], k=3)
            splxprime = Spline1D(xgrid, PFvec[1 + 2S + sprime, :], k=3)
            splTT = Spline1D(xgrid, PFvec[1 + 3S + sprime, :], k=3)
            cf[s_, sprime] = y -> splc(y)
            nf[s_, sprime] = y -> spln(y)
            xprimef[s_, sprime] = y -> splxprime(y)
            TTf[s_, sprime] = y -> splTT(y)
        end
    end
    policies = (cf, nf, xprimef, TTf)
    return Vf, policies
end


function Tau(pab::RecursiveAllocation,
             c::AbstractArray,
         n::AbstractArray)
    model = pab.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1. .+ Un ./ (model.Θ .* Uc)
end

Tau(pab::RecursiveAllocation, c::Real, n::Real) = Tau(pab, [c], [n])


function time0_allocation(pab::RecursiveAllocation, B_::Real, s0::Integer)
    T, Vf = pab.T, pab.Vf
    xbar = T.xbar
    z0 = get_policies_time0(T, B_, s0, Vf, xbar)

    c0, n0, xprime0, T0 = z0[2], z0[3], z0[4], z0[5]
    return c0, n0, xprime0, T0
end


function simulate(pab::RecursiveAllocation,
                  B_::TF, s_0::Integer, T::Integer,
                  sHist::Vector=simulate(pab.mc, T, init=s_0)) where {TF <:
AbstractFloat}
    model, mc, Vf, S = pab.model, pab.mc, pab.Vf, pab.S
    Π, Uc = model.Π, model.Uc
    cf, nf, xprimef, TTf = pab.policies
```

```
        cHist = Array{TF}(undef, T)
        nHist = Array{TF}(undef, T)
        Bhist = Array{TF}(undef, T)
        xHist = Array{TF}(undef, T)
        TauHist = Array{TF}(undef, T)
        THist = Array{TF}(undef, T)
        μHist = Array{TF}(undef, T)

        #time0
       cHist[1], nHist[1], xHist[1], THist[1]  = time0_allocation(pab, B_, s_0)
        TauHist[1] = Tau(pab, cHist[1], nHist[1])[s_0]
        Bhist[1] = B_
        μHist[1] = Vf[s_0](xHist[1])

        #time 1 onward
        for t in 2:T
            s_, x, s = sHist[t-1], xHist[t-1], sHist[t]
            c = Array{TF}(undef, S)
            n = Array{TF}(undef, S)
            xprime = Array{TF}(undef, S)
            TT = Array{TF}(undef, S)
            for sprime=1:S
                c[sprime], n[sprime], xprime[sprime], TT[sprime] =
                    cf[s_, sprime](x), nf[s_, sprime](x),
                    xprimef[s_, sprime](x), TTf[s_, sprime](x)
            end

            Tau_val = Tau(pab, c, n)[s]
            u_c = Uc(c, n)
            Eu_c = dot(Π[s_, :], u_c)

            μHist[t] = Vf[s](xprime[s])

            cHist[t], nHist[t], Bhist[t], TauHist[t] = c[s], n[s], x/Eu_c,
↪Tau_val
            xHist[t], THist[t] = xprime[s], TT[s]
        end
        return cHist, nHist, Bhist, xHist, TauHist, THist, μHist, sHist
    end


    function BellmanEquation_Recursive(model::Model{TF},
                                       xgrid::AbstractVector{TF},
                                   policies0::Array) where {TF <: AbstractFloat}

        S = size(model.Π, 1) # number of states
        xbar = [minimum(xgrid), maximum(xgrid)]
        time_0 = false
        z0 = Array{Array}(undef, length(xgrid), S)
        cf, nf, xprimef = policies0[1], policies0[2], policies0[3]
        for s in 1:S
            for (i_x, x) in enumerate(xgrid)
                cs = Array{TF}(undef, S)
                ns = Array{TF}(undef, S)
                xprimes = Array{TF}(undef, S)
                for j = 1:S
                    cs[j], ns[j], xprimes[j] = cf[s, j](x), nf[s, j](x),
↪xprimef[s, j](x)
```

