Primer on LFPy2.0

CNS2019 Tutorial T8 part II

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Slides: https://tinyurl.com/CNS2019-LFPy

Outline

Why model extracellular potentials?

- **Increase understanding of experimental measurements:**
  - Action potential waveforms:
    - Gold et al. *J Neurophysiol* (2006)
    - Pettersen & Einevoll. *Biophys J* (2008)
    - Hagen et al. *J Neurosci Methods* (2015)
    - Ness et al. *Neuroinform* (2015)
    - Michalikova et al. J Neurophysiol (2018)
  - Active ion channel component of LFP:
    - Schomburg et al. *J. Neurosci* (2012)
    - Reimann et al. *Neuron* (2013)
    - Ness et al. *J Physiol* (2016); *J Neurosci* (2018)

Why model extracellular potentials?

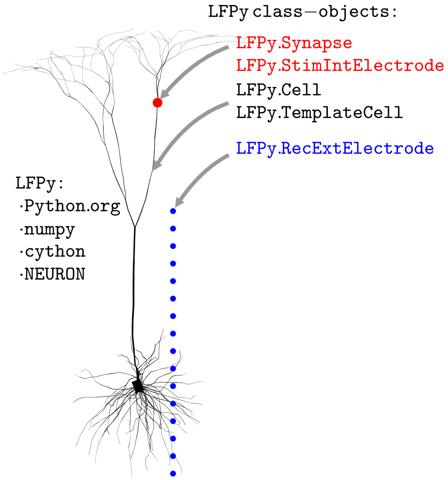
- **Increase understanding of experimental measurements:**
  - Spectral content of LFP:
    - Lindén et al. *J Comput Neurosci* (2010)
    - Tomsett et al. *Brain Struct Funct* (2014)
  - Reach of LFP:
    - Lindén et al. *Neuron* (2011)
    - Łęski et al. *PLOS Comput Biol* (2013)
    - Hagen et al. *J Neurosci* (2017) (monosynaptic)
  - EEG and MEG:
    - Næss et al. *Front Human Neurosci* (2017)
    - Hagen et al. *Front Neuroinform* (2018)
    - Mäki-Marttunen et al. *Cereb Cortex* (2019)
  - Effect of network correlations:
    - Hagen et al. *Cereb Cortex* (2016)
  - Single-axon pre- and post-synaptic LFPs
    - McColgan et al. *BioR$_x$iv* (2017)
    - Hagen et al. *J Neurosci* (2017)

Why model extracellular potentials?

- **Methods validation (with known ground truth):**
  - Spike sorting:
    - Franke et al. *Proc IEEE Eng Med Biol Soc* (2010)
    - Einevoll et al. *Curr Op Neurobiol* (2012),
    - Thorbergsson et al. *J Neurosci Methods* (2013)
    - Hagen et al. *J Neurosci Methods* (2015)
    - Buccino et al. *J Neurophysiol, J Neur Eng* (2018)
  - Current-source density (CSD) reconstruction:
    - Pettersen et al. *J Comput Neurosci* (2008)
    - Łęski et al. *Neuroinform* (2011)
    - Głąbska et al. *PLOS One* (2014)
    - Ness et al. *Neuroinform* (2015)
    - Cserpan et al. *eLife* (2017)
  - Laminar Population Analysis (LPA)
    (Einevoll et al. *J Neurophysiol* (2007))
    - Głąbska et al. *Front Neuroinform* (2016)

LFPy - Introduction

- Methods implementation
  - multicompartment neurons, networks
  - extracellular potentials
  - ‘distal’ EEG and MEG signals
- Implemented in `Python`
- Uses `NEURON` under the hood
- Class objects represent:
  - cells, populations, networks
  - synapses
  - intracellular electrodes
  - extracellular electrodes
- Homepages w. documentation:
  http://LFPy.rtfd.io
  https://github.com/LFPy/LFPy



LFPy

Developed by:

- Henrik Lindén, Espen Hagen, Szymon Łęski, Eivind S. Norheim, Klas H. Pettersen, Torbjørn V. Ness, Solveig Næss, Alessio Buccino, Svenn-Arne Dragly, Alex Stasik, Gaute T. Einevoll
- It's open source - anyone can contribute!

Homepages:

- https://LFPy.rtfd.io (documentation)
- https://github.com/LFPy/LFPy
  (source code, revision and issue tracking, pull requests)

LFPy Homepage

(Looking for the old LFPy documentation? Follow link)

LFPy is a Python package for calculation of extracellular potentials from multicompartment neuron models and recurrent networks of multicompartment neurons. It relies on the NEURON simulator and uses the Python interface it provides.

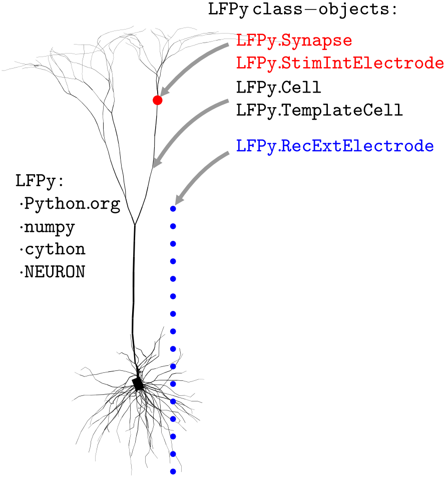
Active development of LFPy, as well as issue tracking and revision tracking, relies on GitHub.com and git (git-scm.com). Clone LFPy on GitHub.com: `git clone https://github.com/LFPy/LFPy.git`

LFPy provides a set of easy-to-use Python classes for setting up your model, running your simulations and calculating the extracellular potentials arising from activity in your model neuron. If you have a model working in NEURON or NeuroML2 already, it is likely that it can be adapted to work with LFPy.

LFPy - Introduction

Why Python?

- Open source
- Easy, flexible coding
- Plethora of available packages for visualizations and analysis
- http://pypi.python.org: $\mathcal{O}(187,000)$ projects
- Interfacing other programming languages and software
  - `C, C++, Fortran, ...`
  - `NEURON, NEST, Brian, PyNN, Nengo, ...`



LFPy - Introduction

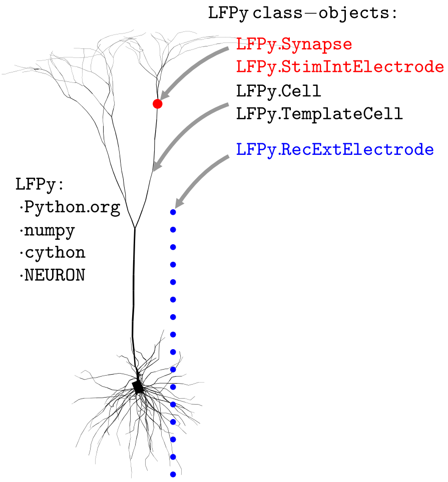
Python class objects

- Object Oriented Programming (OOP)
- arbitrary amounts and kinds of data
- contains methods and attributes
- created @ runtime, modifiable:

```python
class MyClass(object):
    def __init__(self, arg0=1, arg1='hi!'):
        '''init class MyClass'''
        self.arg0 = arg0
        self.arg1 = arg1
    def myClassMethod(self, arg=2):
        '''do some operation'''
        return self.arg0 + arg
if __name__ == "__main__":
    c = MyClass(arg0=3,
                arg1='hello')
    print(c.myClassMethod(arg2=3))
    print(c.arg1)
```

LFPy - Requirements

- `Python 2.7 & >=3.4`
- Essential dependencies (install/runtime):
  - `neuron>=7.6.5`
  - `setuptools>=23.1.0`
  - `numpy>=1.8`
  - `scipy>=0.14`
  - `Cython>=0.20`
  - `h5py>=2.5`
  - `mpi4py>=1.2`
  - `matplotlib>=2.0`
- Soft (examples etc.):
  - `ipython`
  - `jupyter notebook`
  - `py.test, sphinx`



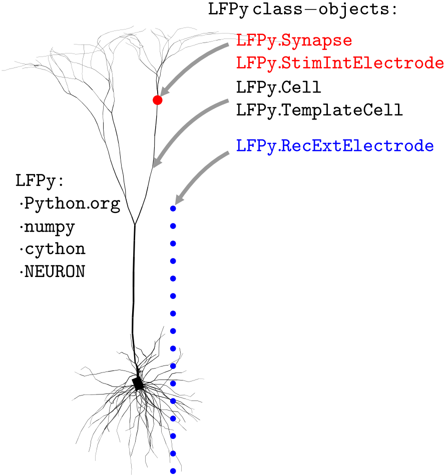
LFPy - Requirements

Python distributions:

- Python.org
- Anaconda/Miniconda
- Enthought Canopy
- Python(x,y)
- ...

LFPy platforms:

- *nix (Linux, Unix)
- macOS
- Windows



LFPy - Installation

Installation:

Easy method:

- `pip install LFPy --user`

As super user:

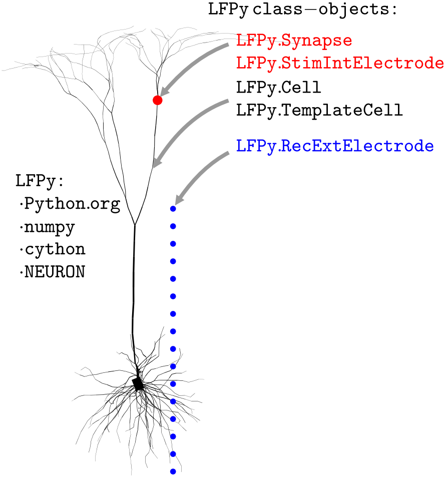
- `sudo pip install LFPy`

Upgrading previous install:

- `pip install --upgrade LFPy --no-deps`

Getting rid of it:

- `pip uninstall LFPy`



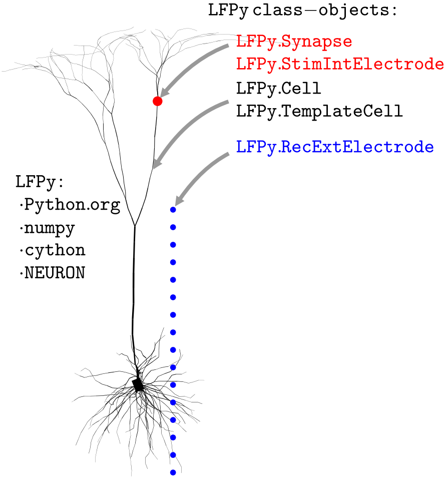
LFPy - Installation w. Conda (macos/linux)

Installation:
Get Anaconda Python
(https://anaconda.org)
In current environment:

- `conda config --add channels conda-forge`
- `conda config --set channel_priority strict`
- `conda install lfpy`

New environment:

- `conda create -n lfpyenv python=3 lfpy`
- `conda activate lfpyenv`
- (`conda install ipython` etc.)



