Electronics

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0.1 Foreword

1 Aim of This Textbook

The aim of this textbook is to explain the design and function of electronic circuits and components. The text covers electronic circuit components, DC analysis, and AC analysis.

It should be useful to beginner hobbyists as well as beginner engineering students, teaching both theory and practical applications.

It should be thought of as a companion project to the Wikipedia articles about electronics. While Wikipedia covers many details about the technology used in electronics components and related fields, the Electronics Wikibook covers a lot of the "how-to" aspects that aren't covered in an encyclopedia. The book will focus on how to use the components to build useful circuits.

2 Preface

2.1 Importance of Electronics

Electronics is the study and use of devices that control the flow of electrons (or other charged particles). These devices can be used to process information or perform tasks using electromagnetic power.

Electronic circuits can be found in numerous household products, including such items as telephones, computers, and CD players. Electronic devices have also allowed greatly increased precision in scientific measurements.

Interest in the field of electronics increased around 1900 and the advent of radio. Interest reached an all-time high in the 1940s, 50s, 60s, with the invention of transistor radios, the launch of Sputnik, and the science and math educational push to win the space race. Interest in electronics as a hobby in the 1970s led to the advent of the personal computer (PC).

Electronics have since seen a decline in hobbyist interest. Electronics is now generally studied as part of a college-level program in electrical engineering.

This book is an attempt at reviving the hobbyist mentality that made electronics so big in the first place, by making electronics concepts more accessible and giving practical knowledge, as well as providing technical information for the student.

3 Charge and Coulomb's Law

Two atoms are walking down the street. The first atom says to the second atom "I think I lost an electron!" The second says "Are you sure?" To which the first states "I'm **positive** !"

3.1 Basic Understanding

Conductors

Materials which contain movable charges that can flow with minimal resistance.

Insulators

Materials with few or no movable charges, or with charges which flow with extremely high resistance.

Semiconductors

Materials whose behavior ranges between that of a conductor and that of an insulator under different conditions. Their conducting behavior may be heavily dependent on temperature. They are useful because we are able to change their conducting behavior to be dependent on many other factors.

The Atom

An atom contains a positively charged nucleus and one or more negatively charged electrons. The atom exists in three states: neutral, positively charged, and negatively charged. A neutral atom has the same number of electrons and protons, a positively charged atom has more protons than electrons and a negatively charged atom has more electrons than protons.

(+) and (-) Ions

An ion is an atom that has an unequal number of electrons and protons. Ions are formed when a neutral atom gains or loses electrons during a chemical reaction. In a battery, the positive side has + ions, means there are fewer electrons than protons, giving it an overall positive charge, and -ve side, more electrons than protons, giving it an overall negative charge. +ve and -ve charge will attract each other, and it is the use of such an attractive force that allows the battery to do work.

Note: Electric current is not the same as electron flow as is widely mistaken. Firstly, the total current has the opposite direction compared to electron flow. This is a lucky "mistake" on our forefathers' part to put it this way. It is also because of this lucky legacy that we are reminded that electricity can flow in materials other than metals alone. For example, in

water, it is not electrons that flow, it is ions, and the +ve ions and -ve ions flow in opposite directions, contributing half of the total current each.

3.2 Balance of Charge

Atoms, the smallest particles of matter that retain the properties of the matter, are made of protons[1], electrons[2], and neutrons[3]. **Protons** have a positive charge, **Electrons** have a negative charge that cancels the proton's positive charge. **Neutrons** are particles that are similar to a proton but have a neutral charge. There are no differences between positive and negative charges except that particles with the same charge **repel** each other and particles with opposite charges **attract** each other. If a solitary positive proton and negative electron are placed near each other they will come together to form a hydrogen atom. This repulsion and attraction (force between stationary charged particles) is known as the**Electrostatic Force** and extends theoretically to infinity, but is diluted as the distance between particles increases.

When an atom has one or more missing electrons it is left with a **positive** charge, and when an atom has at least one extra electron it has a **negative** charge. Having a positive or a negative charge makes an atom an **ion** . Atoms only gain and lose protons and neutrons through fusion[4], fission[5], and radioactive decay[6]. Although atoms are made of many particles and objects are made of many atoms, they behave similarly to charged particles in terms of how they repel and attract.

In an **atom** the protons and neutrons combine to form a tightly bound nucleus. This nucleus is surrounded by a vast cloud of electrons circling it at a distance but held near the protons by electromagnetic attraction (the electrostatic force discussed earlier). The cloud exists as a series of overlapping **shells / bands** in which the inner **valence** bands are filled with electrons and are tightly bound to the atom. The outer **conduction** bands contain no electrons except those that have accelerated to the conduction bands by gaining energy. With enough energy an electron will escape an atom (compare with the escape velocity of a space rocket). When an electron in the conduction band decelerates and falls to another conduction band or the valence band a photon is emitted. This is known as the **photoelectric effect** .

A **laser** is formed when electrons travel back and forth between conduction bands emitting synchronized photons.

1. When the conduction and valence bands overlap, the atom is a **conductor** and allows for the free movement of electrons. Conductors are metals and can be thought of as a bunch of atomic nuclei surrounded by a churning "sea of electrons".

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1   http://en.wikipedia.org/wiki/protons
2   http://en.wikipedia.org/wiki/electrons
3   http://en.wikipedia.org/wiki/neutrons
4   http://en.wikipedia.org/wiki/Nuclear_fusion
5   http://en.wikipedia.org/wiki/Nuclear_fission
6   http://en.wikipedia.org/wiki/Radioactive_decay

2. When there is a large energy level gap between the conduction and valence bands, the atom is an **insulator** ; it traps electrons. Many insulators are non-metals and are good at blocking the flow of electrons.

3. When there is a small energy level gap between the conduction and valence bands, the atom is a **semiconductor** . Semiconductors behave like conductors and insulators, and work using the conduction and valence bands. The electrons in the outer valence band are known as **holes** . They behave like positive charges because of how they flow. In semiconductors electrons collide with the material and their progress is halted. This makes the electrons have an **effective mass** that is less than their normal mass. In some semiconductors holes have a larger effective mass than the conduction electrons.

Electronic devices are based on the idea of exploiting the differences between conductors, insulators, and semiconductors but also exploit known physical phenomena such as electromagnetism and phosphorescence.

3.3 Conductors

In a metal the electrons of an object are free to move from atom to atom. Due to their mutual repulsion (calculable via Coulomb's Law [7]), the valence electrons are forced from the centre of the object and spread out evenly across its surface in order to be as far apart as possible. This **cavity** of empty space is known as a **Faraday Cage** and stops **electromagnetic radiation** , such as charge, radio waves, and **EMP** [8]s (Electro-Magnetic Pulses) from entering and leaving the object. If there are holes in the Faraday Cage then radiation can pass.

One of the interesting things to do with conductors is demonstrate the transfer of charge between metal spheres. Start by taking two identical and uncharged metal spheres which are each suspended by insulators (such as a pieces of string). The first step involves putting sphere 1 next to but not touching sphere 2. This causes all the electrons in sphere 2 to travel away from sphere 1 to the far end of sphere 2. So sphere 2 now has a negative end filled with electrons and a positive end lacking electrons. Next sphere 2 is **grounded** by contact with a conductor connected with the earth and the earth takes its electrons leaving sphere 2 with a positive charge. The positive charge (absence of electrons) spreads evenly across the surface due to its lack of electrons. If suspended by strings, the relatively negatively charged sphere 1 will attract the relatively positively charged sphere 2.

3.4 Insulators

In an insulator the charges of a material are stuck and cannot flow. This allows an imbalance of charge to build up on the surface of the object by way of the triboelectric effect. The **triboelectric effect** (rubbing electricity effect) involves the exchange of electrons when two different insulators such as glass, hard rubber, amber, or even the seat of one's trousers, come into contact. The polarity and strength of the charges produced differ according to

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7   http://en.wikibooks.org/wiki/Electrodynamics%2FCoulombs%20Law
8   http://en.wikibooks.org/wiki/Electronics%2FSignal%20Propagation

the material composition and its surface smoothness. For example, glass rubbed with silk will build up a charge, as will hard rubber rubbed with fur. The effect is greatly enhanced by rubbing materials together.

- **Van de Graaff Generator:** A **charge pump** (pump for electrons) that generates static electricity. In a Van de Graaff generator, a conveyor belt uses rubbing to pick up electrons, which are then deposited on metal brushes. The end result is a charge difference.

Because the material being rubbed is now charged, contact with an uncharged object or an object with the opposite charge may cause a discharge of the built-up **static electricity** by way of a spark. A person simply walking across a carpet may build up enough charge to cause a spark to travel over a centimetre. The spark is powerful enough to attract dust particles to cloth, destroy electrical equipment, ignite gas fumes, and create lightning. In extreme cases the spark can destroy factories that deal with gunpowder and explosives. The best way to remove static electricity is by discharging it through grounding. Humid air will also slowly discharge static electricity. This is one reason cells[9] and capacitors[10] lose charge over time.

Note: The concept of an insulator changes depending on the applied voltage. Air looks like an insulator when a low voltage is applied. But it breaks down as an insulator, becomes ionised, at about ten kilovolts per centimetre. A person could put their shoe across the terminals of a car battery and it would look like an insulator. But putting a shoe across a ten kilovolt powerline will cause a short.

Figure 12

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9   Chapter 5 on page 21
10   Chapter 7 on page 43

3.5 Quantity of Charge

Protons and electrons have opposite but equal charge. Because in almost all cases, the charge on protons or electrons is the smallest amount of charge commonly discussed, the quantity of charge of one proton is considered one positive **elementary charge** and the charge of one electron is one negative **elementary charge** . Because atoms and such particles are so small, and charge in amounts of multi-trillions of elementary charges are usually discussed, a much larger unit of charge is typically used. The **coulomb** is a unit of charge, which can be expressed as a positive or negative number, which is equal to approximately 6.2415×10^{18} elementary charges. Accordingly, an elementary charge is equal to approximately 1.602×10^{-19} coulombs. The commonly used abbreviation for the coulomb is a capital **C** . The SI[11] definition of a coulomb is the quantity of charge which passes a point over a period of 1 second (s) when a current of 1 ampere[12] (A) flows past that point, i.e., C = A·s or A = C/s. You may find it helpful during later lessons to retain this picture in your mind (even though you may not recall the exact number). An ampere[13] is one of the fundamental units in physics from which various other units are defined, such as the coulomb.

3.6 Force between Charges: Coulomb's Law

The repulsive or attractive **electrostatic force** between charges decreases as the charges are located further from each other by the square of the distance between them. An equation called **Coulomb's law** determines the electrostatic force between two charged objects. The following picture shows a charge q at a certain point with another charge Q at a distance of r away from it. The presence of Q causes an electrostatic force to be exerted on q .