```
                end
                z0[i_x, s] = vcat(cs, ns, xprimes, zeros(S))
            end
        end
        cFB, nFB, IFB, xFB, zFB = find_first_best(model, S, 2)
        return BellmanEquation_Recursive(model, S, xbar, time_0, z0, cFB, nFB,
↪xFB, zFB)
    end



    function get_policies_time1(T::BellmanEquation_Recursive,
                                i_x::Integer,
                                x::Real,
                                s_::Integer,
                                Vf::AbstractArray{Function},
                                xbar::AbstractVector)
        model, S = T.model, T.S
        β, Θ, G, Π = model.β, model.Θ, model.G, model.Π
        U,Uc,Un = model.U, model.Uc, model.Un

        S_possible = sum(Π[s_, :].>0)
        sprimei_possible = findall(Π[s_, :].>0)

        function objf(z, grad)
            c, xprime = z[1:S_possible], z[S_possible+1:2S_possible]
            n = (c .+ G[sprimei_possible]) ./ Θ[sprimei_possible]
            Vprime = [Vf[sprimei_possible[si]](xprime[si]) for si in 1:
↪S_possible]
            return -dot(Π[s_, sprimei_possible], U.(c, n) + β * Vprime)
        end

        function cons(out, z, grad)
            c, xprime, TT =
                z[1:S_possible], z[S_possible + 1:2S_possible], z[2S_possible +
    1:3S_possible]
            n = (c .+ G[sprimei_possible]) ./ Θ[sprimei_possible]
            u_c = Uc.(c, n)
            Eu_c = dot(Π[s_, sprimei_possible], u_c)
            out .= x * u_c/Eu_c - u_c .* (c - TT) - Un(c, n) .* n - β * xprime
        end
        function cons_no_trans(out, z, grad)
            c, xprime = z[1:S_possible], z[S_possible + 1:2S_possible]
            n = (c .+ G[sprimei_possible]) ./ Θ[sprimei_possible]
            u_c = Uc.(c, n)
            Eu_c = dot(Π[s_, sprimei_possible], u_c)
            out .= x * u_c / Eu_c - u_c .* c - Un(c, n) .* n - β * xprime
        end

        if model.transfers == true
            lb = vcat(zeros(S_possible), ones(S_possible)*xbar[1],
↪zeros(S_possible))
            if model.n_less_than_one == true
                ub = vcat(ones(S_possible) - G[sprimei_possible],
                        ones(S_possible) * xbar[2], ones(S_possible))
            else
                ub = vcat(100 * ones(S_possible),
                        ones(S_possible) * xbar[2],
```

```
                        100 * ones(S_possible))
            end
            init = vcat(T.z0[i_x, s_][sprimei_possible],
                        T.z0[i_x, s_][2S .+ sprimei_possible],
                        T.z0[i_x, s_][3S .+ sprimei_possible])
            opt = Opt(:LN_COBYLA, 3S_possible)
            equality_constraint!(opt, cons, zeros(S_possible))
        else
            lb = vcat(zeros(S_possible), ones(S_possible)*xbar[1])
            if model.n_less_than_one == true
                ub = vcat(ones(S_possible)-G[sprimei_possible],
↪ones(S_possible)*xbar[2])
            else
                ub = vcat(ones(S_possible), ones(S_possible) * xbar[2])
            end
            init = vcat(T.z0[i_x, s_][sprimei_possible],
                        T.z0[i_x, s_][2S .+ sprimei_possible])
            opt = Opt(:LN_COBYLA, 2S_possible)
            equality_constraint!(opt, cons_no_trans, zeros(S_possible))
        end
        init[init .> ub] = ub[init .> ub]
        init[init .< lb] = lb[init .< lb]

        min_objective!(opt, objf)
        lower_bounds!(opt, lb)
        upper_bounds!(opt, ub)
        maxeval!(opt, 10000000)
        maxtime!(opt, 10)
        ftol_rel!(opt, 1e-8)
        ftol_abs!(opt, 1e-8)

        (minf, minx, ret) = optimize(opt, init)

        if ret != :SUCCESS && ret != :ROUNDOFF_LIMITED && ret != :
↪MAXEVAL_REACHED &&
            ret != :FTOL_REACHED && ret != :MAXTIME_REACHED
            error("optimization failed: ret = $ret")
        end