LFPy - Installation

Install using `LFPy` source files:

- Tar.gz-archive:

```
cd $HOME/Sources
wget https://github.com/LFPy/LFPy/archive/LFPy-2.0.3.tar.gz
tar -xzvf LFPy-2.0.3.tar.gz
```

  (unzipped in folder `LFPy-2.0.3`)

- Development version:

```
cd $HOME/Sources
git clone https://github.com/LFPy/LFPy.git LFPy
cd LFPy
git checkout master
```

- Tagged versions:

```
git tag -l # list tags
git checkout v2.0.3
```

- `git`: Much-used distributed source code management system. See https://git-scm.com

LFPy - Installation

Install using `LFPy` source files:

- Perform a local installation:

```
cd $HOME/Sources/LFPy
pip install -r requirements.txt --user
python setup.py install --user
```

- Global installation (super user):

```
sudo python setup.py install
```

- Use LFPy from source folder (for active development):

```
python setup.py develop --user
```

LFPy - Installation

Test installation:

With Python:

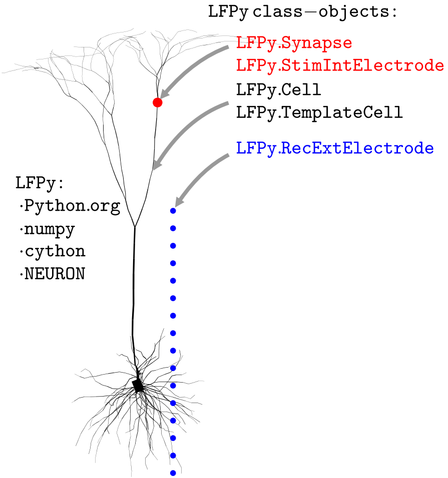
- `python -c "import LFPy"`

  NEURON -- VERSION 7.7.0-5-g0905f228...

With NEURON:

- `nrngui -python -c "import LFPy"`

  NEURON -- VERSION 7.7.0-5-g0905f228...



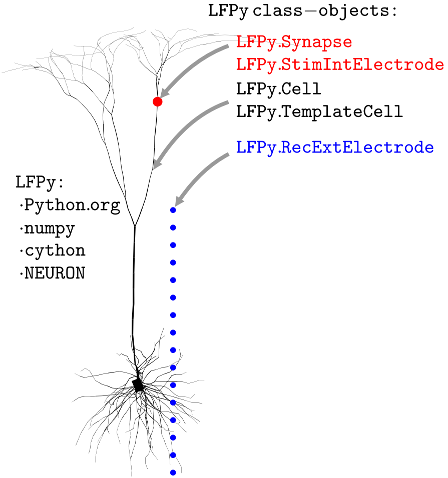
LFPy - Class overview

Main LFPy classes:

- Cell, TemplateCell, NetworkCell
- Network, NetworkPopulation
- Synapse, StimIntElectrode
- RecExtElectrode, RecMEAElectrode
- OneSphereVolumeConductor, FourSphereVolumeConductor, InfiniteVolumeConductor
- MEG

Auxilliary classes and functions:

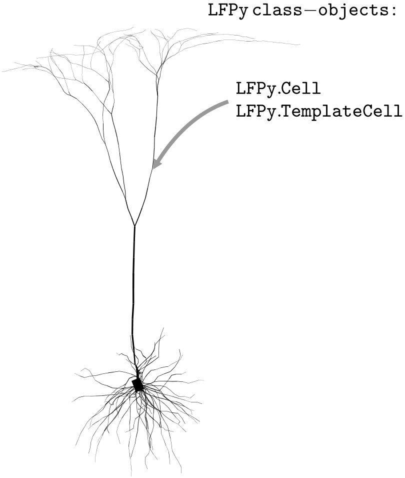
- lfpcalc.calc_lfp.⋆
- inputgenerators.⋆
- tools.⋆ and more...



LFPy - Class overview

LFPy.Cell:

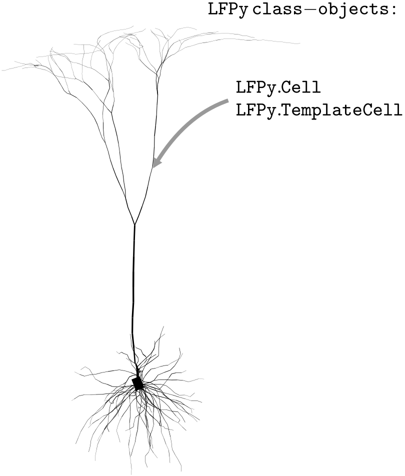
- Uses NEURON under the hood
- Sets neuron properties:
  - neuron geometry
  - membrane mechanisms ('pas', 'hh', ...)
  - number of compartments ('d_lambda' rule; Hines&Carnevale. *Neuroscientist* (2001))
  - Sets cell location and rotation
- Simulation control
  - duration
  - record variables



LFPy - Class overview

LFPy.Cell:

- Keyword arguments:
  - morphology file (morphology)
  - passive parameters (passive, cm, Ra, V_init, g_pas, e_pas)
  - time and space discretization (nsegs_methods)
  - simulation duration (tstop)
  - custom codes (custom_code)

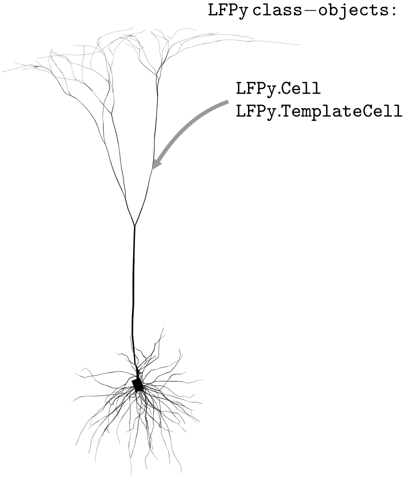


LFPy - Class overview

LFPy.Cell:

- Download morphology (`j4a.hoc` file) https://goo.gl/twpdrX
- Create parameter dictionary

```
# Define cell parameters
cell_parameters = dict(
    morphology='j4a.hoc',
    cm=1.,          # uF cm-2
    Ra=150.,        # ohm cm
    v_init=-65.,  # mV
    passive=True,
    passive_parameters=dict(
        g_pas=1./3E4, # S cm-2
        e_pas=-65.,    # mV
    ),
    tstop=100.,   # ms
)
```



LFPy - Class overview

LFPy.Cell:

- Create `cell` object:

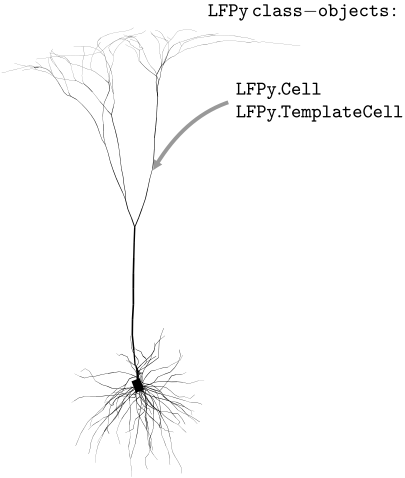
```
cell = LFPy.Cell(
    **cell_parameters)
```

- Position and align cell:

```
cell.set_pos(
    x=0., y=0., z=0.) # um
cell.set_rotation(
    x=4.99, y=-4.33, z=3.14) # rad
```

- (`cell` stimulation)
- simulate & plot `cell` response

```
cell.simulate(rec_isyn=True/False,
              rec_istim=True/False,
              rec_imem=True/False,
              rec_vmem=True/False)
import matplotlib.pyplot as plt
plt.plot(cell.tvec, cell.somav)
```



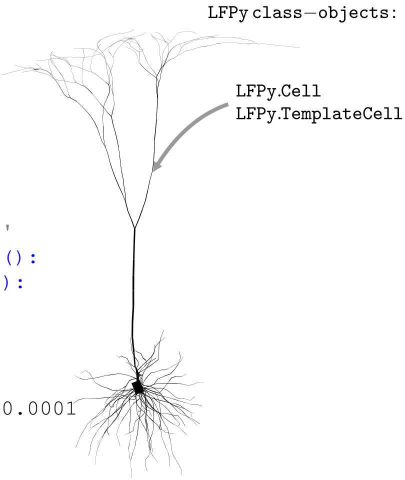
LFPy - Class overview

LFPy.Cell:

- Customizing the model:
  - passive mechanism disabled by default
  - `custom_fun` argument

```
def my_biophys():
    '''set custom parameters'''
    for sec in neuron.h.allsec():
        if "soma" in sec.name():
            sec.insert("hh")
        else:
            sec.insert("pas")
            for seg in sec:
                seg.pas.g_pas=0.0001
cell = LFPy.Cell(morphology,
    custom_fun=[my_biophys],
    **cell_parameters)
```

  - `custom_code` point to code files



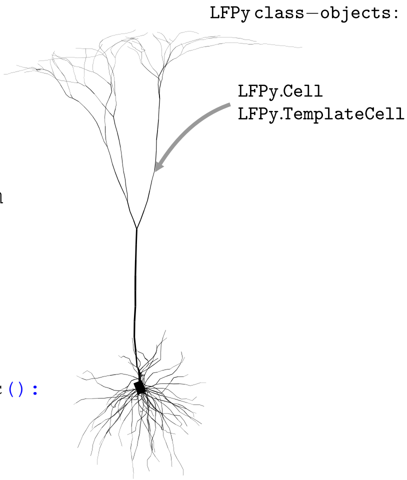
LFPy - Class overview

LFPy.Cell:

- Important `Cell`-class methods:
  - `c.get_idx`
  - `c.get_closest_idx`
  - `c.get_rand_idx_area_norm`
  - `c.get_idx_name`
- Important class attributes:
  - `c.totnsegs`

    ```
    i = 0:
    for sec in neuron.h.allsec():
        for seg in sec:
            i += 1
    ```

  - `c.⋆start, c.⋆mid, c.⋆end`
    $\star \in [x, y, z]$



LFPy - Class overview

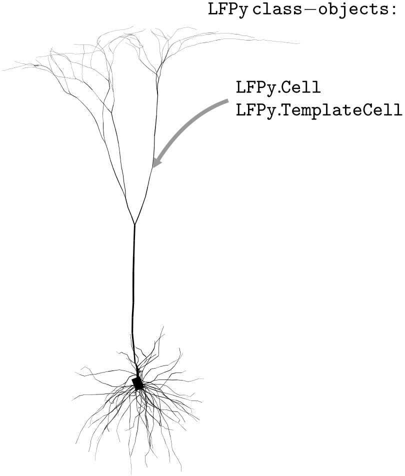
LFPy.Cell:

- **LFPy.Cell** objects are transparent to NEURON:

```
import LFPy
import neuron.h as nrn

cell = LFPy.Cell('j4a.hoc',
                 passive=True)
for sec in nrn.soma:
    sec.insert("hh")
    for seg in sec:
        seg.pas.g_pas = 0.
```

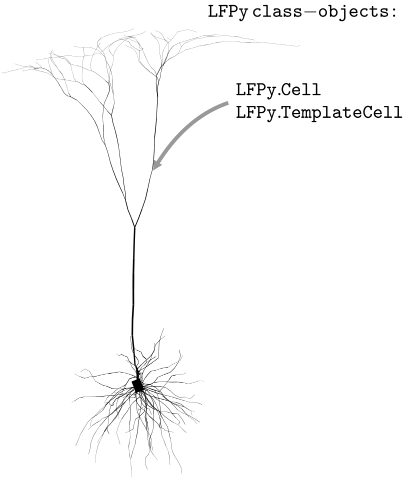
(only ‘HH’ conductances in soma)



LFPy - Class overview

LFPy.Cell: Sections created in Python:

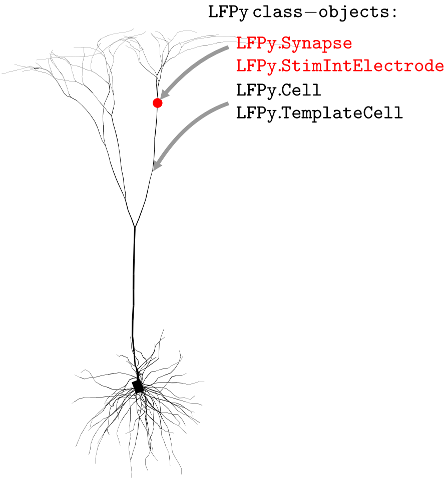
```
import neuron, LFPy
morph = neuron.h.SectionList()
soma = neuron.h.Section(name='soma')
dend = neuron.h.Section(name='dend')
morph.append(sec=soma)
morph.append(sec=dend)
soma.L = 30
soma.diam = 30
dend.L = 300
dend.diam = 2
dend.connect(soma, 1, 0)
cell = LFPy.Cell(morphology=morph,
                 delete_sections=False,
                 passive=True,
                 **kwargs)
...
```