$\vec{F}$ = electrostatic force on q due to Q if attractive

$\vec{F}$ = electrostatic force on q due to Q if repulsive
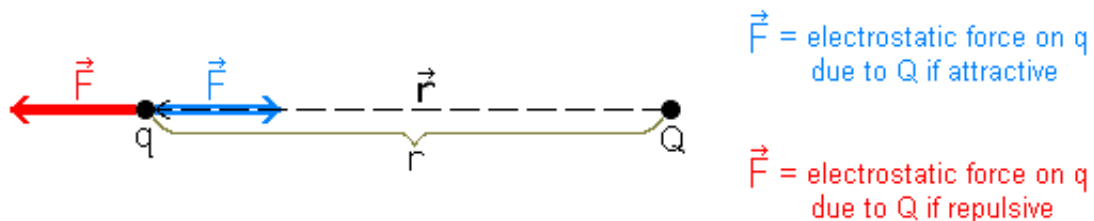
Figure 13

The magnitude of the electrostatic force F , on a charge q , due to another charge Q , equals **Coulomb's constant** multiplied by the product of the two charges (in coulombs) divided by the square of the distance r , between the charges q and Q . Here a capital Q and small q

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11   http://en.wikipedia.org/wiki/SI
12   http://en.wikibooks.org/wiki/Electronics%2FVoltage%2C%20Current%2C%20and%20Power
13   http://en.wikipedia.org/wiki/ampere

are scalar[14] quantities used for symbolizing the two charges, but other symbols such as q_1 and q_2 have been used in other sources. These symbols for charge were used for consistency with the electric field[15] article in Wikipedia and are consistent with the Reference below.

$$F = \frac{kqQ}{r^2}$$

$F =$ magnitude of electrostatic force on charge q due to another charge Q

$r =$ distance (magnitude quantity in above equation) between q and Q

$k =$ Coulomb's constant $= 8.9875 \times 10^9$ N·m²/C² in free space

The value of Coulomb's constant given here is such that the preceding Coulomb's Law equation will work if both q and Q are given in units of coulombs, r in metres, and F in newtons and there is no dielectric material between the charges. A **dielectric material** is one that reduces the electrostatic force when placed between charges. Furthermore, Coulomb's constant can be given by:

$$k = \frac{1}{4\pi\epsilon}$$

where $\epsilon =$ **permittivity** . When there is no dielectric material between the charges (for example, in free space or a vacuum),

$$\epsilon_0$$

$$= 8.85419 \times 10^{-12} \text{ C}^2/(\text{N·m}^2).$$

Air is only very weakly dielectric and the value above for ϵ_0 will work well enough with air between the charges. If a dielectric material is present, then

$$\epsilon = \kappa\epsilon_0$$

where κ is the **dielectric constant** which depends on the dielectric material. In a vacuum (free space), $\kappa = 1$ and thus $\epsilon = \epsilon_0$. For air, $\kappa = 1.0006$. Typically, solid insulating materials have values of $\kappa > 1$ and will reduce electric force between charges. The dielectric constant can also be called **relative permittivity** , symbolized as ϵ_r in Wikipedia[16].

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14   http://en.wikibooks.org/wiki/scalar
15   http://en.wikipedia.org/wiki/Electric%20field
16   http://en.wikipedia.org/wiki/Dielectric

Highly charged particles close to each other exert heavy forces on each other; if the charges are less or they are farther apart, the force is less. As the charges move far enough apart, their effect on each other becomes negligible.

Any force on an object is a vector[17] quantity. Vector quantities such as forces are characterized by a numerical magnitude (i. e. basically the size of the force) and a direction. A vector is often pictured by an arrow pointing in the direction. In a force vector, the direction is the one in which the force pulls the object. The symbol $\vec{F}$ is used here for the electric force vector. If charges q and Q are either both positive or both negative, then they will repel each other. This means the direction of the electric force $\vec{F}$ on q due to Q is away from Q in exactly the opposite direction, as shown by the red arrow in the preceding diagram. If one of the charges is positive and the other negative, then they will attract each other. This means that the direction of $\vec{F}$ on q due to Q is exactly in the direction towards Q , as shown by the blue arrow in the preceding diagram. The Coulomb's equation shown above will give a magnitude for a repulsive force away from the Q charge. A property of a vector is that if its magnitude is negative, the vector will be equal to a vector with an equivalent but positive magnitude and exactly the opposite direction. So, if the magnitude given by the above equation is negative due to opposite charges, the direction of the resulting force will be directly opposite of away from Q , meaning the force will be towards Q , an attractive force. In other sources, different variations of Coulombs' Law are given, including vector formulas in some cases (see Wikipedia link and reference(s) below).

In many situations, there may be many charges, Q_1, Q_2, Q_3, through Q_n , on the charge q in question. Each of the Q_1 through Q_n charges will exert an electric force on q . The direction of the force depends on the location of the surrounding charges. A Coulomb's Law calculation between q and a corresponding Q_i charge would give the magnitude of the electric force exerted by each of the Q_i charges for $i = 1$ through n , **but** the direction of each of the component forces must also be used to determine the individual force vectors, $\vec{F_1}, \vec{F_2}, \vec{F_3}, ..., \vec{F_n}$. To determine the total electric force on q , the electric force contributions from each of these charges add up as **vector** quantities, not just like ordinary (or scalar) numbers.

$$\vec{F_e} = \vec{F_1} + \vec{F_2} + \vec{F_3} + ... + \vec{F_n}$$

The total electric force on q is additive to any other forces affecting it, but all of the forces are to be added together as **vectors** to obtain the total force on the charged object q . In many cases, there are billions of electrons or other charges present, so that geometrical distributions of charges are used with equations stemming from Coulomb's Law. Practically speaking, such calculations are usually of more interest to a physicist than an electrician, electrical engineer, or electronics hobbyist, so they will not be discussed much more in this book, except in the section on capacitors.

In addition to the electrostatic forces described here, electromagnetic forces are created when the charges are moving. These will be described later.

Reference(s):

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17   http://en.wikibooks.org/wiki/vector

- College Physics Volume 2 by Doug Davis, Saunders College Publishing, Orlando, FL, 1994

- Wikipedia:Coulomb's Law[18]

- Wikipedia:Dielectric constant[19]

- GCSE Science/Static Electricity[20]
- GCSE Science/Advanced static electricity topics[21]

Next: Voltage, Current, and Power[22]

Return to: Electronics[23] Outline

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18   http://en.wikipedia.org/wiki/Coulomb%27s%20Law
19   http://en.wikipedia.org/wiki/Dielectric%20constant
20   http://en.wikibooks.org/wiki/GCSE%20Science%2FStatic%20Electricity
21   http://en.wikibooks.org/wiki/GCSE%20Science%2FAdvanced%20static%20electricity%
     20topics
22   http://en.wikibooks.org/wiki/Electronics%2FVoltage%2C%20Current%2C%20and%20Power
23   http://en.wikibooks.org/wiki/Electronics

4 Basic Concepts

4.1 What is Electronics?

Electronics is the study of flow of electrons in various materials or space subjected to various conditions. In the past, electronics dealt with the study of Vacuum Tubes or Thermionic valves, today it mainly deals with flow of electrons in semiconductors. However, despite these technological differences, the main focus of electronics remains the controlled flow of electrons through a medium. By controlling the flow of electrons, we can make them perform special tasks, such as power an induction motor or heat a resistive coil.

Plumbing Analogy A simple way to understand electrical circuits is to think of them as pipes. Let's say you have a simple circuit with a voltage source and a resistor between the positive and negative terminals on the source. When the circuit is powered, electrons will move from the negative terminal, through the resistor, and into the positive terminal. The resistor is basically a path of conduction that resists the movement of electrons. This circuit could also be represented as a plumbing network. In the plumbing network, the resistor would be equivalent to a section of pipe, where the water is forced to move around several barriers to pass through, effectively slowing its flow. If the pipe is level, no water will flow in an organized fashion, since the pressure is equal throughout the pipe. However, if we tilt the pipe to a vertical position (similar to turning on a voltage source), a pressure difference is created (similar to a voltage difference) and the water begins flowing through the pipe. This flow of water is similar to the flow of electrons in a circuit.

4.2 Electricity

To understand electronics, you need to understand electricity and what it is. Basically, electricity is the flow of electrons due to a difference in electrical charge between two points. This difference in charge is created due to a difference in electron density. If you have a point where the electron density is higher than the electron density at another point, the electrons in the area of higher density will want to balance the charge by migrating towards the area with lower density. This migration is referred to as electrical current. Thus, flow in an electrical circuit is induced by putting more electrons on one side of the circuit than the other, forcing them to move through the circuit to balance the charge density.

4.3 Electric Charge

In normal conditions all matter has a neutral or has a zero net charge. When an object receives an electron the object becomes negatively charged. When an object gives up an

electron the object becomes positively charged. Each charge possesses electric field lines and charge quantities. A positive charge possesses charge quantities of +Q and has electric field lines going outward. A negative charge possesses charge quantities of -Q and has electric field lines going inward. In general, like charges will oppose each other and opposite charges will attract each other. Hence, it is a property of matter.

4.3.1 Coulomb's Law

The force of attraction between two charges can be calculated by Coulomb's Law. Below would be the calculation between a positive and negative charge.

$$F = k\frac{Q+.Q-}{r^2}$$

4.3.2 Ampere's Law

The electric force, F, on a charge, Q, within an electric field, E, are related by Ampere's Law. On an atomic basis, this is the force that gives rise to current.

$$F = EQ$$

4.3.3 Lorentz's Law

When a charge in motion passes through a magnetic field. The magnetic field will push a positive charge upward and negative charge downward in the direction perpendicular to the initial direction traveled. The magnetic force on the charge is calculated by Lorennt's Law

$$F = QvB$$

$$F = -QvB$$

4.3.4 ElectroMagnetic Force

The sum of Ampere's Force and Lorentz's Force exert on a charge is called EletroMagnetic Force

$$F = F + F = QE + QvB = Q(E + vB)$$

$$F = F + F = QE - QvB = Q(E - vB)$$

4.4 Electricity and Matter

All matter interacts with Electricity, and are divided into three categories: Conductors, Semi Conductors, and Non Conductors.

Conductor[1]

Matter that conducts Electricity easily. Metals like Zinc (Zn) and Copper (Cu) conduct electricity very easily. Therefore, they are used to make Conductors.

Non-Conductor[2]

Matter that does not conduct Electricity at all. Non-Metals like Wood and Rubber do not conduct electricity so easily. Therefore, they are used to make Non-Conductors.

Semi Conductor[3]

Matter that conducts electricity in a manner between that of Conductors and Non-Conductors. For example, Silicon (Si) and Germanium (Ge) conduct electricity better than non-conductors but worse than conductors. Therefore, they are used to make Semi Conductors.