        T.z0[i_x, s_][sprimei_possible] = minx[1:S_possible]
        T.z0[i_x, s_][S .+ sprimei_possible] = minx[1:S_possible] .+
↪G[sprimei_possible]
        T.z0[i_x, s_][2S .+ sprimei_possible] = minx[S_possible .+ 1:
↪2S_possible]
        if model.transfers == true
            T.z0[i_x, s_][3S .+ sprimei_possible] = minx[2S_possible + 1:
↪3S_possible]
        else
            T.z0[i_x, s_][3S .+ sprimei_possible] = zeros(S)
        end

        return vcat(-minf, T.z0[i_x, s_])
    end


    function get_policies_time0(T::BellmanEquation_Recursive,
                                B_::Real,
                                s0::Integer,
```

```
                                Vf::AbstractArray{Function},
                                xbar::AbstractVector)
        model = T.model
        β, Θ, G = model.β, model.Θ, model.G
        U, Uc, Un = model.U, model.Uc, model.Un

        function objf(z, grad)
            c, xprime = z[1], z[2]
            n = (c + G[s0]) / Θ[s0]
            return -(U(c, n) + β * Vf[s0](xprime))
        end

        function cons(z,grad)
            c, xprime, TT = z[1], z[2], z[3]
            n = (c + G[s0]) / Θ[s0]
            return -Uc(c, n) * (c - B_ - TT) - Un(c, n) * n - β * xprime
        end
        cons_no_trans(z, grad) = cons(vcat(z, 0), grad)

        if model.transfers == true
            lb = [0.0, xbar[1], 0.0]
            if model.n_less_than_one == true
                ub = [1 - G[s0], xbar[2], 100]
            else
                ub = [100.0, xbar[2], 100.0]
            end
            init = vcat(T.zFB[s0][1], T.zFB[s0][3], T.zFB[s0][4])
            init = [0.95124922, -1.15926816,  0.0]
            opt = Opt(:LN_COBYLA, 3)
            equality_constraint!(opt, cons)
        else
            lb = [0.0, xbar[1]]
            if model.n_less_than_one == true
                ub = [1-G[s0], xbar[2]]
            else
                ub = [100, xbar[2]]
            end
            init = vcat(T.zFB[s0][1], T.zFB[s0][3])
            init = [0.95124922, -1.15926816]
            opt = Opt(:LN_COBYLA, 2)
            equality_constraint!(opt, cons_no_trans)
        end
        init[init .> ub] = ub[init .> ub]
        init[init .< lb] = lb[init .< lb]


        min_objective!(opt, objf)
        lower_bounds!(opt, lb)
        upper_bounds!(opt, ub)
        maxeval!(opt, 100000000)
        maxtime!(opt, 30)

        (minf, minx, ret) = optimize(opt, init)

        if ret != :SUCCESS && ret != :ROUNDOFF_LIMITED && ret != :
↪MAXEVAL_REACHED &&
            ret != :FTOL_REACHED
                error("optimization failed: ret = $ret")
```

```
    end

    if model.transfers == true
        return -minf, minx[1], minx[1]+G[s0], minx[2], minx[3]
    else
        return -minf, minx[1], minx[1]+G[s0], minx[2], 0
    end
end
```