LFPy - Class overview

LFPy.Synapse:

- Attach synapse-objects onto `cell`
- event-activated point currents
- Keyword arguments:
  - `cell`-object
  - compartment index (`idx`)
  - synapse type (`ExpSyn`, `Exp2syn`, `AlphaSynapse`)
  - mechanism arguments (`e`, `tau`, `weight`, ...)
  - record synapse current (`record_current`)
- Feed in activation times: drawn offline or on the fly



LFPy - Class overview

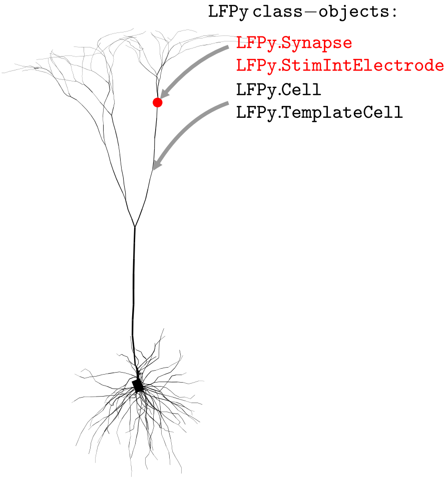
LFPy.Synapse:

- Define synapse parameters

```
synapse_parameters = dict(
    idx=cell.get_closest_idx(
        x=-200., # um
        y=0.,    # um
        z=800.), # um
    syntype='ExpSyn',
    e=0.,         # mV
    tau=5.,       # ms
    weight=.001,  # uS
    record_current=True,)
```

- Create synapse, set activation time

```
syn = LFPy.Synapse(cell,
    **synapse_parameters)
```



LFPy - Class overview

LFPy.Synapse:

- Create synapse, set activation time

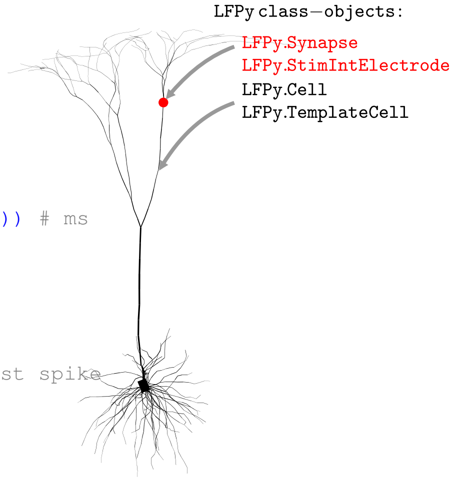
```
syn = LFPy.Synapse(cell,
    **synapse_parameters)
```

- set offline activation time(s)

```
syn.set_spike_times(np.array([20.])) # ms
```

- generate activation time(s) on the fly

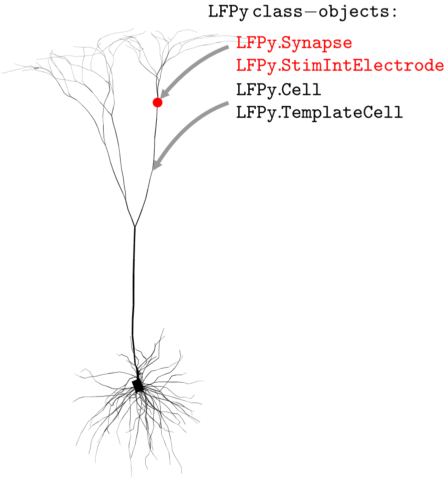
```
syn.set_spike_times_w_netstim(
    noise=1, # Poisson statistics
    start=0, # likeliest time of 1st spike
    number=1E3, # number of spikes
    interval=20, # ms, mean ISI
)
```



LFPy - Class overview

LFPy.StimIntElectrode:

- Represents intracellular point electrodes
  - voltage clamp (`VClamp`)
  - current clamp (`IClamp`)
  - single-electrode V clamp (`SEClamp`)
- Not modeled as transmembrane currents
- currents into intracellular medium
- Mimics experimental setups



LFPy - Class overview

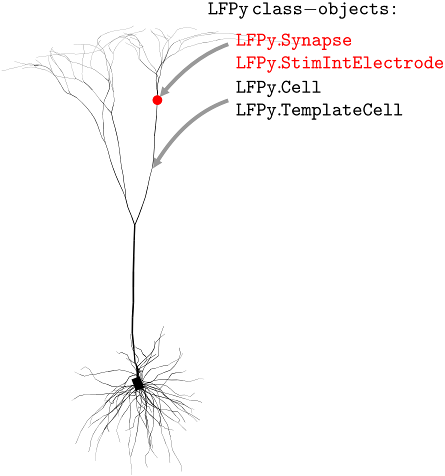
LFPy.StimIntElectrode:

- Define point process parameters

```
# Define synapse parameters
pointproc_parameters = dict(
    idx = 0,
    record_current = True,
    pptype = 'IClamp',
    amp = 1,     # nA
    dur = 20,    # ms
    delay = 10) # ms
```

- Create point process:

```
stim = LFPy.StimIntElectrode(
    cell=cell,
    **pointproc_parameters)
```



LFPy - Class overview

Plotting stimulus currents

- run

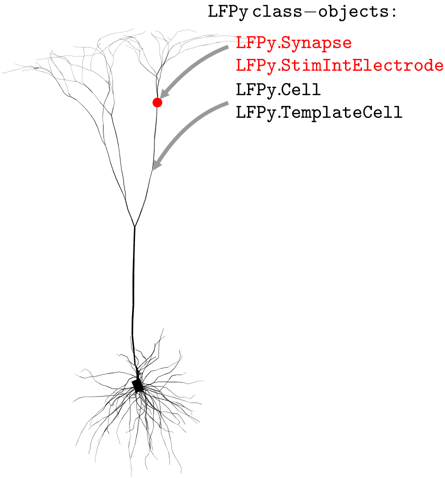
```
cell.simulate(rec_isyn=True,
              rec_istim=True)
```

- draw `LFPy.Synapse` current

```
import matplotlib.pyplot as plt
plt.subplot(211)
plt.plot(cell.tvec, syn.i)
```

- draw `LFPy.StimIntElectrode` current

```
plt.subplot(212)
plt.plot(cell.tvec, stim.i)
```

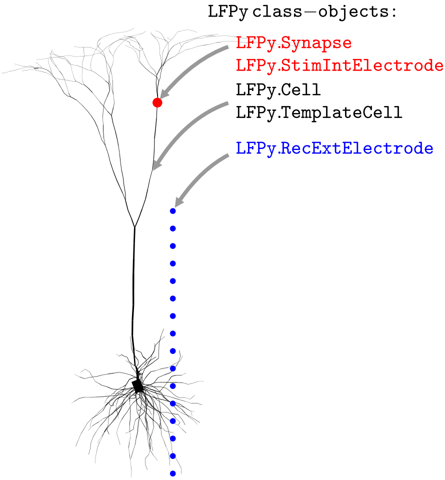


Questions?

LFPy - Class overview

LFPy.RecExtElectrode:

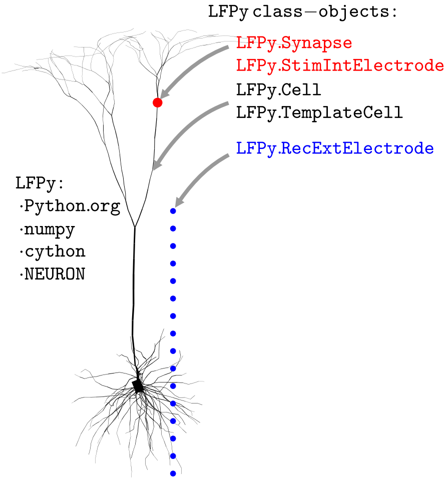
- Extracellular recording devices
- Main arguments:
  - `cell` objects (geometry, currents)
  - contact point coordinates `x,y,z`
  - extracellular conductivity `sigma`
  - `method` (pointsource/linesource)
- Optional:
  - radius and surface normal vectors of contacts (`r, N`)
  - *n*-point surface area averaged potential (`n`)



LFPy - Class overview

LFPy.RecExtElectrode:

```
# Run simulation, record currents
cell.simulate(rec_imem=True)
# Define electrode parameters
electrode_parameters = dict(
    sigma=0.3,          # S/m
    x=[-130., -220.], # um
    y=[   0.,    0.], # um
    z=[   0.,  700.], # um
)
# Create electrode object
electrode = LFPy.RecExtElectrode(
    cell=cell,
    **electrode_parameters)
# Calculate LFPs
electrode.calc_lfp()
plt.plot(cell.tvec, electrode.LFP.T)
plt.show()
```



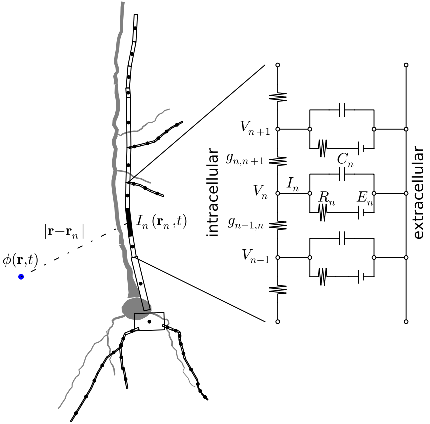
Forward modeling of extracellular potentials

Biophysical background:

- Current balance intracellular node point, compartment n:

$$I_n = C_n \frac{dV_n}{dt} - \frac{V_n - E_n}{R_n} =$$
$$g_{n,n+1}(V_{n+1} - V_n)$$
$$-g_{n-1,n}(V_n - V_{n-1})$$

- Simulated using **NEURON** (neuron.yale.edu) Hines et al. (2009))
- Extracellular potentials are computed from I_n



Lindén et al. (2014)

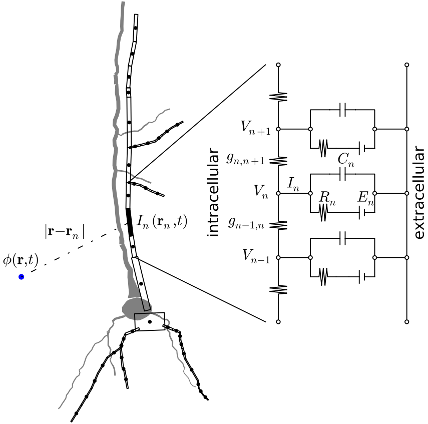
Forward modeling of extracellular potentials

Biophysical background:

- Poisson's equation in electrostatics

$$\nabla \cdot (\sigma \nabla \phi) = -C$$

$\phi(\mathbf{r}, t)$ - electric potential
$C(\mathbf{r}, t)$ - current source density
$\sigma(\mathbf{r})$ - conductivity



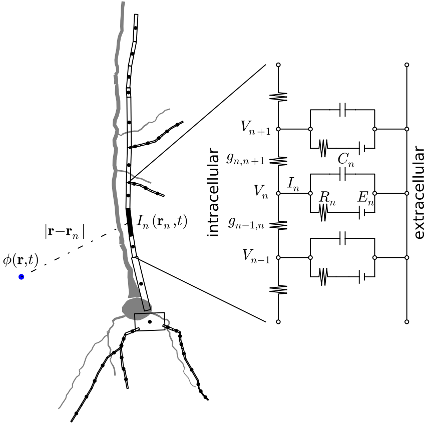
Lindén et al. (2014)