4.5 Electricity and Conductors

Normally, all conductors have a zero net charge . If there is an electric force that exerts a pressure on the charges in the conductor to force charges to move in a straight line result in a stream of electric charge moving in a straight line

4.5.1 Voltage

The pressure the electric force exert on the charges is called *voltage* denoted as V measured in Volt (V) and defined as the *ratio of Work Done on Charge*

$V = \frac{W}{Q}$

$$V = \frac{P}{I}$$

4.5.2 Current

The moving of straight lines of electric charges in the conductor is called *current* denoted as I measured in Ampere (A) and defined as *Charge flow through an area in a unit of time*

$I = \frac{Q}{t}$

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1   http://en.wikibooks.org/wiki/Conductor
2   http://en.wikibooks.org/wiki/Non-Conductor
3   http://en.wikibooks.org/wiki/Semi%20Conductor

4.5.3 Conductance

Conductance is defined as *the ratio of current over voltage* denoted as Y measured in mho

$Y = \frac{I}{V}$

4.5.4 Resistance

Resistance is defined as *the ratio of voltage over current* denoted as R measured in Ohm

$R = \frac{V}{I}$

Generally, resistance of any conductor is found to increase with increasing temperature

For Conductor

R = Ro(1 + nT)

For Semi Conductor

R = Ro e^{nT}

When a conductor conducts electricity, it dissipates heat energy into the surrounding . This results in a loss of electric energy transmitted . *If the electric supply energy is* P_V *and the electric loss energy is* P_R Then the electric energy delivered:

P = P_V - P_R

$P = IV - I^2 R = IV - \frac{V^2}{R}$

$P = I(V - IR) = V(I - \frac{V}{R})$

$P = Cos\theta$

4.6 Black Body Radiation

Further experience with conductors that conduct electricity . It is observed that all conductors that conduct electricity exhibit

1. Change in Temperature
2. Release Radiant Heat Energy into the surrounding

4.6.1 Experiment

Connect a conductor with an electric source in a closed loop . Plot the value I at different f to have a I - f diagram

4.6.2 Observation

for f<fo

Current increasing with increasing f .

Radiant heat is a wave travels at velocity v = λf carries energy E = m v^2 .

for f=fo,

Current stops increasing .

Radiant heat is a wave travels at velocity v = c (speed of Light) carries energy E = hfo .

for f>fo,

Current remains at the value of current at fo .

Radiant heat is a wave travels at velocity v = c (speed of Light) carries energy E = h nfo

4.6.3 Conclusion

1. All conductor that conducts Electricity has a threshold frequency fo
2. The Radiant Heat Energy is a Light Wave of dual Wave Particle characteristic. Sometimes it behaves like Particle, sometimes it behaves like Wave
3. At Frequency f > fo . The energy of the Light is quantized . it can only have the value of multiple integer of fo . E = hf = h nfo

5 Cells

5.1 Cells
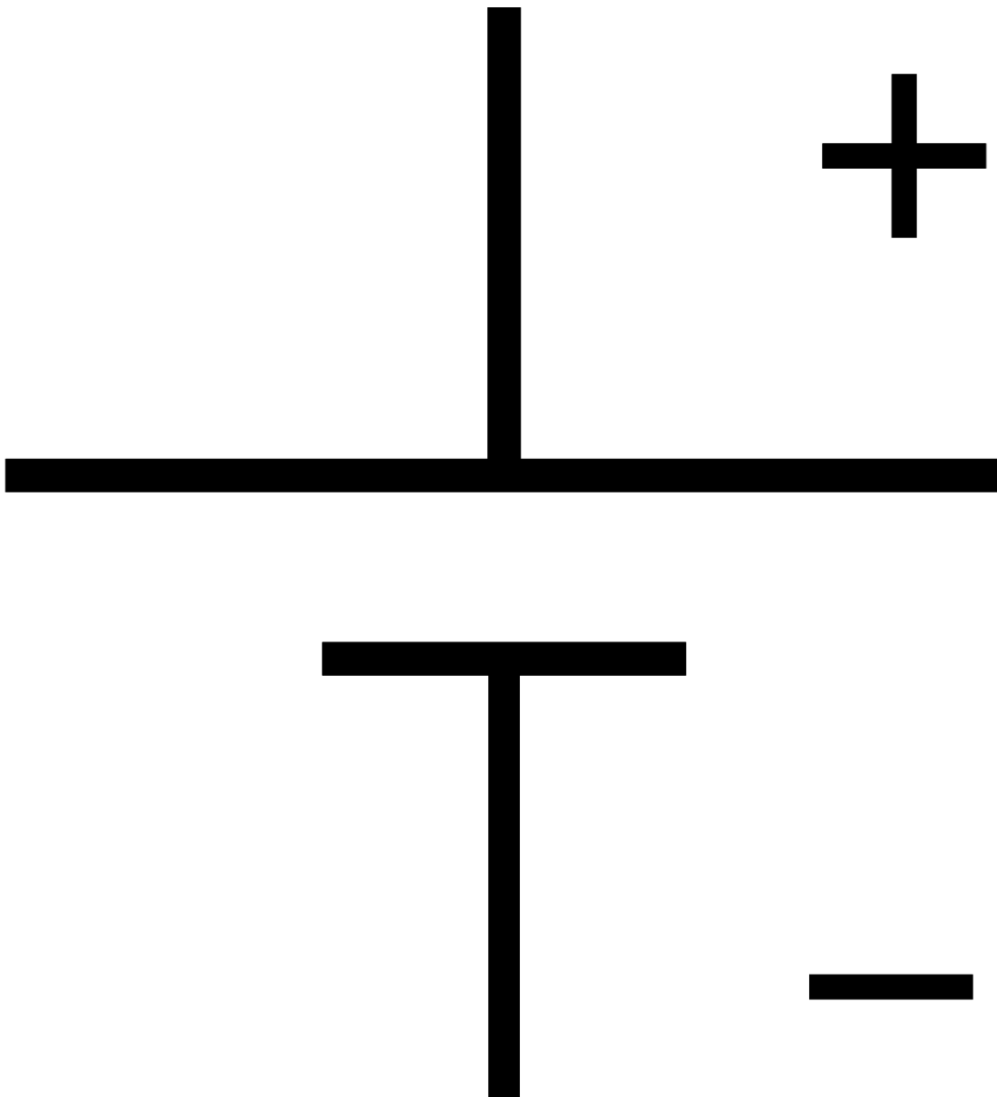
Figure 14

- Cell: Two materials with a voltage difference between them. This causes current to flow, which does work. Electrons travel from the cathode, do some work, and are absorbed by the anode.

- Anode: Destination of electrons.
- Cathode: Source of electrons.
- ions: An atom with an imbalance of electrons.

- cell operation: The cell runs and electrons are depleted at the cathode and accumulate at the anode. This creates a reverse voltage which stops the flow of electrons.

- irreversible: At some point the voltage difference reactions between the cathode and anode will decrease to a point that the cell in unusable. At this point, in an irreversible cell, the voltage difference is irreplaceably lost, and the cell is of no further use.
- reversible: Able to run the cell backwards.
- rechargeable: In a rechargeable cell, when the voltage difference between the cathode and anode decreases, the cell can be recharged, thereby increasing the voltage difference to a suitable level to allow continued use.

humid air will discharge cells.

cells are usually made of toxic or corrosive substances, for example lead and sulphuric acid. Such substances have been known to explode.

- Electronegativity http://en.wikipedia.org/wiki/Electronegativity

What is the relationship between voltage and electronegativity?

Electronegativity is a concept in chemistry used to measure and predict the relative likelihood of a chemical reaction causing electrons to shift from one chemical to another resulting in ions and molecular bonds. A battery cell operates by allowing two chemicals to react and supply ions to the anode and cathode. When the supply of a reactant is consumed, the battery is dead. It no longer produces different electrical potential at the anode and cathode driven by the chemical reaction.

Voltage is the electrical potential of a point due to surrounding measurable electric charge distributions and points as calculated by application Coulomb's Law. Voltage difference between two points connected by a conductor results in electron flow.

6 Resistors

6.1 Resistor
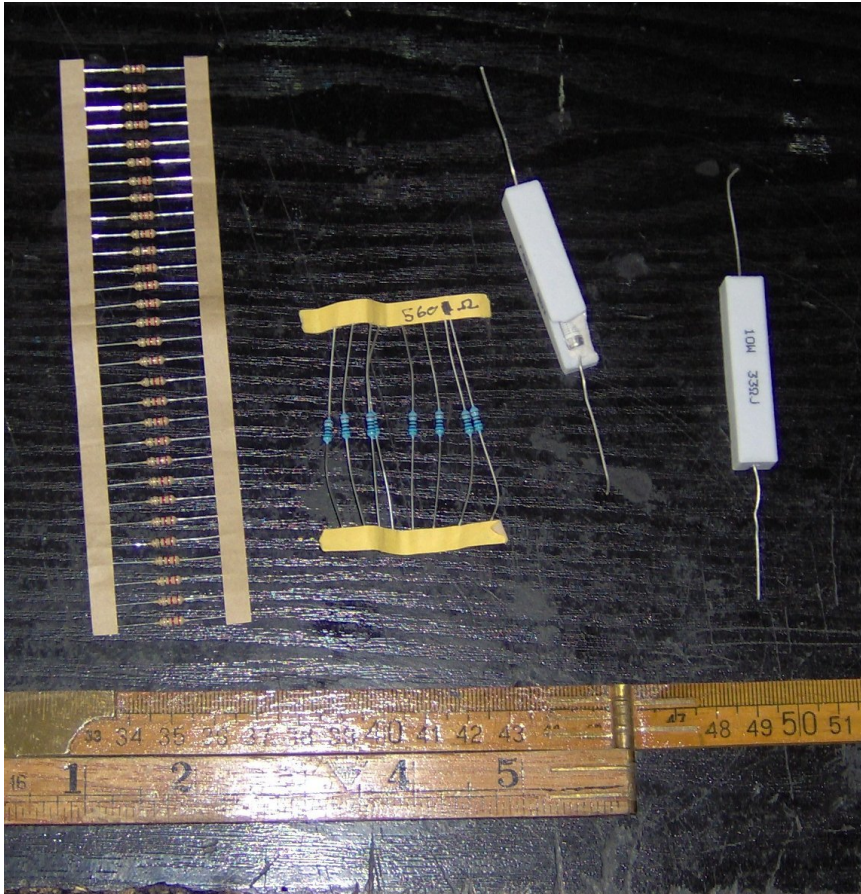
Figure 15

A resistor is a block or material that limits the flow of current. The greater the resistance, the lower the current will be, assuming the same voltage imposed on the resistor. The hydraulic analogy of a resistor would be the pipe with water flowing through it. The wider the diameter of a pipe, the higher the water flow through the pipe, assuming the same pressure difference on the terminals of a pipe.

6.2 Resistor's Symbol

Resistors have two leads (points of contact) to which the resistor can be connected to an electrical circuit. A symbol for a resistor used in electrical circuit diagrams is shown below.

—⋀⋀—

The endpoints at the left and right sides of the symbol indicate the points of contact for the resistor. The ratio of the voltage to current will always be positive, since a higher voltage on one side of a resistor is a positive voltage, and a current will flow from the positive side to the negative side, resulting in a positive current. If the voltage is reversed, the current is reversed, leading again to a positive resistance.