```
Out[4]: get_policies_time0 (generic function with 2 methods)
```

63.5 Examples

We now turn to some examples.

63.5.1 Anticipated One-Period War

In our lecture on optimal taxation with state contingent debt we studied how the government manages uncertainty in a simple setting.

As in that lecture, we assume the one-period utility function

$$u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma}$$

Note

For convenience in matching our computer code, we have expressed utility as a function of n rather than leisure l

We consider the same government expenditure process studied in the lecture on optimal taxation with state contingent debt.

Government expenditures are known for sure in all periods except one

- For $t < 3$ or $t > 3$ we assume that $g_t = g_l = 0.1$.
- At $t = 3$ a war occurs with probability 0.5.
  - If there is war, $g_3 = g_h = 0.2$.
  - If there is no war $g_3 = g_l = 0.1$.

A useful trick is to define components of the state vector as the following six (t, g) pairs:

$$(0, g_l), (1, g_l), (2, g_l), (3, g_l), (3, g_h), (t \geq 4, g_l)$$

We think of these 6 states as corresponding to $s = 1, 2, 3, 4, 5, 6$.

The transition matrix is

$$P = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The government expenditure at each state is

$$g = \begin{pmatrix} 0.1 \\ 0.1 \\ 0.1 \\ 0.1 \\ 0.2 \\ 0.1 \end{pmatrix}$$

We assume the same utility parameters as in the Lucas-Stokey economy.

This utility function is implemented in the following constructor

In [5]:
```
function crra_utility(;
        β = 0.9,
        σ = 2.0,
        γ = 2.0,
        Π = 0.5 * ones(2, 2),
        G = [0.1, 0.2],
        Θ = ones(Float64, 2),
        transfers = false
        )
        function U(c, n)
            if σ == 1.0
                U = log(c)
            else
                U = (c.^(1.0 - σ) - 1.0) / (1.0 - σ)
            end
            return U - n.^(1 + γ) / (1 + γ)
        end
        # Derivatives of utility function
        Uc(c,n) =  c.^(-σ)
        Ucc(c,n) = -σ * c.^(-σ - 1.0)
        Un(c,n) = -n.^γ
        Unn(c,n) = -γ * n.^(γ - 1.0)
        n_less_than_one = false
        return Model(β, Π, G, Θ, transfers,
                     U, Uc, Ucc, Un, Unn, n_less_than_one)
    end
```

Out[5]:
```
crra_utility (generic function with 1 method)
```

The following figure plots the Ramsey plan under both complete and incomplete markets for both possible realizations of the state at time $t = 3$.

Optimal policies when the government has access to state contingent debt are represented by black lines, while the optimal policies when there is only a risk free bond are in red.

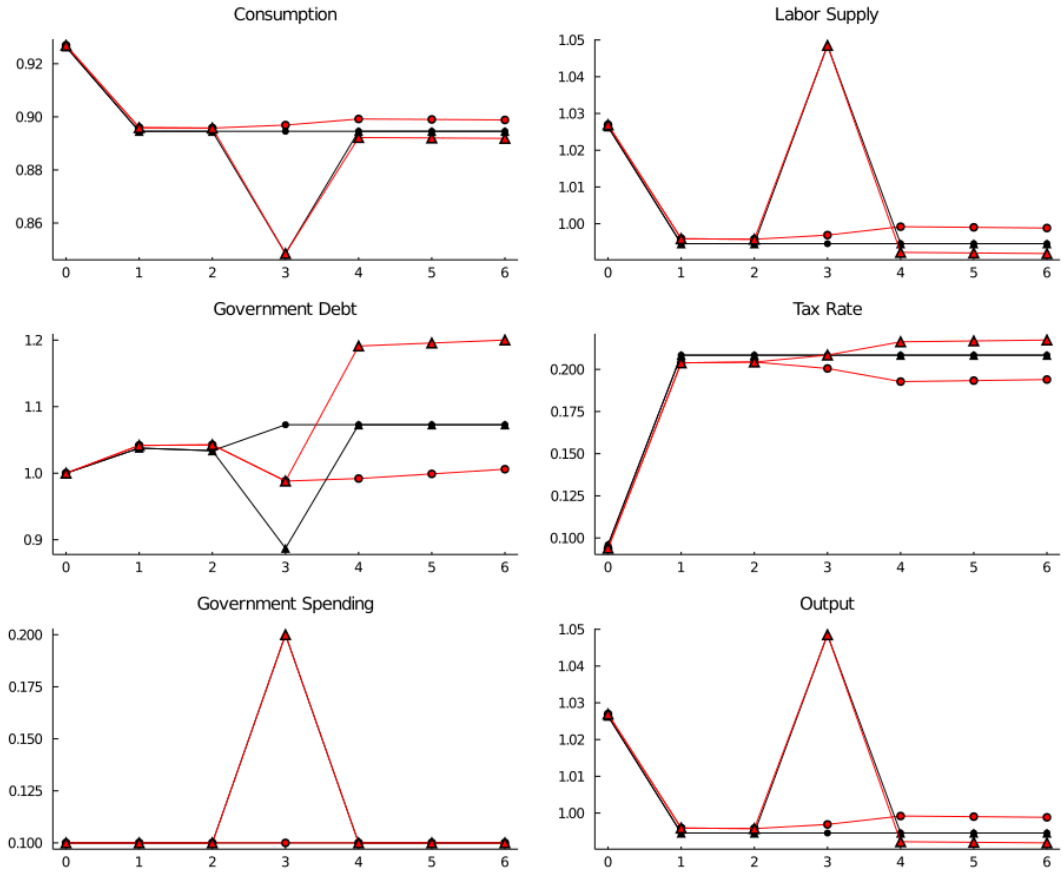
Paths with circles are histories in which there is peace, while those with triangle denote war.