Forward modeling of extracellular potentials

Biophysical background:

- Assumptions:
  - Quasi-static approximation of Maxwell's equations
  - Extracellular medium:
    - linear
    - isotropic
    - homogeneous
    - ohmic

    (scalar, real σ)
- $\phi(r \to \infty) = 0$



Lindén et al. (2014)

Forward modeling of extracellular potentials

Biophysical background:

- Quasi-static approximation of Maxwell's equations:

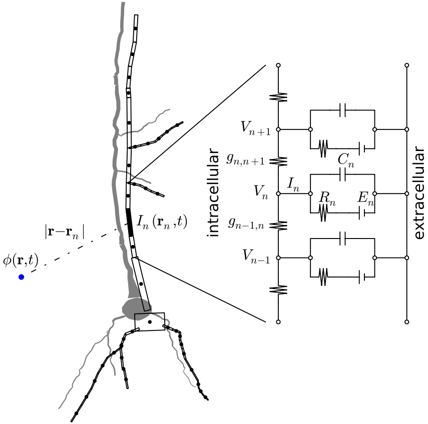
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \approx 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \mu(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}) \approx \mu \mathbf{J}$$

- $\mathbf{E}$ - electric field; ρ - charge density; ϵ_0 - free space permittivity; $\mathbf{B}$ - magnetic field; μ - permeability; $\mathbf{J}$ - sum of ohmic and polarization currents



Lindén et al. (2014)

Forward modeling of extracellular potentials

Biophysical background:

- Source current in conductive media
- Ohm's law in passive nonmagnetic media

$$\mathbf{J} = \sigma \mathbf{E} + \frac{\partial \mathbf{P}}{\partial t} \approx \sigma \mathbf{E}$$

$$(\mathbf{P} = (\epsilon - \epsilon_0)\mathbf{E} : \text{ polarization})$$

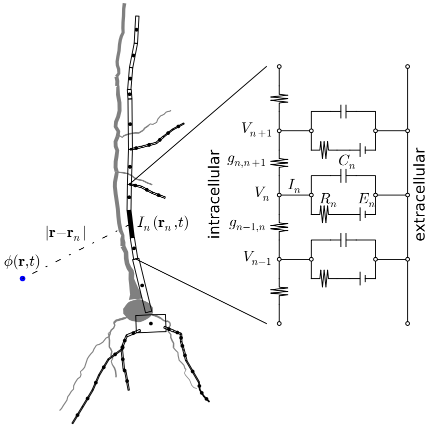
$$\nabla \times \mathbf{E} = 0$$

$$\rightarrow \mathbf{E} = -\nabla \phi \text{ , thus}$$

$$\mathbf{J} = -\sigma \nabla \phi$$

$$(C \equiv \nabla \cdot \mathbf{J})$$

- σ - assumed scalar, real



Lindén et al. (2014)

Forward modeling of extracellular potentials

Biophysical background:

- Assuming a point current source

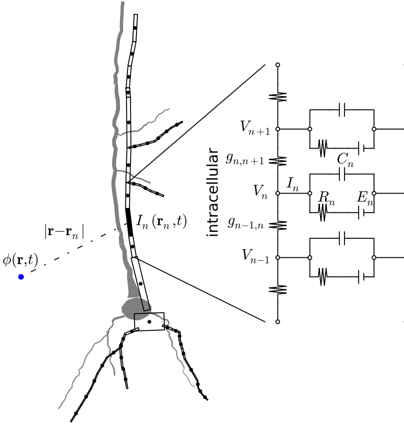
$$\mathbf{J} = \frac{I_0}{4\pi r^2}\hat{\mathbf{r}} \; , \; \hat{\mathbf{r}} : \text{ radial unit vector}$$

$$-\sigma\nabla\phi = \frac{I_0}{4\pi r^2}\hat{\mathbf{r}} \; , \; \nabla\phi = \frac{\partial\phi}{\partial r}$$

$$\frac{\partial\phi}{\partial r} = -\frac{I_0}{4\pi\sigma r^2}$$

- integration w. respect to r yields

$$\phi(r) = \frac{I_0}{4\pi\sigma r}$$



Lindén et al. (2014)

Forward modeling of extracellular potentials

Biophysical background:

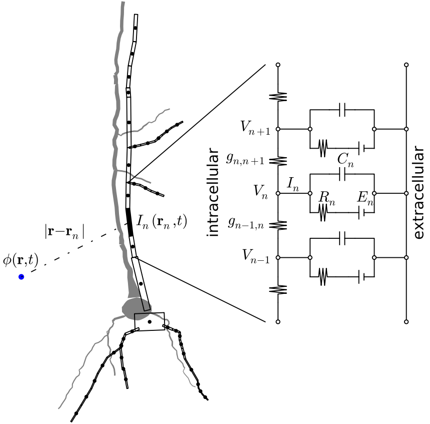
- Point current source

$$\phi(\mathbf{r}, t) = \frac{1}{4\pi\sigma} \frac{I_0(t)}{|\mathbf{r} - \mathbf{r}_0|} \ ,$$

where $\mathbf{r}$ is measurement location,
$\mathbf{r}_0$ source location

- Linear summation N point sources

$$\phi(\mathbf{r}, t) = \frac{1}{4\pi\sigma} \sum_{n=1}^{N} \frac{I_n(t)}{|\mathbf{r} - \mathbf{r}_n|}$$



Lindén et al. (2014)

Forward modeling of extracellular potentials

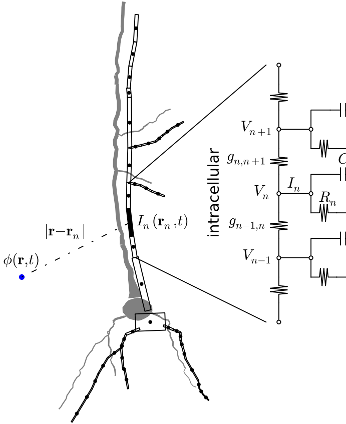
Biophysical background:

- Line sources (homog. current density)

$$\phi(\mathbf{r},t) = \frac{1}{4\pi\sigma}\sum_{n=1}^{N} I_n(t)\int \frac{d\mathbf{r}_n}{|\mathbf{r}-\mathbf{r}_n|}$$

$$= \frac{1}{4\pi\sigma}\sum_{n=1}^{N} \frac{I_n(t)}{\Delta s_n} \ln\left|\frac{\sqrt{h_n^2 + r_{\perp n}^2} - h_n}{\sqrt{l_n^2 + r_{\perp j}^2} - l_n}\right|$$

- Δs_n - segment length; h_n - longitudal distance to one end of segment; $r_{\perp n}$ - perpendicular distance to segment axis; $l_n = \delta s_n + h_n$.
- see Holt & Koch. (1999), *J Comput Neurosci* 6:169-184



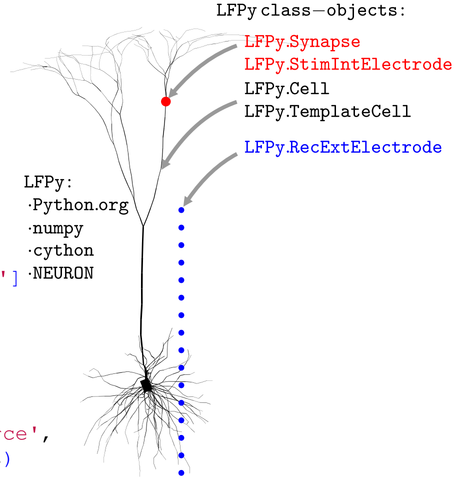
Lindén et al. (2014)

LFPy - Class overview

LFPy.RecExtElectrode:

- class supports
  - point sources
  - line sources
  - point soma - line dendrites
  - keyword argument

```
method in ['pointsource',
           'linesource',
           'soma_as_point']
```



- Usage

```
# Create electrode object
electrode = LFPy.RecExtElectrode(
            cell, method='linesource',
            **electrode_parameters)
```

LFPy - Class overview

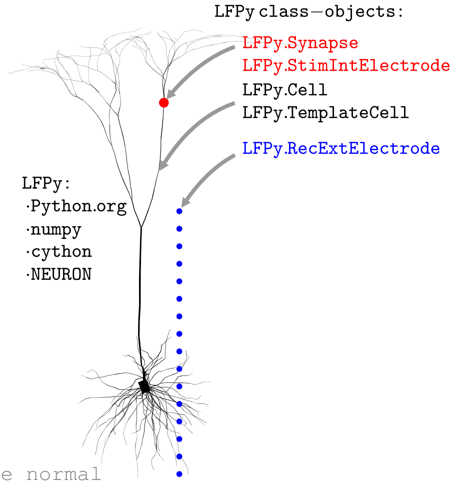
LFPy.RecExtElectrode:

- So far - point electrodes
- Real electrodes have finite extent
- “disk” electrode approximation

$$\phi_{\text{disc}}(\mathbf{u}, t) = \frac{1}{A_S} \iint_S \phi(\mathbf{u}, t)\, d^2 r$$
$$\approx \frac{1}{n} \sum_{i=1}^{n} \phi(\mathbf{u}_i, t)$$

- keyword arguments:

```
r = 10. # um, contact radius
n = 50  # n-point average
N = np.array([[0, 1, 0]]) # surface normal
```

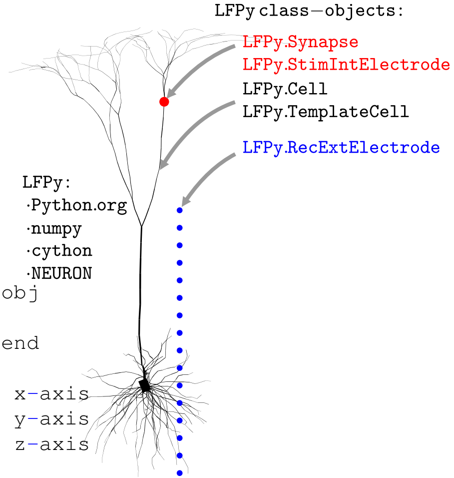


LFPy - Class overview

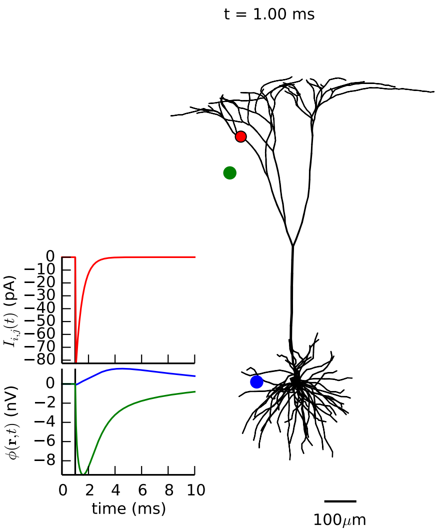
LFPy.lfpcalc.calc_lfp_*():

- Public methods
- used by **LFPy.RecExtElectrode**
  - calc_lfp_pointsource()
  - calc_lfp_linesource()
  - calc_lfp_som_as_point()
- keyword arguments:

```
cell: LFPy.Cell/LFPy.TemplateCell obj
    cell.imem
    cell.*start, cell.*mid, cell.*end
    cell.diam
x: double, extracellular position, x-axis
y: double, extracellular position, y-axis
z: double, extracellular position, z-axis
sigma: double, conductivity
```