6.3 Resistance

Resistance is a characteristic of Resistor indicates the measurement of current opposition . Resistance has a symbol R measured in Ohm (Ω) . The ratio of voltage to current is referred to as Ohm's Law, and is one of the most basic laws that govern electronics.

$$R = \frac{V}{I}$$

An ohm is the amount of resistance which passes one ampere of current when a one volt potential is placed across it. (The ohm is actually defined as the resistance which dissipates one watt of power when one ampere of current is passed through it.)

$$1\Omega = \frac{1 \text{ V}}{1 \text{ A}}$$

Resistance can vary from very small to very large. A superconductor has zero resistance, while something like the input to an op-amp can have a resistance near 10^{12} Ω, and even higher resistances are possible.

6.3.1 Resistance and Temperature

For most materials, resistance increases with increasing Temperature

For Conductor . $R = R_o(1 + nT)$

For Semi Conductor . $R = R_o e^n T$

6.3.2 Resistance and Electric Power Loss

Resistance converts Electrical Energy into Heat this causes Electric Energy Loss.

$$P_r = I^2 R = \frac{V^2}{R}$$

NOTE : Resistors which dissipate large amounts of power are cooled so that they are not destroyed, typically with finned heatsinks.

If Electric Energy Supply is P_v and Electric Energy Loss is P_r Then, Electric Energy Delivered is

$$P = p_v - P_r$$

$$P = VI - I^2 R = I(V - IR)$$

$$P = VI - \frac{V^2}{R} = V(I - \frac{V}{R})$$

The ratio of Electric Energy Delivered over Electric Energy Supplied indicates the Efficiency of Electric Power Supply

$$n = \frac{P}{P_v} = \frac{V - IR}{V} = \frac{I - \frac{V}{R}}{I} = \frac{P_v Cos\theta}{P_v}$$

$$n = Cos\theta$$

6.4 Resistor's Labeling (See also Identification)

A manufactured resistor is usually labeled with the nominal value (value to be manufactured to) and sometimes a tolerance. Rectangular resistors will usually contain numbers that indicate a resistance and a multiplier. If there are three or four numbers on the resistor, the first numbers are a resistance value, and the last number refers to the number of zeroes in the multiplier. If there is an R in the value, the R takes the place of the decimal point.

Examples

2003 means $200 \times 10^3 = 200k\Omega$

600 means $60 \times 10^0 = 60\Omega$

2R5 means 2.5Ω

R01 means 0.01Ω

Cylindrical resistors (axial) usually have colored bands that indicate a number and a multiplier. Resistance bands are next to each other, with a tolerance band slightly farther away from the resistance bands. Starting from the resistance band side of the resistor, each colour represents a number in the same fashion as the number system shown above.

Colour System

Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
0	1	2	3	4	5	6	7	8	9

Clue : B.B.ROY of Great Britain was a Very Good Worker. **Additional Colours** : A gold band in the multiplier position means 0.1, but means a 5% tolerance in the tolerance position. A silver band in the multiplier position means 0.01, but means 10% in the tolerance position.

6.5 Resistor's Construction

The resistance R of a component is dependent on its physical dimension and can be calculated using:

$$R = \frac{\rho L}{A}$$

where

ρ is the electrical resistivity (resistance to electricity) of the material,

L is the length of the material

A is the cross-sectional area of the material.

If you increase ρ or L you increase the resistance of the material, but if you increase A you decrease the resistance of the material.

6.5.1 Resistivity of the Material

Every material has its own resistivity, depending on its physical makeup. Most metals are conductors and have very low resistivity; whereas, insulators such as rubber, wood, and air all have very high resistivity. The inverse of resistivity is conductivity, which is measured in units of Siemens/metre (S/m) or, equivalently. mhos/metre.

In the following chart, it is not immediately obvious how the unit ohm-meter is selected. Considering a solid block of the material to be tested, one can readily see that the resistance of the block will decrease as its cross-sectional area increases (thus widening the conceptual "pipe"), and will increase as the length of the block increases (lengthening the "pipe"). Given a fixed length, the resistance will increase as the cross-sectional area decreases; the resistance, multiplied by the area, will be a constant. If the cross-sectional area is held constant, as the length is increased, the resistance increases in proportion, so the resistance divided by the length is similarly a constant. Thus the bulk resistance of a material is typically measured in ohm meters squared per meter, which simplifies to ohm - meter (Ω-m).

Conductors Ω-m (Ohm-meter)	
Silver	1.59×10^{-8}
Copper	1.72×10^{-8}
Gold	2.44×10^{-8}
Aluminum	2.83×10^{-8}
Tungsten	5.6×10^{-8}
Iron	10×10^{-8}

Conductors Ω-m (Ohm-meter)

Platinum	11×10^{-8}
Lead	22×10^{-8}
Nichrome	1.50×10^{-6} (A nickel-chromium alloy commonly used in heating elements)
Graphite	$\tilde{}10^{-6}$
Carbon	3.5×10^{-5}

Semiconductors

Pure Germanium	0.6
Pure Silicon	640
Common purified water	$\tilde{}10^{3}$
Ultra-pure water	$\tilde{}10^{5}$
Pure Gallium Arsenide	$\tilde{}10^{6}$

Insulators

Diamond	$\tilde{}10^{10}$
Glass	10^{10} to 10^{14}
Mica	9×10^{13}
Rubber	10^{13} to 10^{16}
Organic polymers	$\tilde{}10^{14}$
Sulfur	$\tilde{}10^{15}$
Quartz (fused)	5 to 75×10^{16}
Air	very high

Silver, copper, gold, and aluminum are popular materials for wires, due to low resistivity. Silicon and germanium are used as semiconductors. Glass, rubber, quartz crystal, and air are popular dielectrics, due to high resistivity.

Many materials, such as air, have a non-linear resistance curve. Normal undisturbed air has a high resistance, but air with a high enough voltage applied will become ionized and conduct very easily.

The resistivity of a material also depends on its temperature. Normally, the hotter an object is, the more resistance it has. At high temperatures, the resistance is proportional to the absolute temperature. At low temperatures, the formula is more complicated, and what counts as a high or low temperature depends on what the resistor is made from. In some materials the resistivity drops to zero below a certain temperature. This is known as superconductivity, and has many useful applications.

(Some materials, such as silicon, have less resistance at higher temperatures.)

For all resistors, the *change* in resistance for a *small* increase in temperature is *directly proportional* to the *change* in temperature.

Current passing through a resistor will warm it up. Many components have heat sinks to dissipate that heat. The heatsink keeps the component from melting or setting something on fire.

6.5.2 Length

The length of an object is directly proportional to its resistance. As shown in the diagram below, 1 unit cubed of material has 1 ohm of resistance. However, when 4 units are stacked lengthwise and a connection is made to the front and back sides respectively, the total resistance is 4 ohms. This is because the length of the unit is 4, whereas the cross-sectional area remains 1. However, if you were to make connections on the sides, the exact opposite would be true: the cross-sectional area would be 4 and the length 1, resulting in 0.25 ohms total resistance.
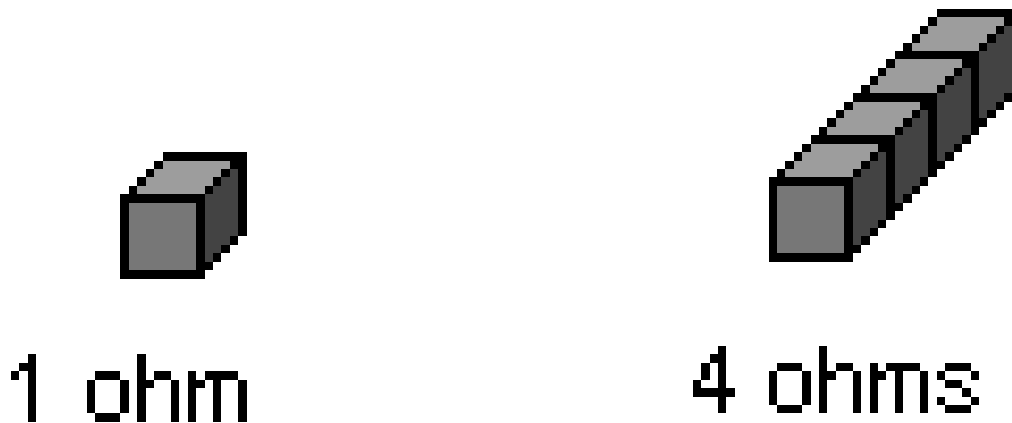
Figure 17

6.5.3 Cross-Sectional Area

Increasing area is the same as having resistors in parallel, so as you increase the area you add more paths for current to take.

The resistance of a material is inversely proportional to its cross-sectional area. This is shown in the diagram below, where 1 unit cubed has one ohm of resistance. However, if 4 units cubed are stacked on top of each other in the fashion such that there is 4 units squared of cross-sectional area, and the electrical connections are made to the front and back such that the connections are on the largest sides, the resultant resistance would be 0.25 ohms.

Additional note: There are two reasons why a small cross-sectional area tends to raise resistance. One is that the electrons, all having the same negative charge, repel each other. Thus there is resistance to many being forced into a small space. The other reason is that they collide, causing "scattering," and therefore they are diverted from their original directions. (More discussion is on page 27 of "Industrial Electronics," by D. J. Shanefield, Noyes Publications, Boston, 2001.)
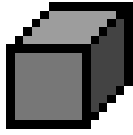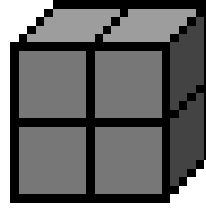
Figure 18