```
In [6]: time_example = crra_utility(G=[0.1, 0.1, 0.1, 0.2, 0.1, 0.1],
                                    Θ = ones(6)) # Θ can in principle be random

        time_example.Π = [ 0.0 1.0 0.0 0.0 0.0 0.0;
                           0.0 0.0 1.0 0.0 0.0 0.0;
                           0.0 0.0 0.0 0.5 0.5 0.0;
                           0.0 0.0 0.0 0.0 0.0 1.0;
                           0.0 0.0 0.0 0.0 0.0 1.0;
                           0.0 0.0 0.0 0.0 0.0 1.0]

        # Initialize μgrid for value function iteration
        μgrid = range(-0.7, 0.01, length = 200)

        time_example.transfers = true  # Government can use transfers
        time_sequential = SequentialAllocation(time_example) # Solve sequential
    problem

        time_bellman = RecursiveAllocation(time_example, μgrid)

        sHist_h = [1, 2, 3, 4, 6, 6, 6]
        sHist_l = [1, 2, 3, 5, 6, 6, 6]

        sim_seq_h = simulate(time_sequential, 1., 1, 7, sHist_h)
        sim_bel_h = simulate(time_bellman, 1., 1, 7, sHist_h)
        sim_seq_l = simulate(time_sequential, 1., 1, 7, sHist_l)
        sim_bel_l = simulate(time_bellman, 1., 1, 7, sHist_l)

        using Plots
        gr(fmt=:png);
        titles = hcat("Consumption", "Labor Supply", "Government Debt",
                      "Tax Rate", "Government Spending", "Output")
        sim_seq_l_plot = hcat(sim_seq_l[1:3]..., sim_seq_l[4],
                              time_example.G[sHist_l],
                              time_example.Θ[sHist_l] .* sim_seq_l[2])
        sim_bel_l_plot = hcat(sim_bel_l[1:3]..., sim_bel_l[5],
                              time_example.G[sHist_l],
                              time_example.Θ[sHist_l] .* sim_bel_l[2])
        sim_seq_h_plot = hcat(sim_seq_h[1:3]..., sim_seq_h[4],
                              time_example.G[sHist_h],
                              time_example.Θ[sHist_h] .* sim_seq_h[2])
        sim_bel_h_plot = hcat(sim_bel_h[1:3]..., sim_bel_h[5],
                              time_example.G[sHist_h],
                              time_example.Θ[sHist_h] .* sim_bel_h[2])
        p = plot(size = (920, 750), layout =(3, 2),
         xaxis=(0:6), grid=false, titlefont=Plots.font("sans-serif", 10))
        plot!(p, title = titles)
        for i=1:6
            plot!(p[i], 0:6, sim_seq_l_plot[:, i], marker=:circle, color=:black,
    lab="")
            plot!(p[i], 0:6, sim_bel_l_plot[:, i], marker=:circle, color=:red,
    lab="")
            plot!(p[i], 0:6, sim_seq_h_plot[:, i], marker=:utriangle, color=:
    black, lab="")
            plot!(p[i], 0:6, sim_bel_h_plot[:, i], marker=:utriangle, color=:red,
    lab="")
        end
```