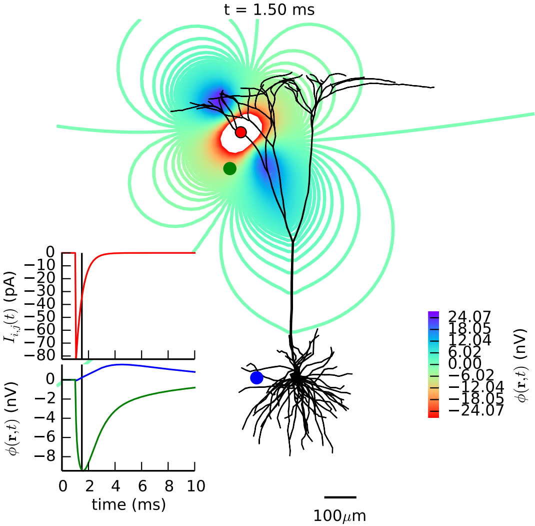


Forward modeling of extracellular potentials



Passive propagation of synapse current input in passive cable model

Forward modeling of extracellular potentials



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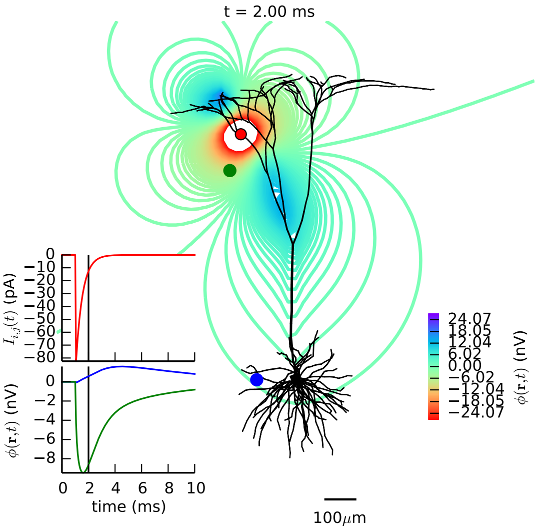
Forward modeling of extracellular potentials



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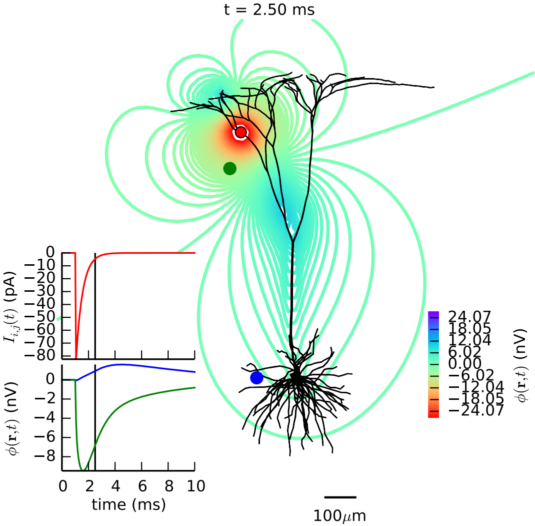
Forward modeling of extracellular potentials



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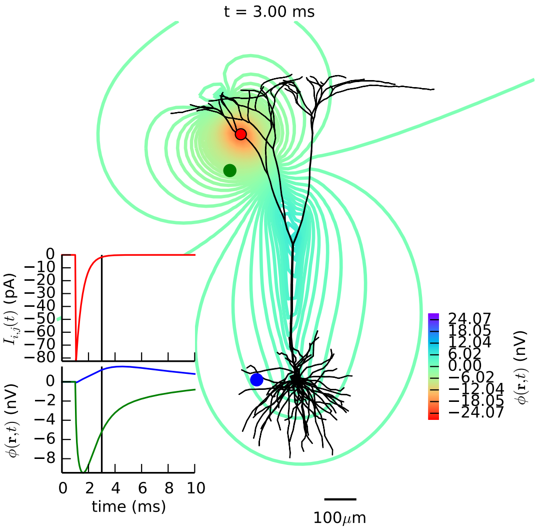

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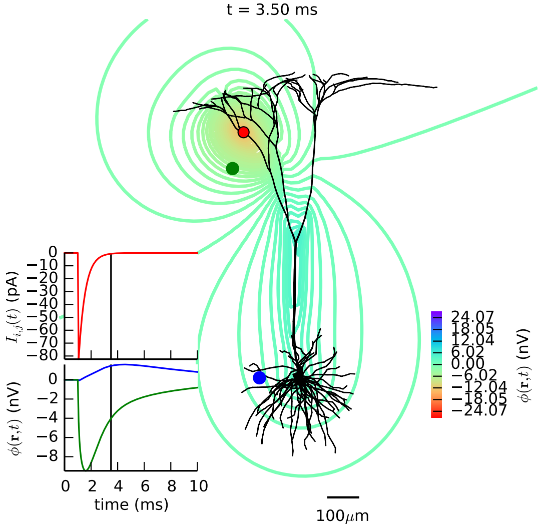

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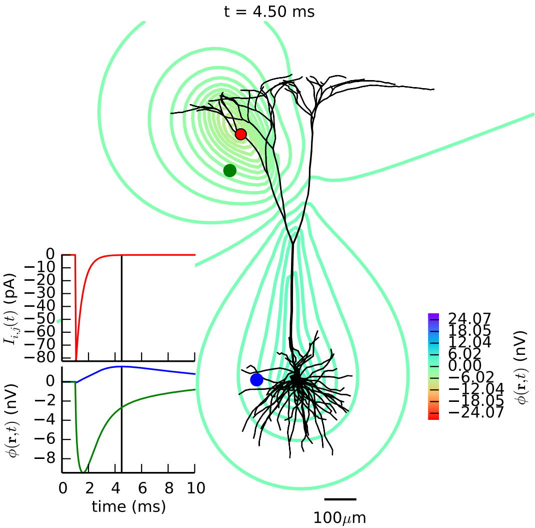

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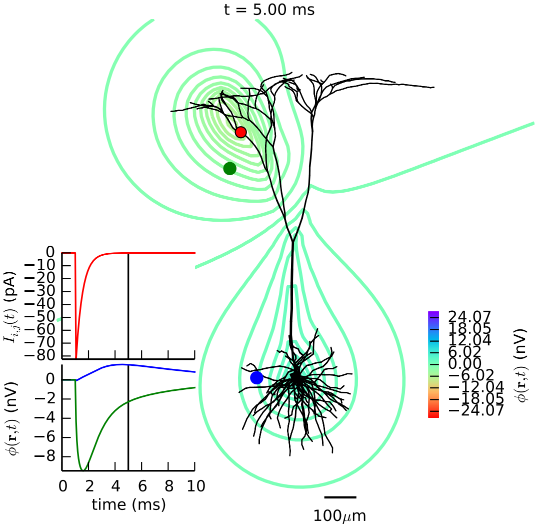
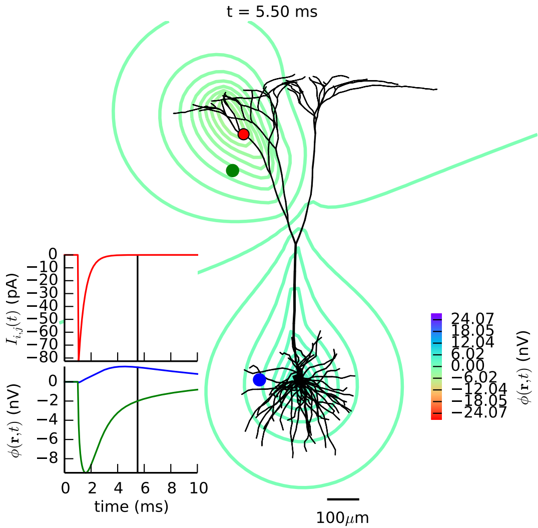


Passive propagation of synapse current input in passive cable model

Forward modeling of extracellular potentials



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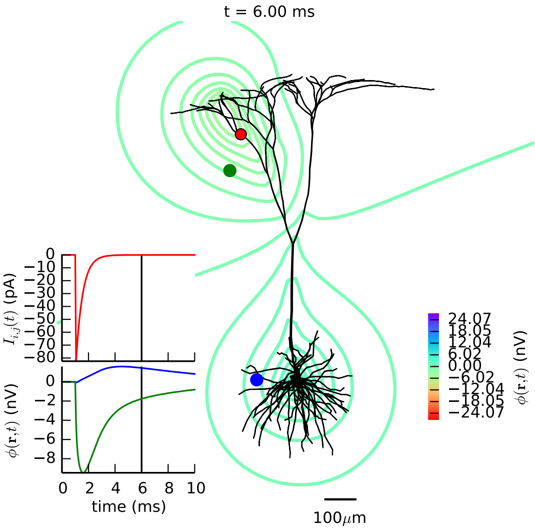
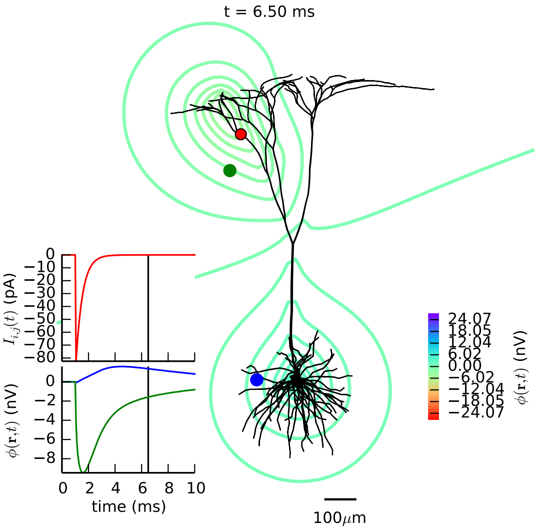
Forward modeling of extracellular potentials



Passive propagation of synapse current input in passive cable model

Forward modeling of extracellular potentials



Passive propagation of synapse current input in passive cable model

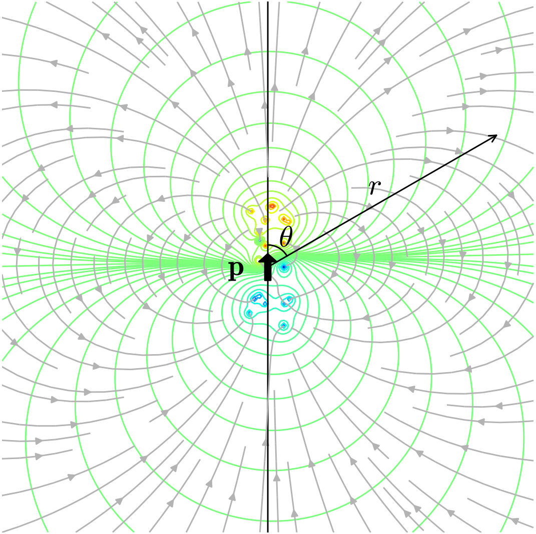
EEG and MEG signal predictions

- Multipole expansion of potential of arbitrary source distribution:

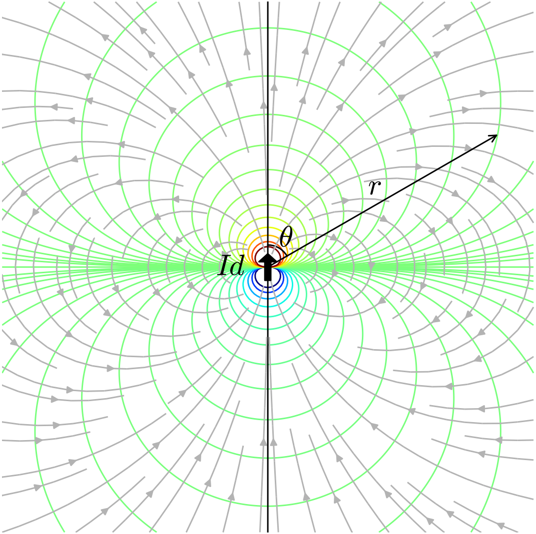
$$
\begin{aligned}
\phi(\mathbf{r}) &= \frac{1}{4\pi\sigma} \sum_{n=1}^{N} \frac{I_n}{|\mathbf{r} - \mathbf{r}_n|} d\mathbf{r} \\
&\equiv \sum_{m=1}^{\infty} \phi_m \\
\phi_1 &= \frac{\sum_{n=1}^{N} I_n}{4\pi\sigma r}, \phi_2 = \frac{\mathbf{p} \cdot \mathbf{r}}{4\pi\sigma r^3} \\
\phi_3 &\propto \frac{1}{r^3}, \ \phi_4 \propto \frac{1}{r^4}, \ldots
\end{aligned}
$$

- current dipole: $\mathbf{p} = \sum_{n=1}^{N} I_n \mathbf{r}_n$
- neurons equivalent to closed electric circuits: no monopoles!
- quadropole and higher terms can be ignored at some distance

EEG and MEG signal predictions



EEG and MEG signal predictions



EEG and MEG signal predictions

- Electric potential in infinite homogeneous medium

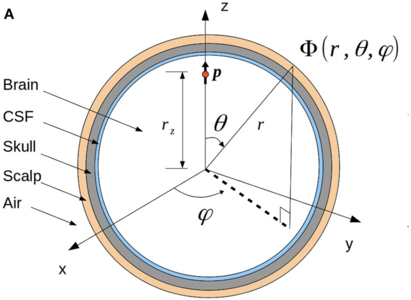
$$V = \frac{\mathbf{p} \cdot \mathbf{r}}{4\pi\sigma r^3}$$

EEG and MEG signal predictions

- Electric potential in infinite homogeneous medium

$$V = \frac{\mathbf{p} \cdot \mathbf{r}}{4\pi\sigma r^3}$$

- The head is not a homogeneous volume conductor
- Analytical four-sphere volume conductor model (Næss et al., Front Human Neurosci, 2017)



EEG and MEG signal predictions

class `LFPy.FourSphereVolumeConductor`:

```
from LFPy import Cell, FourSphereVolumeConductor
import numpy as np
# ....
cell.simulate(rec_current_dipole_moment=True)
# geometry
radii = [79000., 80000., 85000., 90000.] # um
sigmas = [0.3, 1.5, 0.015, 0.3] # S/m
sensor_locations = np.array([[0., 0., 90000.]]) # um
dipole_location = np.array([0., 0., 78000.]) # um
# instantiate 4-sphere model class, compute potential
sphere = LFPy.FourSphereVolumeConductor(radii, sigmas,
                                        sensor_locations)
phi = sphere_model.calc_potential(cell.current_dipole_moment,
                                  dipole_location)
```

EEG and MEG signal predictions

- Magnetic field of dipole (magnetostatic Biot-Savart law)

$$
\begin{aligned}
\mathbf{B} &= \frac{\mu}{4\pi}\frac{\mathbf{p}\times\mathbf{r}}{r^3} \ . \\
\mathbf{B} &= \mu\mathbf{H} + M
\end{aligned}
$$

  permeability $\mu \approx \mu_0 \equiv 4\pi \cdot 10^{-7}$ Tm/A,
  magnetization $M \approx 0$

- class LFPy.MEG:

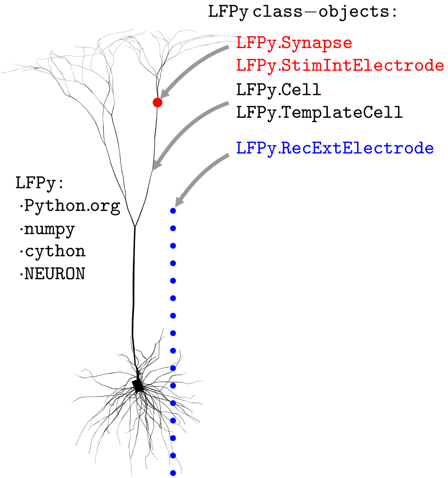
```
cell.simulate(rec_current_dipole_moment=True)
dipole_location = np.array([0, 0, 0]) # um
sensor_locations = np.array([[1E4, 0, 0]]) # um
meg = LFPy.MEG(sensor_locations, mu=4*np.pi*1E-7)
H = meg.calculate_H(cell.current_dipole_moment, dipole_location)
B = H*meg.mu
```

- Negligible contribution of volume currents in spherically symmetric conductors (Hämäläinen et al., Rev Modern Physics 1993)

LFPy - Class overview

Documentation and resources:

- LFPy homepage (http://LFPy.rtfd.io)
- autodoc w. `sphinx`:
  `cd /path/to/LFPy`
  `sphinx-build -b html documentation docs`
  see `docs/index.html`
- IPython magic (`numpy.sin?`, `LFPy.Synapse??`)
- NEURON homepage (http://www.neuron.yale.edu/)

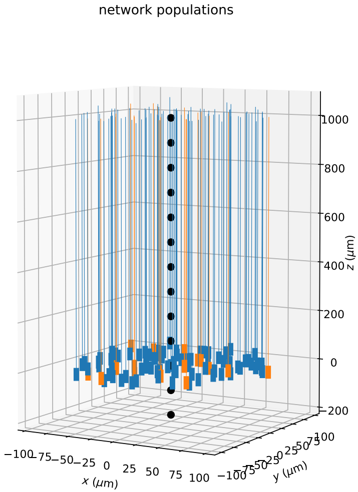


LFPy - Class overview

LFPy.Network:

- Facilitates creation of networks:
    - populations
    - neurons
    - connections
    - parallel management
    - forward-model predictions (through RexExtElectrode)
- Main arguments and setup:

```
from LFPy import Network
networkParams = dict(
    dt=2**-4,     # ms
    tstop=1200., # ms
    v_init=-65., # mV
    celsius=6.5, # 'C
    OUTPUTPATH='network_output')
network = Network(**networkParams)
```



LFPy - Class overview

LFPy.NetworkCell:

- Inherited from `TemplateCell`
- Retains all `Cell/TemplateCell` functionality
- Adds methods for spike detection/connections
- Parameterization:

```
cellParams = dict(
    morphology='BallAndStick.hoc',
    templatefile='BallAndStickTemplate.hoc',
    templatename='BallAndStickTemplate',
    templateargs=None,
    delete_sections=False,)
cell = LFPy.NetworkCell(**cellParams)
```

- Cells set up as part of a `NetworkPopulation`

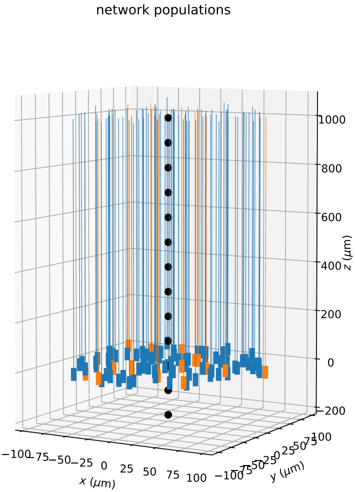
LFPy - Class overview

LFPy.NetworkPopulation:

- Represents populations of N NetworkCell instances
- Cells distributed across MPI ranks

```
popParams = dict(
    Cell=NetworkCell,
    cell_args = cellParams,
    pop_args = dict(
        radius=100., # um
        loc=0.,      # um
        scale=20.),  # um
    rotation_args=dict(x=0., y=0.), # rad
)
network.create_population(name=name,
                          POP_SIZE=size,
                          **popParams)
```

- Cells set up as part of a population



LFPy - Class overview

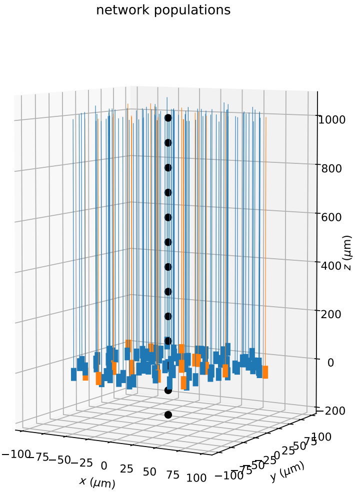
LFPy.Network:

- `Network` objects are transparent

  `network.populations[name].cells[cellID]`

- Create connections:

```
# connection matrix (boolean)
connectivity =
network.get_connectivity_rand(
     pre=name,
     post=name, connprob=connprob)
# connect populations
conncount, syncount = network.connect(
     pre=name, post=name,
     connectivity=connectivity,
     syntype=synapseModel,
     synparams=synapseParameters,
     **kwargs)
```



LFPy - Class overview

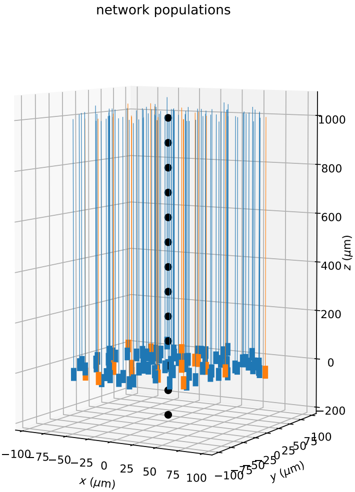
LFPy.Network:

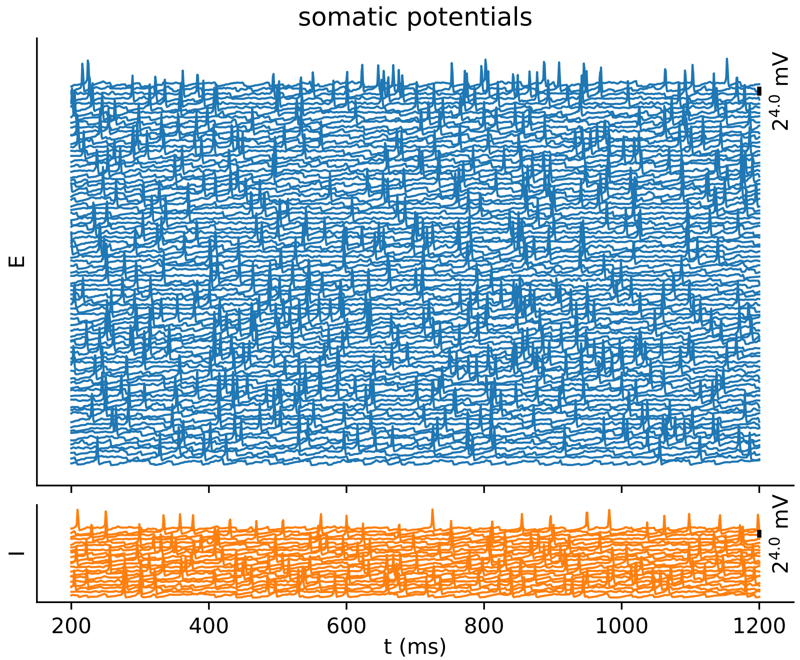
- Extracellular recording device:

```
electrodeParams = dict(**kwargs)
electrode =
RecExtElectrode(**electrodeParams)
```