6.5.4 Example

For instance, if you wanted to calculate the resistance of a 1 cm high, 1 cm wide, 5 cm deep block of copper, as shown in the diagram below:
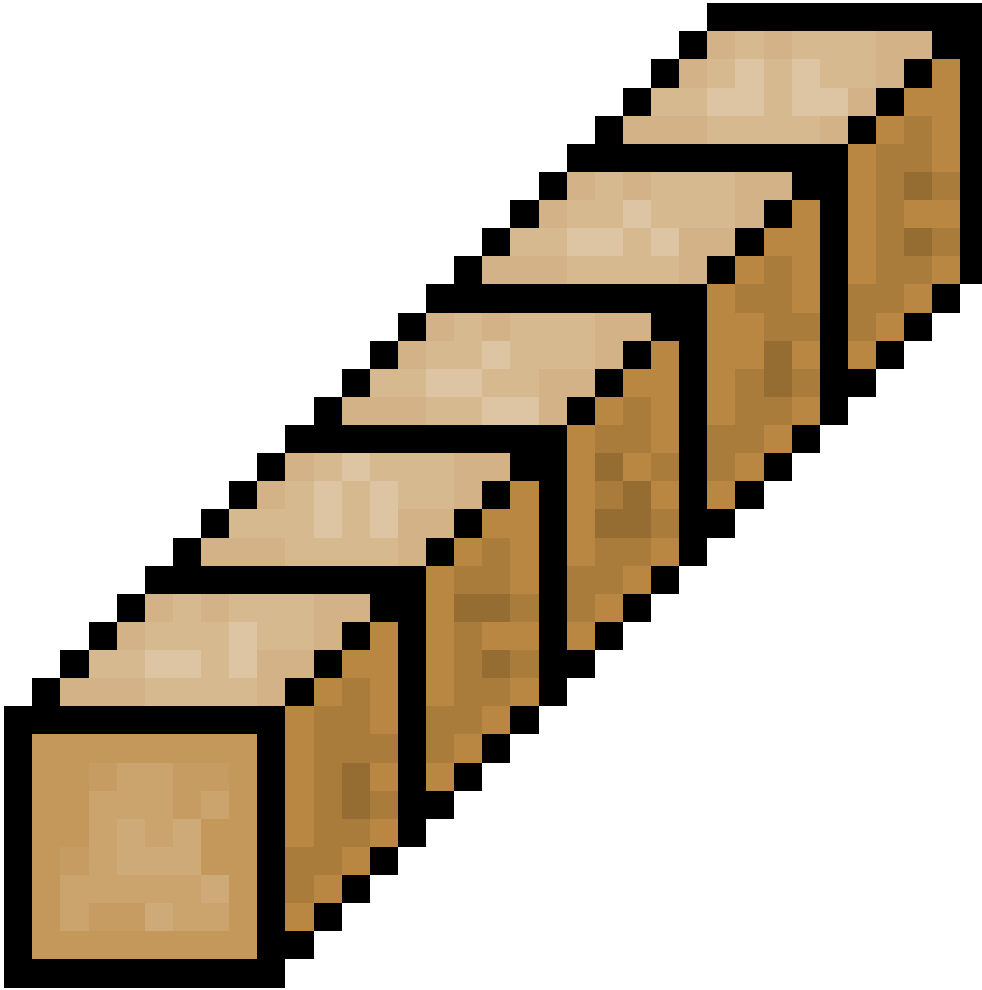
Figure 19

You would first need to decide how it's oriented. Suppose you want to use it from front to back (lengthwise), like a piece of wire, with electrical contacts on the front and rear faces. Next you need to find the length, L. As shown, it is 5 cm long (0.05 m). Then, we look up the resistivity of copper on the table, 1.6×10^{-8} Ω-meters. Lastly, we calculate the cross-sectional area of the conductor, which is 1 cm $\times$ 1 cm = 1 cm^2 (0.0001 m^2). Then, we put it all in the formula, converting cm to m:

$$\frac{0.05 \text{ m} \cdot 1.6 \times 10^{-8} \text{ } \Omega \cdot \text{m}}{0.0001 \text{ m}^2} = \frac{0.08 \times 10^{-8} \text{ } \Omega \cdot \text{m}^2}{0.0001 \text{ m}^2}$$

units m^2 cancel:

$$\frac{0.08 \times 10^{-8} \text{ } \Omega}{0.0001}$$

Which, after evaluating, gives you a final value of 8.0×10^{-6} Ω, or 8 microohms, a very small resistance. The method shown above included the units to demonstrate how the units cancel out, but the calculation will work as long as you use consistent units.

Internet Hint: Google calculator can do calculations like this for you, automatically converting units. This example can be calculated with this link: `http://www.google.com/search?q=%281.6*10%5E-8+ohm+meter%29+*+%285+cm%29+%2F+%281+cm%29%5E2&`

6.5.5 Properties of the material

- **Wirewound** : Used for power resistors, since the power per volume ratio is highest. These usually have the lowest noise.

- **Carbon Film** : These are easy to produce, but usually have lots of noise because of the properties of the material.

- **Metal Film** : These resistors have thermal and voltage noise attributes that are between carbon and wirewound.

- **Ceramic** : Useful for high frequency applications.

6.6 Resistor Connection

6.6.1 Resistors in Series
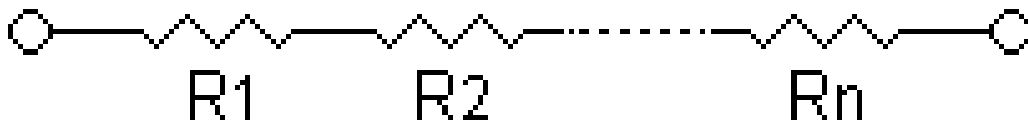
Figure 20

Resistors in series are equivalent to having one long resistor. If the properties of two resistors are equivalent, except the length, the final resistance will be the sum of the two construction methods:

$$R_{EQ} = \frac{\rho L_{EQ}}{A} = \frac{\rho L_1}{A} + \frac{\rho L_2}{A}$$

This means that the resistors add when in series.

$$R_{EQ} = R_1 + R_2 + \cdots + R_n$$

- Christmas tree lights are usually connected in series, with the unfortunate effect that if one light blows, the others will all go out (This happens because the circuit is not complete, if a circuit is not complete then the current cannot flow, hence the light bulbs

all go out). However, most modern Christmas light strings have built in shunt resistors in parallel to the bulb, so that current will flow past the blown light bulb.

6.6.2 Resistors in Parallel
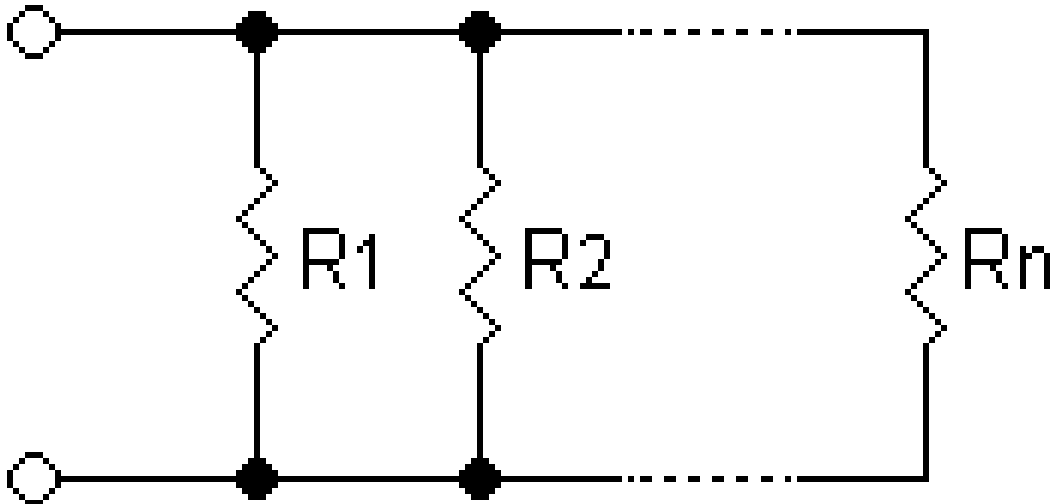
Figure 21

In a parallel circuit, current is divided among multiple paths. This means that two resistors in parallel have a lower equivalent resistance than either of the parallel resistors, since both resistors allow current to pass. Two resistors in parallel will be equivalent to a resistor that is twice as wide:

$$R_{EQ} = \frac{\rho L}{A_{EQ}} = \frac{\rho L}{A_1} + \frac{\rho L}{A_2}$$

Since conductances (the inverse of resistance) add in parallel, you get the following equation:

$$\frac{1}{R_{EQ}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

For example, two 4 Ω resistors in parallel have an equivalent resistance of only 2 Ω.

To simplify mathematical equations, resistances in parallel can be represented with two vertical lines "||" (as in geometry). For two resistors the parallel formula simplifies to:

$$R_{EQ} = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

6.6.3 Combinations of series and parallel
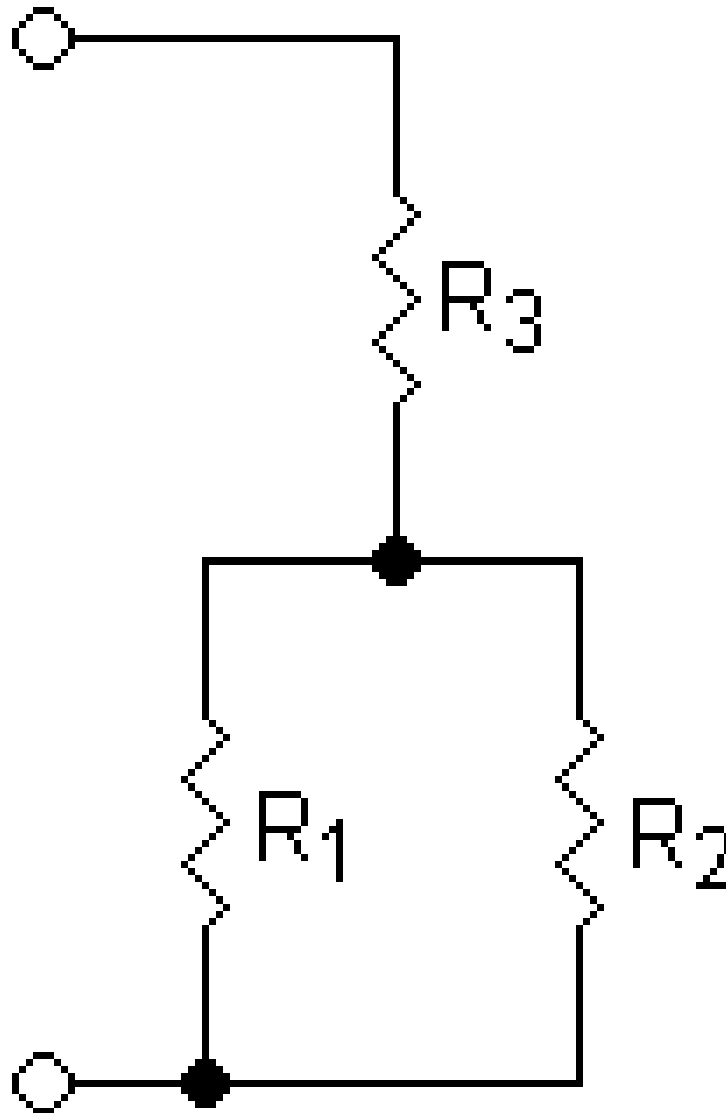
Figure 22

Resistors in parallel are evaluated as if in a mathematical set of "parentheses." The most basic group of resistors in parallel is evaluated first, then the group in series with the new equivalent resistor, then the next group of resistors in parallel, and so on. For example, the above portion would be evaluated as follows:

$$R_{EQ} = (R_1 \| R_2) + R_3 = \frac{R_1 R_2}{R_1 + R_2} + R_3$$

6.7 Resistor variations

- **Variable Resistor** or **Potentiometer**

Variable resistors are tunable, meaning you can turn a dial or slide a contact and change the resistance. They are used as knobs to control the volume of a stereo, or as a dimmer for a lamp. The term Potentiometer is often abbreviated as 'pot'. It is constructed like a resistor, but has a sliding tap contact. Potentiometers are used as Voltage Dividers[1]. It is rare to find a variable resistor with only two leads. Most are potentiometers with three leads, even if one is not connected to anything.