```
p
```

```
    diff = 0.01954181139136142
diff = 0.020296606343314445
diff = 0.01825290333882874
diff = 0.01732330130265356
diff = 0.002438290769982288
diff = 0.0017049947758874273
diff = 0.001491200081454862
diff = 0.0008415716013777662
diff = 0.0006551802043226648
diff = 0.0005101110034210979
diff = 0.00045899123671075637
diff = 0.0004130378473633363
diff = 0.00037165554806329687
diff = 0.00033441325852100494
diff = 0.0003008983054583036
diff = 0.0002707536359176724
diff = 0.00024362702609734803
diff = 0.0002192208026612293
diff = 0.00019723701023064875
diff = 0.00017750553015148367
diff = 0.00015972217622243714
diff = 0.00014373496579809245
diff = 0.00012934400797986716
diff = 0.00011639475826865351
diff = 0.00010474335075915266
diff = 9.425940404825291e-5
```

Out[6]:



How a Ramsey planner responds to war depends on the structure of the asset market.

If it is able to trade state-contingent debt, then at time $t = 2$

- the government purchases an Arrow security that pays off when $g_3 = g_h$
- the government sells an Arrow security that pays off when $g_3 = g_l$
- These purchases are designed in such a way that regardless of whether or not there is a war at $t = 3$, the government will begin period $t = 4$ with the *same* government debt.

This pattern facilities smoothing tax rates across states.

The government without state contingent debt cannot do this.

Instead, it must enter time $t = 3$ with the same level of debt falling due whether there is peace or war at $t = 3$.

It responds to this constraint by smoothing tax rates across time.

To finance a war it raises taxes and issues more debt.

To service the additional debt burden, it raises taxes in all future periods.

The absence of state contingent debt leads to an important difference in the optimal tax policy.

When the Ramsey planner has access to state contingent debt, the optimal tax policy is history independent

- the tax rate is a function of the current level of government spending only, given the Lagrange multiplier on the implementability constraint.

Without state contingent debt, the optimal tax rate is history dependent.

- A war at time $t = 3$ causes a permanent increase in the tax rate.

Perpetual War Alert

History dependence occurs more dramatically in a case in which the government perpetually faces the prospect of war.

This case was studied in the final example of the lecture on optimal taxation with state-contingent debt.

There, each period the government faces a constant probability, 0.5, of war.

In addition, this example features the following preferences

$$u(c, n) = \log(c) + 0.69 \log(1 - n)$$

In accordance, we will re-define our utility function

In [7]:
```
function log_utility(;β = 0.9,
                      ψ = 0.69,
                      Π = 0.5 * ones(2, 2),
                      G = [0.1, 0.2],
                      Θ = ones(2),
                      transfers = false)
    # Derivatives of utility function
    U(c,n) = log(c) + ψ * log(1 - n)
    Uc(c,n) = 1 ./ c
```

```
        Ucc(c,n) = -c.^(-2.0)
        Un(c,n) = -ψ ./ (1.0 .- n)
        Unn(c,n) = -ψ ./ (1.0 .- n).^2.0
        n_less_than_one = true
        return Model(β, Π, G, Θ, transfers,
                     U, Uc, Ucc, Un, Unn, n_less_than_one)
    end
```

```
Out[7]: log_utility (generic function with 1 method)
```

With these preferences, Ramsey tax rates will vary even in the Lucas-Stokey model with state-contingent debt.

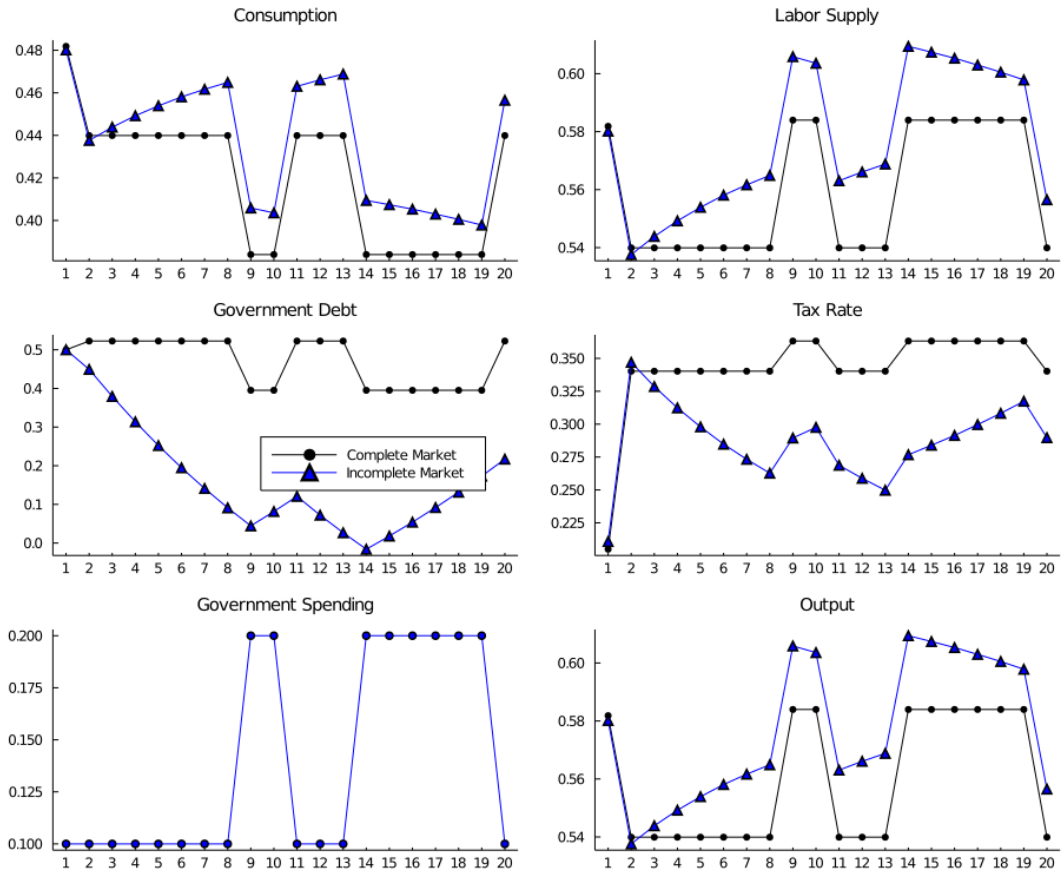
The figure below plots optimal tax policies for both the economy with state contingent debt (circles) and the economy with only a risk-free bond (triangles)