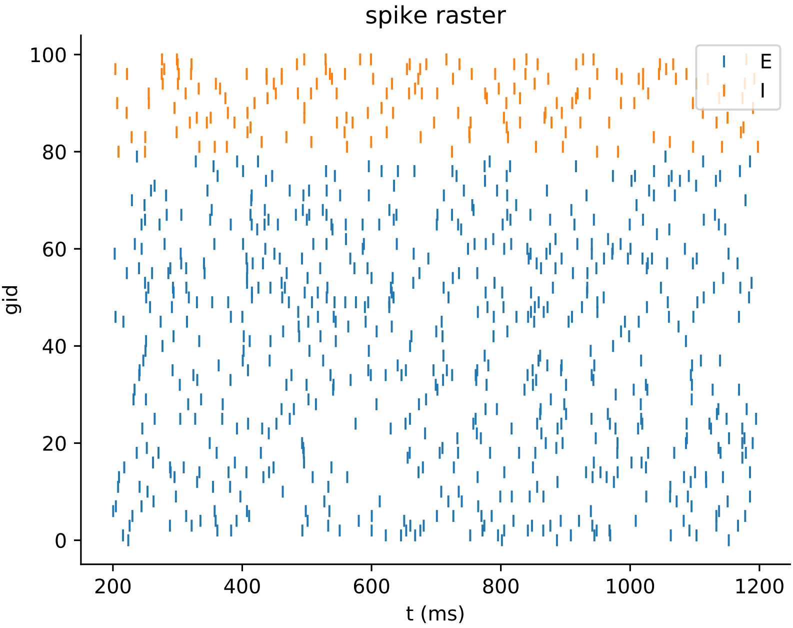
- Running simulation with measurements:

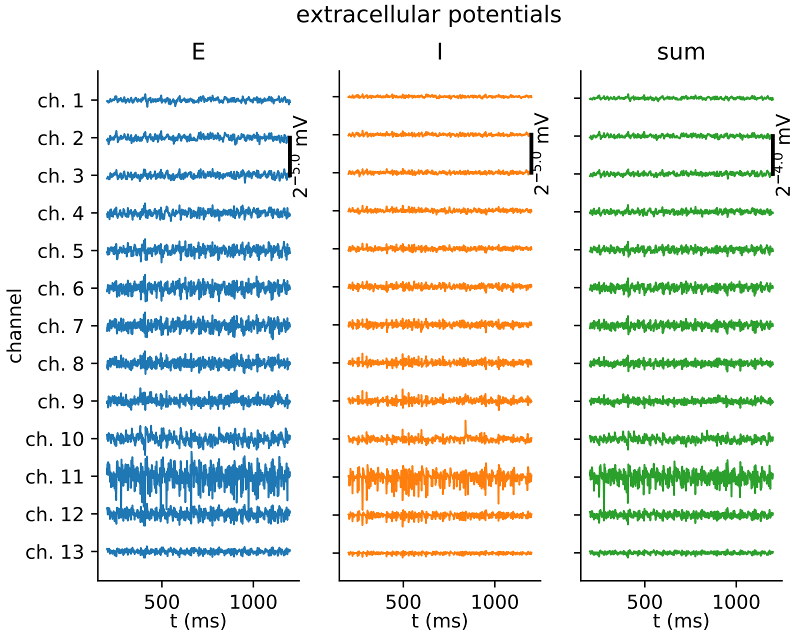
```
# method Network.simulate() parameters:
networkSimulationArguments = dict(
    rec_current_dipole_moment = True,
    rec_pop_contributions = True,
    to_memory = True,
    to_file = False
)
# run simulation:
SPIKES, OUTPUT, DIPOLEMOMENT =
network.simulate(
     electrode=electrode,
     **networkSimulationArguments
```

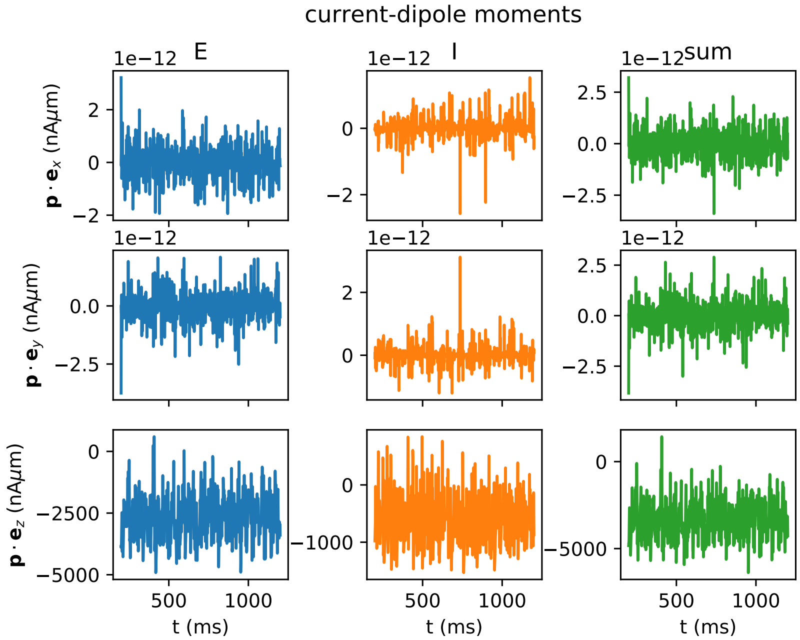




somatic potentials
E
I
$2^{4.0}$ mV
$2^{4.0}$ mV
200
400
600
800
1000
1200
t (ms)


spike raster
E
I
100
80
60
40
20
0
gid
200
400
600
800
1000
1200
t (ms)


extracellular potentials
E
I
sum
channel
ch. 1
ch. 2
ch. 3
ch. 4
ch. 5
ch. 6
ch. 7
ch. 8
ch. 9
ch. 10
ch. 11
ch. 12
ch. 13
$2^{-5.0}$ mV
$2^{-5.0}$ mV
$2^{-4.0}$ mV
500
1000
t (ms)


current-dipole moments
E
I
sum
1e−12
p · e_x (nAμm)
p · e_y (nAμm)
p · e_z (nAμm)
t (ms)
500
1000

Questions?

LFPy - Further reading and material

frontiers in
NEUROINFORMATICS

ORIGINAL RESEARCH ARTICLE
published: 16 January 2014
doi: 10.3389/fninf.2013.00041

LFPy: a tool for biophysical simulation of extracellular potentials generated by detailed model neurons

Henrik Lindén*[1,2†]*, Espen Hagen*[1†]*, Szymon Łęski*[1,3]*, Eivind S. Norheim*[1]*, Klas H. Pettersen*[1,4] *and Gaute T. Einevoll*[1]**

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Electrical extracellular recordings, i.e., recordings of the electrical potentials in the extracellular medium between cells, have been a main work-horse in electrophysiology for almost a century. The high-frequency part of the signal ($\gtrsim$500 Hz), i.e., the *multi-unit activity (MUA)*, contains information about the firing of action potentials in surrounding neurons, while the low-frequency part, the *local field potential (LFP)*, contains information about how these neurons integrate synaptic inputs. As the recorded extracellular signals arise from multiple neural processes, their interpretation is typically ambiguous and

https://doi.org/10.3389/fninf.2013.00041

LFPy - Further reading and material

frontiers in Neuroinformatics

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ORIGINAL RESEARCH ARTICLE

Front. Neuroinform., 18 December 2018 | https://doi.org/10.3389/fninf.2018.00092

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Multimodal Modeling of Neural Network Activity: Computing LFP, ECoG, EEG, and MEG Signals With LFPy 2.0

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https://doi.org/10.3389/fninf.2018.00092

LFPy - Further reading and material

LFPy
latest

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- Download LFPy
- Developing LFPy
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- LFPy on the Neuroscience Gateway Portal
- LFPy Tutorial
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LFPy

Local Field Potentials in Python

LFPy Homepage

(Looking for the old LFPy documentation? Follow link)

LFPy is a Python package for calculation of extracellular potentials from multicompartment neuron models and recurrent networks of multicompartment neurons. It relies on the NEURON simulator and uses the Python interface it provides.

Active development of LFPy, as well as issue tracking and revision tracking, relies on GitHub.com and git (git-scm.com). Clone LFPy on GitHub.com: `git clone https://github.com/LFPy/LFPy.git`

LFPy provides a set of easy-to-use Python classes for setting up your model, running your simulations and calculating the extracellular potentials arising from activity in your model neuron. If you have a model working in NEURON or NeuroML2 already, it is likely that it can be adapted to work with LFPy.

LFPy - Further reading and material

LFPy
latest

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  - class PointProcess
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  - class StimIntElectrode
  - class RecExtElectrode
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Edit on GitHub

Module LFPy

Initialization of LFPy, a Python module for simulating extracellular potentials.

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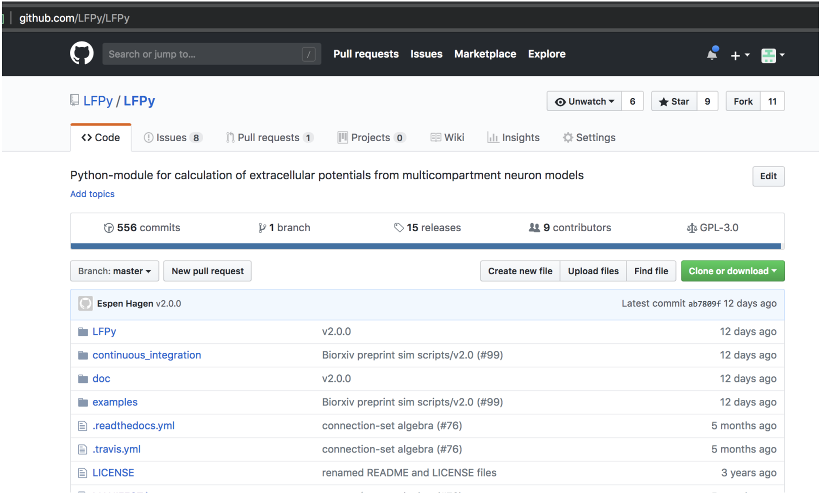
Classes:

- Cell - The pythonic neuron object itself laying on top of NEURON representing cells
- TemplateCell - Similar to Cell, but for models using cell templates
- Synapse - Convenience class for inserting synapses onto Cell objects
- StimIntElectrode - Convenience class for inserting electrodes onto Cell objects
- PointProcess - Parent class of Synapse and StimIntElectrode
- RecExtElectrode - Class for performing simulations of extracellular potentials

LFPy - Further reading and material



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Original Article

ORIGINAL ARTICLE

Hybrid Scheme for Modeling Local Field Potentials from Point-Neuron Networks

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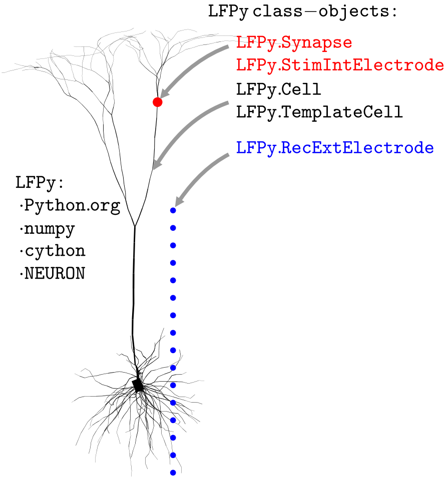
LFPy - Examples

Example **Python** `files`

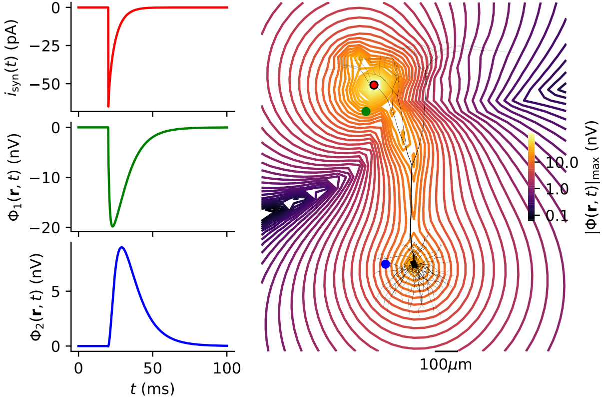
- `/path/to/LFPy/examples`
- Jupyter notebooks (`*.ipynb`)
- Python scripts (`example*.py`)
- Compute extracellular potentials
  - passive vs. active models
  - single-synapse vs. multi-synapse responses
  - extracellular action potential waveforms
  - population signal
- All use **`LFPy.Cell`**, **`LFPy.Synapse`**, **`LFPy.RecExtElectrode`**, **`...`**