- **Rheostat**

A variation of the potentiostat with a high current rating, which is used to control the amount of power going through a load, such as a motor.

- **Thermistor**

Temperature-sensitive resistor, in which the resistance decreases as the temperature rises. They are used in fire alarms, so if things get too hot the current rises and trips a switch that sounds an alarm.

- **LDR** (Light Dependent Resistor) or **Photoresistor**

A resistor which changes values depending on the amount of light shining on its surface. The resistance decreases as the amount of light increases. They are used in street lamps, so when it gets dark the current decreases and turns on the street lamp.

6.8 Applications

- **Voltage division** / **Attenuation** : Sometimes a voltage will be too large to measure, so a means to linearly reduce the voltage is required. Placing two resistors in series to ground will provide a point in the middle to tap. Resistor R_A is placed between the input voltage and the output node, and the resistor R_B is placed between the output node and ground. This creates a voltage divider to lessen the output voltage. Typically, the resistors are near the value of ˜10kΩ. The Thevenin model of the circuit gives an output resistance $R_{OUT} = R_A || R_B$. A larger output resistance will more likely be affected by the input resistance of the measuring circuit (this is a desired effect in the transistor biasing circuits). Placement of the voltage divider should be close to the measuring circuit, to minimize noise (in this arrangement, it will be also lessened Rb/(Ra + Rb) times). The output voltage of the voltage divider is

$$V_{output} = \frac{R_B}{R_A + R_B} V_{input}$$

- **Pull-up** / **Pull-down** : If there is nothing to drive a signal node, the node will be left "floating" (for example, such a situation occurs at the trigger input of a car alarm system when the driver has switched off the internal lamp). This may lead to unintended

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1   http://en.wikibooks.org/wiki/Electronics%2FVoltage%20Dividers

values being measured, or causing side-effects when the voltage is propagated down the remainder of the circuit. To prevent this, a relatively high value resistor (usually ˜10kΩ to ˜1MΩ) is placed between the node and ground (pull-down) or a high voltage (pull-up) to bring the voltage of the "floating" node near to the voltage it is being pulled. A resistive voltage divider is another example where the upper resistor "pulls" the output point up toward the input voltage while the lower resistor "pulls" the output point toward the ground. This idea is evolved in the circuit of a resistive voltage summer (for example, the resistors R_1 and R_2 of an op-amp inverting amplifier) supplied by two voltages (V_{IN} and -V_{OUT}) having opposite polarities. The two voltage sources "pull" the output point in opposite directions; as a result, if $R_2/R_1 = -V_{OUT}/V_{IN}$, the point becomes a virtual ground. Placement of a pull-up or pull-down resistor does not have a significant effect on the performance of the circuit, if they have high resistances.

- **Current limiting / Isolation** : In order to protect circuits from conditions that may cause too much current in a device, a current limiting resistor is inserted in the middle of the circuit. A digital input to a microcontroller may benefit from a current limiting resistor. The inputs to modern microcontrollers have protection circuitry built in that will protect the input from an overvoltage condition, provided that the current is small enough. For instance, a common microcontroller will be capable of withstanding 20mA. If there are 12V nets on a circuit board, or in a system, the digital input will benefit from a 350Ω resistor (refer to calculation below). Usually a slightly larger resistance is used in practice, but too large of a resistor will cause noise, and may prevent the input from being able to read the voltage. It is good practice to place the resistor as close as possible to the microcontroller input, so that an accidental short on the board will mean that the microcontroller input is likely still protected.

$$R = \frac{12V}{20mA} = 600\Omega$$

- **Line termination / Impedance matching** : The properties of an electric wave propagating through a conductor (such as a wire) create a reflection, which can be viewed as unwanted noise. A reflection can be eliminated by maximizing the power transfer between the conductor and the termination resistor. By matching the resistance (more importantly the impedance), the wave will not cause a reflection. The voltage of the echo V_r is calculated below in reference to the original signal V_o as a function of the conductor impedance Z_C and the terminator impedance Z_T. As the name implies, the termination resistor goes at the end of the conductor.

$$V_r = V_o \frac{Z_C - Z_T}{Z_C + Z_T}$$

- **Current sensing** : Measurement of a current cannot be done directly. There are three major ways to measure a current: a resistor, a hall sensor, and an inductor. The hall sensor and inductor use a property of the magnetic field to sense the current through a nearby conductor. According to Ohm's law, if a current I flows through a resistor R, a voltage V = R.I appears across the resistor. Therefore, the resistor can act as a passive current-to-voltage converter. In this arrangement, the resistor should have a very low value (sometimes on the order of ˜0.01Ω), so it does not affect the current flow or heat up; however, a smaller value has a lower voltage to read, which means more noise may

be introduced. This contradiction is solved in the circuit of an active current-to-voltage converter where the resistor may have a significant resistance as an op-amp compensates the "undesired" voltage drop across it (unfortunately, this remedy may be applied only in low-current measurements). The current sense resistor should be placed as close as possible to where the measurement occurs, in order not to disturb the circuit.

- **Filtering** : Filtering is discussed later, after an introduction to capacitors and inductors. Filters are best placed close to where measurement takes place.

6.9 Specifications

Resistors are available as pre-fabricated, real-world components. The behavior of such components deviates from an ideal resistor in certain ways. Therefore, real-world resistors are not only specified by their resistance, but also by other parameters. In order to select a manufactured resistance, the entire range of specifications should be considered. Usually, exact values do not need to be known, but ranges should be determined.

6.9.1 Nominal Resistance

The nominal resistance is the resistance that can be expected when ordering a resistor. Finding a range for the resistance is necessary, especially when operating on signals. Resistors do not come in all of the values that will be necessary. Sometimes resistor values can be manipulated by shaving off parts of a resistor (in industrial environments this is sometimes done with a LASER to adjust a circuit), or by combining several resistors in series and parallel.

Available resistor values typically come with a resistance value from a so called resistor series. Resistor series are sets of standard, predefined resistance values. The values are actually made up from a geometric sequence within each decade. In every decade there are supposed to be n resistance values, with a constant step factor. The standard resistor values within a decade are derived by using the step factor i

$$i = \sqrt[n]{10}; n = 6, 12, 24, 48$$

rounded to a two digit precision. Resistor series are named En, according to the used value of n in the above formula.

```
  n Values/Decade  Step factor i  Series
  ----------------------------------------
            6            1.47         E6
           12            1.21         E12
           24            1.10         E24
           48            1.05         E48
```

For example, in the E12 series for $n = 12$, the resistance steps in a decade are, after rounding the following 12 values:

```
    1.00, 1.20, 1.50, 1.80, 2.20, 2.70,
    3.30, 3.90, 4.70, 5.60, 6.80, and 8.20
```

and actually available resistors from the E12 series are for example resistors with a nominal value of 120Ω or 4.7kΩ.

6.9.2 Tolerances

A manufactured resistor has a certain tolerance to which the resistance may differ from the nominal value. For example, a 2kΩ resistor may have a tolerance of ±5%, leaving a resistor with a value between 1.9kΩ and 2.1kΩ (i.e. 2kΩ±100Ω). The tolerance must be accounted for when designing circuits. A circuit with an absolute voltage of 5V±0.0V in a voltage divider network with two resistors of 2kΩ±5% will have a resultant voltage of 5V±10% (i.e. 5V±0.1V). The final resistor tolerances are found by taking the derivative of the resistor values, and plugging the absolute deviations into the resulting equation.

The above mentioned E-series which are used to provide standardized nominal resistance values, are also coupled to standardized nominal tolerances. The fewer steps within a decade there are, the larger the allowed tolerance of a resistor from such a series is. More precises resistors, outside of the mentioned E-series are also available, e.g. for high-precision measurement equipment. Common tolerances, colors and key characters used to identify them are for example:

```
  Series   Values/Decade   Tolerance   Color Code   Character Code
  ----------------------------------------------------------------
    E6          6            ±20%         [none]        [none]
    E12         12           ±10%         silver          K
    E24         24           ±5%          gold            J
    E48         48           ±2%          red             G
     -          -            ±1%          brown           F
     -          -            ±0.5%          -             D
     -          -            ±0.25%         -             C
     -          -            ±0.1%          -             B
```

Resistor manufacturers can benefit from this standardization. They manufacture resistors first, and afterwards they measure them. If a resistor does not meet the nominal value within the defined tolerance of one E-series, it might still fit into a lower series, and doesn't have to be thrown away, but can be sold as being compliant to that lower E-series standard. Although typically at a lower price.

Series : Resistors that combine in series add the nominal tolerances together.

Derivation: $dR_T = dR_A + dR_B$

Example: For two resistors in series $R_A = 1.5\text{k}\Omega \pm 130\Omega$ and $R_B = 500\Omega \pm 25\Omega$, the tolerance is $130\Omega + 25\Omega$, resulting in a final resistor value $R_T = 2\text{k}\Omega \pm 155\Omega$.

Parallel : Resistors that combine in parallel have a combined tolerance that is slightly more complex.

Derivation: $dR_P = \frac{dR_A R_B^2 + R_A^2 dR_B}{(R_A + R_B)^2}$

Example: For two resistors in parallel $R_A = 1.5k\Omega\pm130\Omega$ and $R_B = 500\Omega\pm25\Omega$.

6.9.3 Power Rating

Because the purpose of a resistor is to dissipate power in the form of heat, the resistor has a rating (in watts) at which the resistor can continue to dissipate before the temperature overwhelms the resistor and causes it to overheat. When a resistor overheats, the material begins to melt away, which will cause the resistance to increase (usually), until the resistor breaks.

6.9.4 Operating Temperature

Related to power rating, the operating temperature is the temperature that the resistor can continue to operate before being destroyed.

6.9.5 Maximum Voltage

In order to avoid sparkovers or material breakdown a certain maximum voltage over a resistor must not be exceeded. The maximum voltage is part of a resistor's specification, and typically a function of the resistor's physical length, distance of the leads, material and coating.

For example, a resistor with a maximum operating voltage of 1kV can have a length in the area of 2", while a 0.3" resistor can operate under up to several tens of volts, probably up to a hundred volts. When working with dangerous voltages it is essential to check the actual specification of a resistor, instead of only trusting it because of the length.

6.9.6 Temperature Coefficient

This parameter refers to the constant in which the resistance changes per degree Celsius (units in C^{-1}). The change in temperature is not linear over the entire range of temperatures, but can usually be thought of as linear around a certain range (usually around room temperature). However, the resistance should be characterized over a large range if the resistor is to be used as a thermistor in those ranges. The simplified linearized formula for the affect on temperature to a resistor is expressed in an equation:

$$R = R_0[1 + \alpha(T - T_0)]$$

6.9.7 Capacity and Inductance

Real world resistors not only show the physical property of resistance, but also have a certain capacity and inductance. These properties start to become important, if a resistor is used in some high frequency circuitry. Wire wound resistors, for example, show an inductance which typically make them unusable above 1kHz.