```
In [8]: log_example = log_utility()

    log_example.transfers = true                                # Government can
↪use transfers
    log_sequential = SequentialAllocation(log_example)          # Solve
↪sequential problem
    log_bellman = RecursiveAllocation(log_example, μgrid)       # Solve recursive
↪problem

    T = 20
    sHist = [1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1, 1, 2, 2, 2, 2, 2, 2, 1]

    #simulate
    sim_seq = simulate(log_sequential, 0.5, 1, T, sHist)
    sim_bel = simulate(log_bellman, 0.5, 1, T, sHist)

    sim_seq_plot = hcat(sim_seq[1:3]...,
                  sim_seq[4], log_example.G[sHist], log_example.Θ[sHist] .*
↪sim_seq[2])
    sim_bel_plot = hcat(sim_bel[1:3]...,
                  sim_bel[5], log_example.G[sHist], log_example.Θ[sHist] .*
↪sim_bel[2])

    #plot policies
    p = plot(size = (920, 750), layout = grid(3, 2),
             xaxis=(0:T), grid=false, titlefont=Plots.font("sans-serif", 10))
    labels = fill(("", ""), 6)
    labels[3] = ("Complete Market", "Incomplete Market")
    plot!(p, title = titles)
    for i = vcat(collect(1:4), 6)
        plot!(p[i], sim_seq_plot[:, i], marker=:circle, color=:black,
↪lab=labels[i][1])
        plot!(p[i], sim_bel_plot[:, i], marker=:utriangle, color=:blue,
↪lab=labels[i][2],
              legend=:bottomright)
    end
    plot!(p[5], sim_seq_plot[:, 5], marker=:circle, color=:blue, lab="")
```