LFPy - Examples

/path/to/LFPy/examples/example3.ipynb

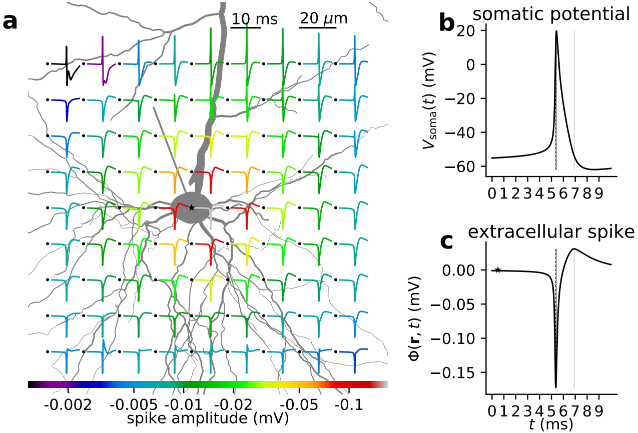
Apical synapse response, passive cable model



LFPy - Examples

/path/to/LFPy/examples/example4.ipynb

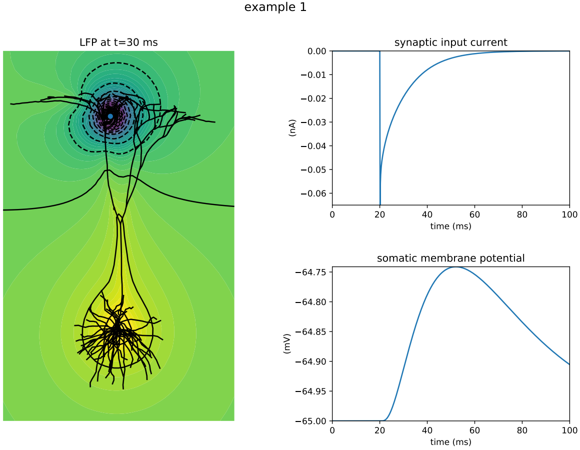
Layer 5b action potential (Hay et al. 2011), LFPy.TemplateCell



LFPy - Examples

`/path/to/LFPy/examples/example5.ipynb`

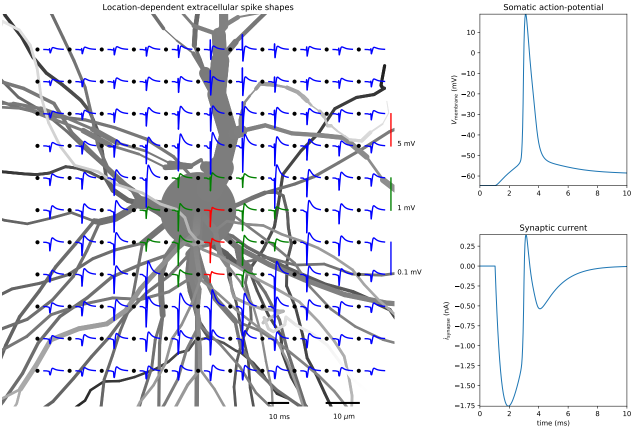
Extracellular potentials, single-synapse input current



LFPy - Examples

/path/to/LFPy/examples/example6.ipynb

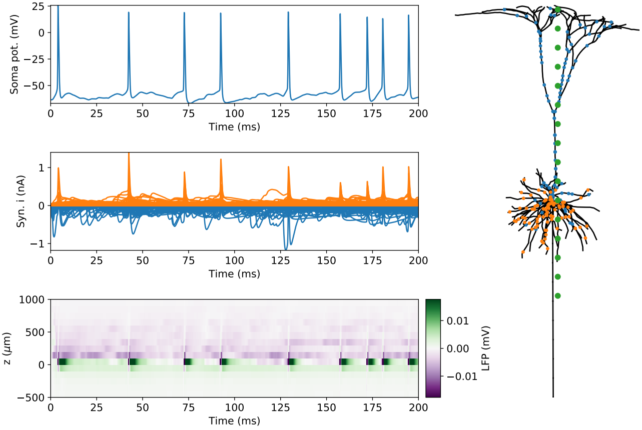
Extracellular potentials for action-potential of L5 pyramidal cell



LFPy - Examples

`/path/to/LFPy/examples/example7.ipynb`

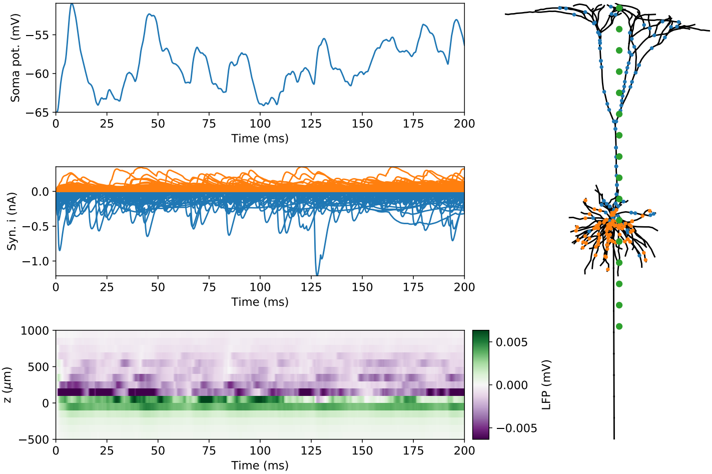
Extracellular potentials, synapse currents, somatic voltage, distributed synapses, active model



LFPy - Examples

/path/to/LFPy/examples/example8.ipynb

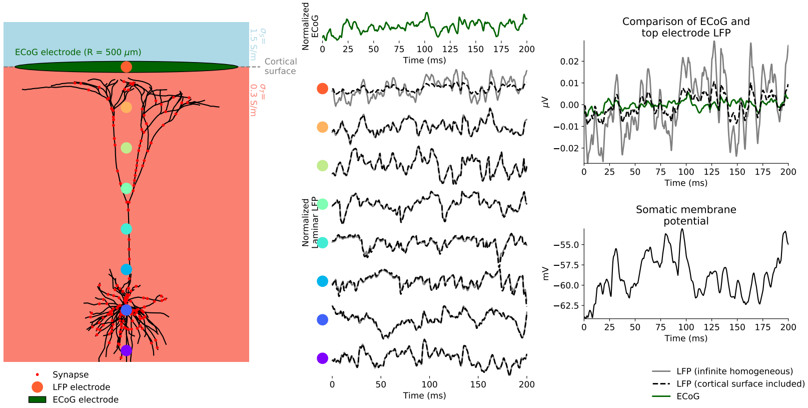
Extracellular potentials, synapse currents, somatic voltage, distributed synapses, passive model



LFPy - Examples

/path/to/LFPy/examples/example_ECoG.py

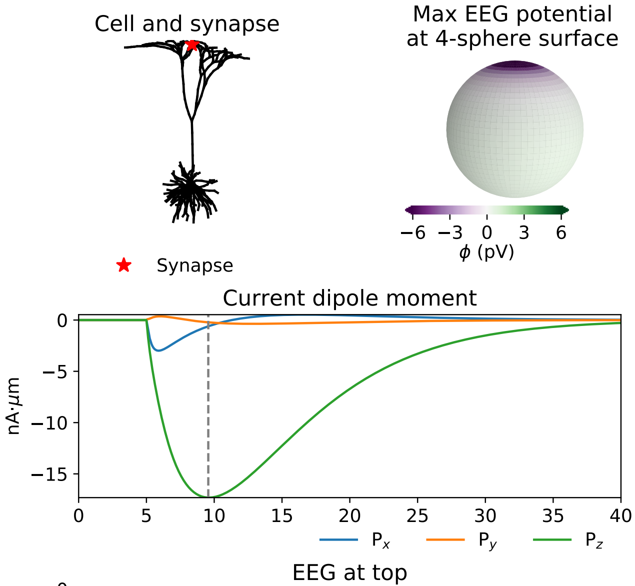
Extracellular potentials as recorded by ECoG contact



LFPy - Examples

`/path/to/LFPy/examples/example_EEG.py`

Single-synapse contribution to surface EEG



Questions?

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- The Norwegian Research Council (NFR) through COBRA, NOTUR - NN4661K
- Organization for Computational Neurosciences

LFPy - Class overview

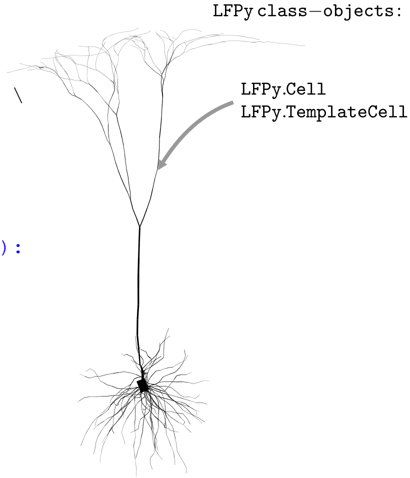
LFPy.Cell:

- Tip on drawing `cell`:

```
from matplotlib.collections import \
    PolyCollection
import matplotlib.pyplot as plt

cell = LFPy.Cell('j4a.hoc')
zips = []
for x, z in cell.get_idx_polygons():
    zips.append(zip(x, z))
polycol = PolyCollection(zips,
            edgecolors='none',
           facecolors='gray')

fig, ax = plt.subplots(1)
ax.add_collection(polycol)
ax.axis(ax.axis('equal'))
plt.show()
```



LFPy - Unit tests

py.test module:

- runs code
- check if output is correct
  (validate LFPy output against analytical
  expressions for equivalent ball&stick models)
- run tests using pytest module:

```
cd /path/to/LFPy
py.test LFPy
```

- output:

```
====== test session starts ======
platform darwin -- Python 3.6.9, pytest-4.6.3, py-1.8.0, pluggy-0.12
rootdir: /Users/ehagen/Repositories/LFPy
plugins: cov-2.7.1
collected 289 items

LFPy/test/test_alias_method.py .....       [  1%]
LFPy/test/test_cell.py .............       [ 26%]
...
== 289 passed in 85.66 seconds ==
```

LFPy - Ephaptic interactions

- Neuron dynamics independent of extracellular predictions!
- `LFPy.Cell.insert_v_ext(v_ext, t_ext):`

```
import LFPy, matplotlib.pyplot as plt, numpy as np
# create cell
cell = LFPy.Cell('morphologies/example_morphology.hoc')
# time vector and extracellular potential for each segment:
dt = cell.timeres_python
t_ext = np.arange(100 / dt + 1) * dt
v_ext = np.random.rand(cell.totnsegs, t_ext.size)-0.5
# insert potentials and record response:
cell.insert_v_ext(v_ext, t_ext)
cell.simulate(rec_imem=True, rec_vmem=True)
# plot
plt.matshow(v_ext); plt.axis('tight'); plt.colorbar()
plt.matshow(cell.imem); plt.axis('tight'); plt.colorbar()
plt.matshow(cell.vmem); plt.axis('tight'); plt.colorbar()
plt.show()
```