6.9.8 Packaging

Resistors can be packaged in any way possible, but are divided into surface mount, through hole, soldering tag and a few more forms. Surface mount is connected to the same side that the resistor is on. Through hole resistors have leads (wires) that typically go through the circuit board and are soldered to the board on the side opposite the resistor, hence the name. Resistors with leads are also used in point-to-point circuits without circuit boards. Soldering tag resistors have lugs to solder wires or high current connectors onto.

Usual packages for surface mount resistors are rectangular, referenced by a length and a width in mils (thousands of an inch). For instance, an 0805 resistor is a rectangle with length .08" x .05", with contacts (metal that connects to the resistor) on either side. Typical through hole resistors are cylindrical, referenced either by the length (such as 0.300") or by a typical power rating that is common to the length (a 1/4W resistor is typically 0.300"). This length does not include the length of the leads.

6.10 Related Wikimedia resources

6.10.1 Wikibooks

- Circuit Idea[2]: Passive voltage-to-current converter[3] shows how the bare resistor can act as a simple voltage-to-current converter.

6.10.2 Wikipedia

- Voltage-to-current converter[4] builds consecutively the passive and active versions of the voltage-to-current converter.

- Current-to-voltage converter[5] is dedicated to the passive and active versions of the inverse current-to-voltage converter.

6.10.3 Further Readings

- **Resistors in Series and Parallel** [6]: Electronics for Beginners

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2   http://en.wikibooks.org/wiki/Circuit%20Idea
3   http://en.wikibooks.org/wiki/Circuit%20Idea%2FPassive%20Voltage-to-Current%20Converter
4   http://en.wikipedia.org/wiki/Voltage-to-current%20converter
5   http://en.wikipedia.org/wiki/Current-to-voltage%20converter
6   http://max-iskram.rhcloud.com/?page_id=137

7 Capacitors

7.1 General remarks
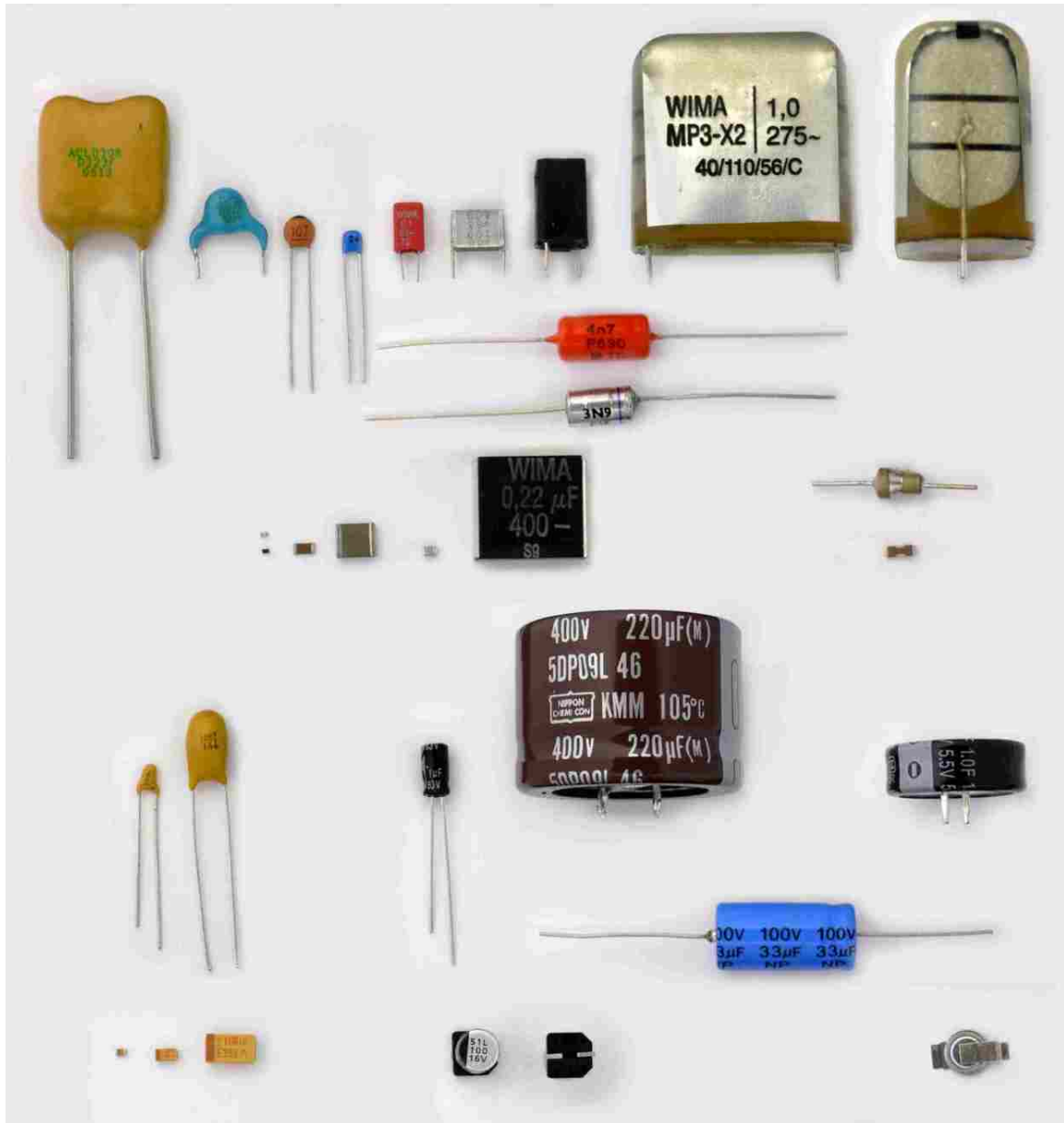
Figure 23   Some different capacitors for electronic equipment

Capacitors are a good example of the fact that even the simplest device can become complicated given 250 years of evolution. (Citation J. Ho, T. R. Jow, St. Boggs, Historical Introduction to Capacitor Technology)[1]

Capacitors , together with resistors, inductors and memristors, belong to the group of "passive components" for electronic equipment. Although in absolute figures the most common capacitors are integrated capacitors, e.g. in DRAMs or in flash memory structures, this article is concentrated on discrete components.

7.2 Capacitors

7.2.1 Theory of conventional construction
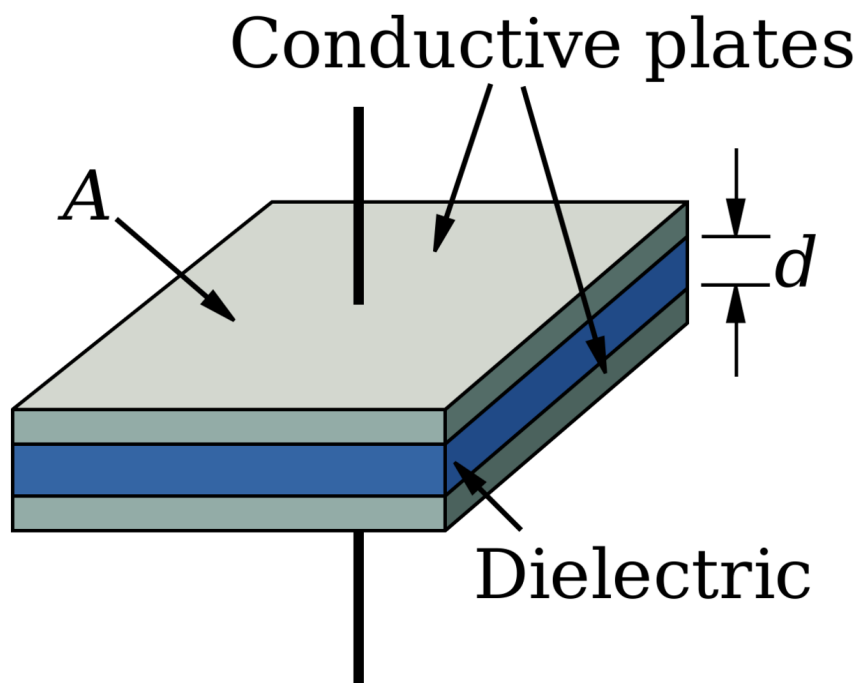
Figure 24   Model of a capacitor

A capacitor (historically known as a "condenser") is a device that stores energy in an electric field, by accumulating an internal imbalance of electric charge. It is made of two conductors separated by a dielectric (insulator). Using the same analogy of water flowing through a pipe, a capacitor can be thought of as a tank, in which the charge can be thought of as a volume of water in the tank. The tank can "charge" and "discharge" in the same manner as a capacitor does to an electric charge. A mechanical analogy is that of a spring. The spring holds a charge when it is pulled back.

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1   J. Ho, T. R. Jow, S. Boggs, Historical Introduction to Capacitor Technology, PDF `http://www.ifre.re.kr/board/filedown.php?seq=179`

When voltage exists one end of the capacitor is getting drained and the other end is getting filled with charge.This is known as charging. Charging creates a charge imbalance between the two plates and creates a reverse voltage that stops the capacitor from charging. As a result, when capacitors are first connected to voltage, charge flows only to stop as the capacitor becomes charged. When a capacitor is charged, current stops flowing and it becomes an open circuit. It is as if the capacitor gained infinite resistance.

You can also think of a capacitor as a fictional battery in series with a fictional resistance. Starting the charging procedure with the capacitor completely discharged, the applied voltage is not counteracted by the fictional battery, because the fictional battery still has zero voltage, and therefore the charging current is at its maximum. As the charging continues, the voltage of the fictional battery increases, and counteracts the applied voltage, so that the charging current decreases as the fictional battery's voltage increases. Finally the fictional battery's voltage equals the applied voltage, so that no current can flow into, nor out of, the capacitor.

Just as the capacitor charges it can be discharged. Think of the capacitor being a fictional battery that supplies at first a maximum current to the "load", but as the discharging continues the voltage of the fictional battery keeps decreasing, and therefore the discharge current also decreases. Finally the voltage of the fictional battery is zero, and therefore the discharge current also is then zero.

This is not the same as dielectric breakdown where the insulator between the capacitor plates breaks down and discharges the capacitor. That only happens at large voltages and the capacitor is usually destroyed in the process. A spectacular example of dielectric breakdown occurs when the two plates of the capacitor are brought into contact. This causes all the charge that has accumulated on both plates to be discharged at once. Such a system is popular for powering tasers which need lots of energy in a very brief period of time.