```
   diff = 0.0007972378476372139
diff = 0.0006423560333504441
```

```
diff = 0.0005517441622530832
diff = 0.00048553930013351857
diff = 0.0004226590836939342
diff = 0.00037550672316976404
diff = 0.0003294032122270672
diff = 0.00029337232321718974
diff = 0.00025856795048240623
diff = 0.00023042624865279873
diff = 0.0002031214087191915
diff = 0.00018115282833643646
diff = 0.00016034374751970243
diff = 0.00014294960573402432
diff = 0.000126758581715890033
diff = 0.00011295205489914281
diff = 0.00010030878977062024
diff = 8.934103186095062e-5
```

Out[8]:



When the government experiences a prolonged period of peace, it is able to reduce government debt and set permanently lower tax rates.

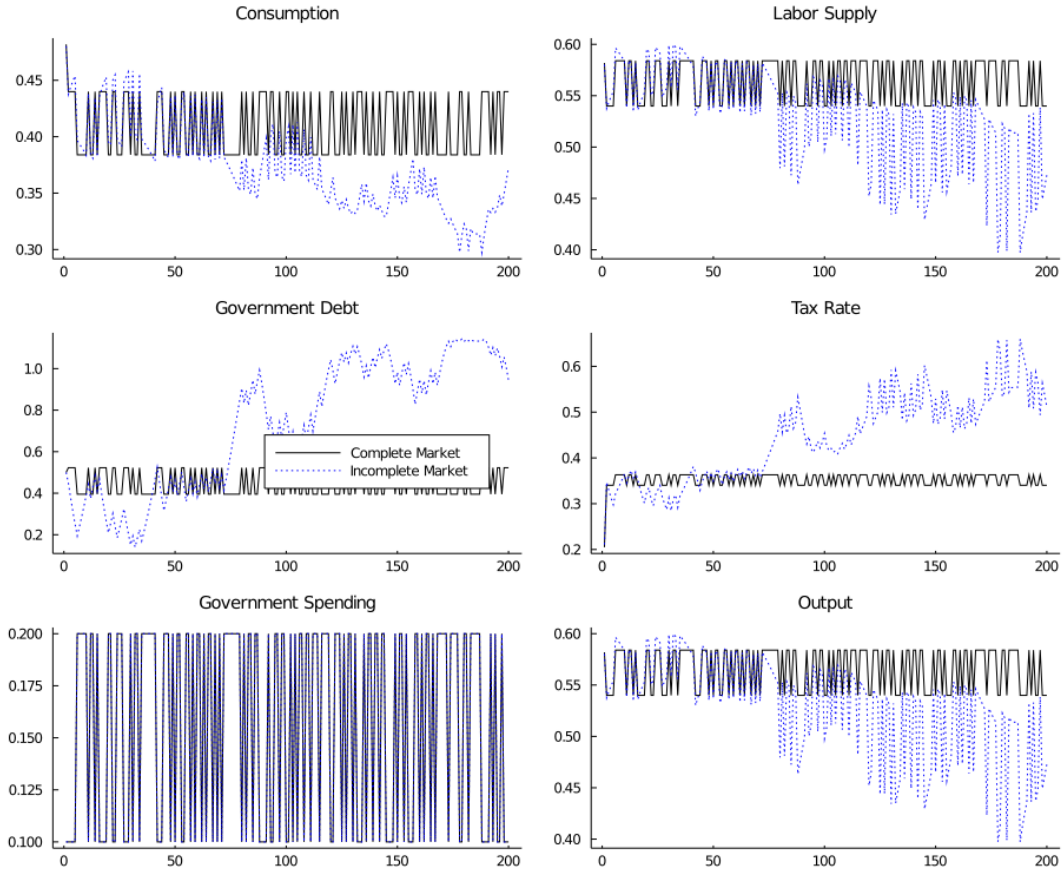
However, the government finances a long war by borrowing and raising taxes.

This results in a drift away from policies with state contingent debt that depends on the history of shocks.

This is even more evident in the following figure that plots the evolution of the two policies over 200 periods

```
In [9]: T_long = 200
        sim_seq_long = simulate(log_sequential, 0.5, 1, T_long)
        sHist_long = sim_seq_long[end-2]
        sim_bel_long = simulate(log_bellman, 0.5, 1, T_long, sHist_long)
        sim_seq_long_plot = hcat(sim_seq_long[1:4]...,
                        log_example.G[sHist_long], log_example.Θ[sHist_long] .*
    ↪sim_seq_long[2])
        sim_bel_long_plot = hcat(sim_bel_long[1:3]..., sim_bel_long[5],
                        log_example.G[sHist_long], log_example.Θ[sHist_long] .*
    ↪sim_bel_long[2])

        p = plot(size = (920, 750), layout = (3, 2), xaxis=(0:50:T_long),
    ↪grid=false,
                    titlefont=Plots.font("sans-serif", 10))
        plot!(p, title = titles)
        for i = 1:6
            plot!(p[i], sim_seq_long_plot[:, i], color=:black, linestyle=:solid,
        lab=labels[i][1])
            plot!(p[i], sim_bel_long_plot[:, i], color=:blue, linestyle=:dot,
    ↪lab=labels[i][2],
                    legend=:bottomright)
        end
        p
```

Out[9]:



Footnotes

[1] In an allocation that solves the Ramsey problem and that levies distorting taxes on labor, why would the government ever want to hand revenues back to the private sector? It would not in an economy with state-contingent debt, since any such allocation could be improved by lowering distortionary taxes rather than handing out lump-sum transfers. But without state-contingent debt there can be circumstances when a government would like to make lump-sum transfers to the private sector.

[2] From the first-order conditions for the Ramsey problem, there exists another realization $\tilde{s}^t$ with the same history up until the previous period, i.e., $\tilde{s}^{t-1} = s^{t-1}$, but where the multiplier on constraint (11) takes a positive value, so $\gamma_t(\tilde{s}^t) > 0$.

Bibliography

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