7.2.2 Theory of electrochemical construction
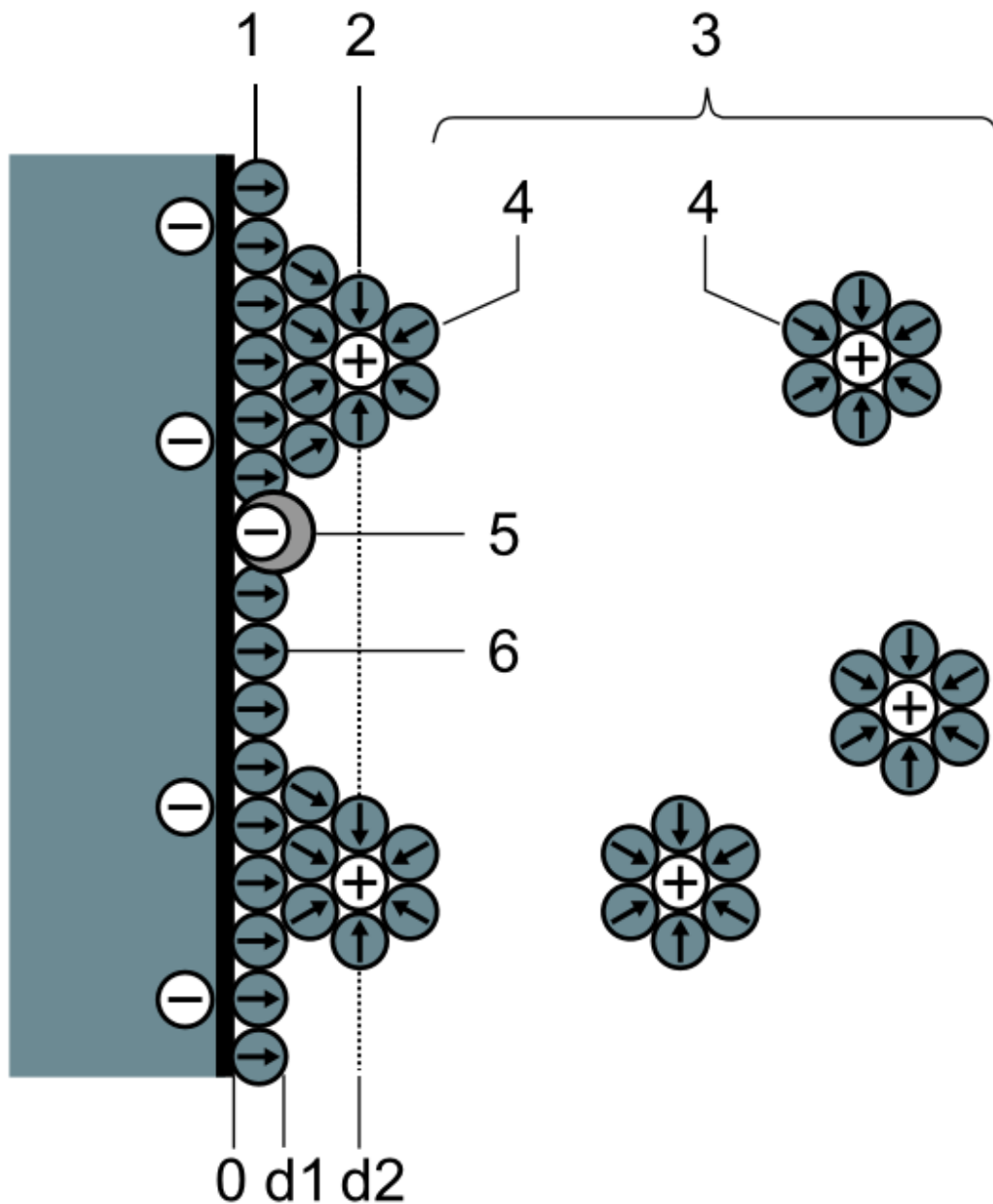
Figure 25   Scheme on double layer on electrode (BMD model).
1. IHP Inner Helmholtz Layer
2. OHP Outer Helmholtz Layer
3. Diffuse layer
4. Solvated ions
5. Specifically adsorptive ions (Pseudocapacitance)
6. Solvent molecule.

Besides the conventional static storage of electric energy in an electric field, two other storage principles to store electric energy in a capacitor exist. They are so-called electrochemical

capacitors. In contrast to ceramic, film and electrolytic capacitors, supercapacitors, also known as electrical double-layer capacitors (EDLC) or ultracapacitors do not have a conventional dielectric. The capacitance value of an electrochemical capacitor is determined by two high-capacity storage principles. These principles are:

- electrostatic storage within Helmholtz double layers achieved on the phase interface between the surface of the electrodes and the electrolyte (**double-layer capacitance**) and the
- electrochemical storage achieved by a faradaic electron charge-transfer by specifically adsorpted ions with redox reactions (**pseudocapacitance**) . Unlike batteries, in the faradaic redox reactions, the ions simply cling to the atomic structure of an electrode without making or braking chemical bonds, and no or negligibly small chemical modifications are involved in charge/discharge.

The ratio of the storage resulting from each principle can vary greatly, depending on electrode design and electrolyte composition. Pseudocapacitance can increase the capacitance value by as much as an order of magnitude over that of the double-layer by itself.[2]

7.3 Capacitance

The capacitance of a capacitor is a ratio of the amount of charge that will be present in the capacitor when a given potential (voltage) exists between its leads. The unit of capacitance is the farad[4] which is equal to one coulomb per volt. This is a very large capacitance for most practical purposes; typical capacitors have values on the order of microfarads or smaller.

$$C = \frac{Q}{V}$$

Where C is the capacitance in farads, V is the potential in volts, and Q is the charge measured in coulombs. Solving this equation for the potential gives:

$$V = \frac{Q}{C}$$

7.4 Capacitor & Direct Current Voltage (DC)

Charge Building

When a Capacitor is connected with electricity source V. Charge will build up on each plates of capacitor of the same amount of charge but different in polarity . This process is called Capacitor Charging

Storing Charge

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2   A Survey of Electrochemical Supercapacitor Technology [3]. . Retrieved 2011-06-24
4   `http://en.wikipedia.org/wiki/Farads`

When both plates are charged up to voltage V then there is no difference in voltage between capacitor's plates and electricity source therefore no current flow in the circuit. This is called Storing Charge

Charge discharge

When the capacitor is connected to ground, current will flow from capacitor to ground until the voltage on capacitor's plates are equal to zero.

Therefore, a Capacitor is a device that can Build up Charge , Store Charge and Release Charge

7.5 Capacitor & Alternating Current Voltage (AC)

7.5.1 Voltage

$$V = \frac{1}{C} \int I dt$$

7.5.2 Current

$$I = C \frac{dV}{dt}$$

7.5.3 Reactance

Reactance is defined as the ratio of Voltage over Current

$$X_C = \frac{1}{\omega C} \angle -90 = \frac{1}{j\omega C} = \frac{1}{sC}$$

7.5.4 Impedance

Impedance is defined as the sum of Capacitor's Resistance and Reactance

$$R_C + X_C = R_C \angle 0 + \frac{1}{\omega C} \angle -90 = R_C + \frac{1}{j\omega C} = R_C + \frac{1}{sC}$$

7.5.5 Angle of Difference between Voltage and Current

For Lossless Capacitor

Current will lead Voltage an angle 90 degree

For Lossy Capacitor

Current will lead Voltage an angle θ degree where

Tan θ = $\frac{1}{\omega C R_C}$ = $\frac{1}{2\pi f C R_C}$ = $\frac{t}{2\pi C R_C}$

Changing the value of R and C will change the value of Phase Angle, Angular Frequency, Frequency and Time

$$\omega = \frac{1}{Tan\theta C R_C}$$

$$f = \frac{1}{2\pi Tan\theta C R_C}$$

$$t = 2\pi Tan\theta C R_C$$

7.6 Capacitor Connection

7.6.1 Capacitors in Series

Capacitors in series are the same as increasing the distance between two capacitor plates. As well, it should be noted that placing two 100 V capacitors in series results in the same as having one capacitor with the total maximum voltage of 200 V. This, however, is not recommended to be done in practice, especially with capacitors of different values. In a capacitor network in series, **all capacitors can have a different voltage over them** .
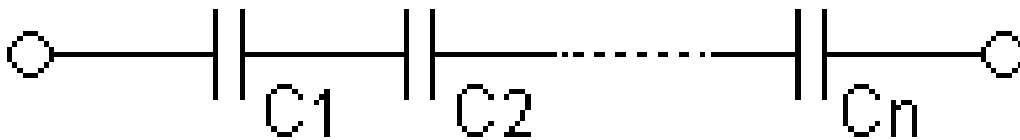
Figure 26

In a series configuration, the capacitance of all the capacitors combined is the reciprocal of the sum of the reciprocals of the capacitance of all the capacitors.

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$

7.6.2 Capacitors in Parallel

Capacitors in parallel are the same as increasing the total surface area of the capacitors to create a larger capacitor with more capacitance. In a capacitor network in parallel, **all**

capacitors have the same voltage over them .
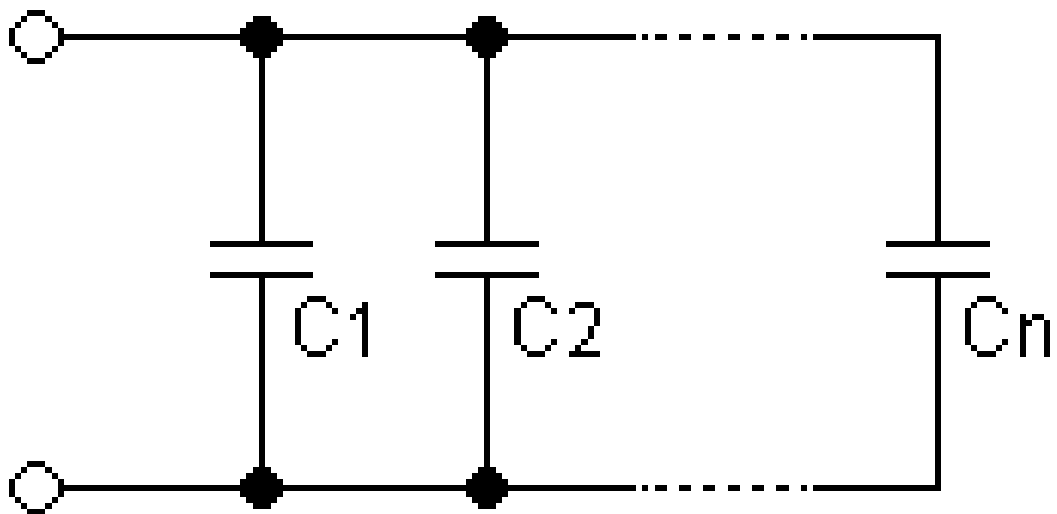
Figure 27

In a parallel configuration, the capacitance of the capacitors in parallel is the sum of the capacitance of all the capacitors.

$$C_{eq} = C_1 + C_2 + \cdots + C_n$$

7.7 RC Circuit

7.7.1 Introduction

An **RC** circuit is short for 'Resistor-Capacitor' circuit. A capacitor takes a finite amount of time to discharge through a resistor, which varies with the values of the resistor and capacitor. A capacitor acts interestingly in an electronic circuit, practically speaking as a combination of a voltage source and a variable resistor.

7.7.2 Basics

Below is a simple RC Circuit:
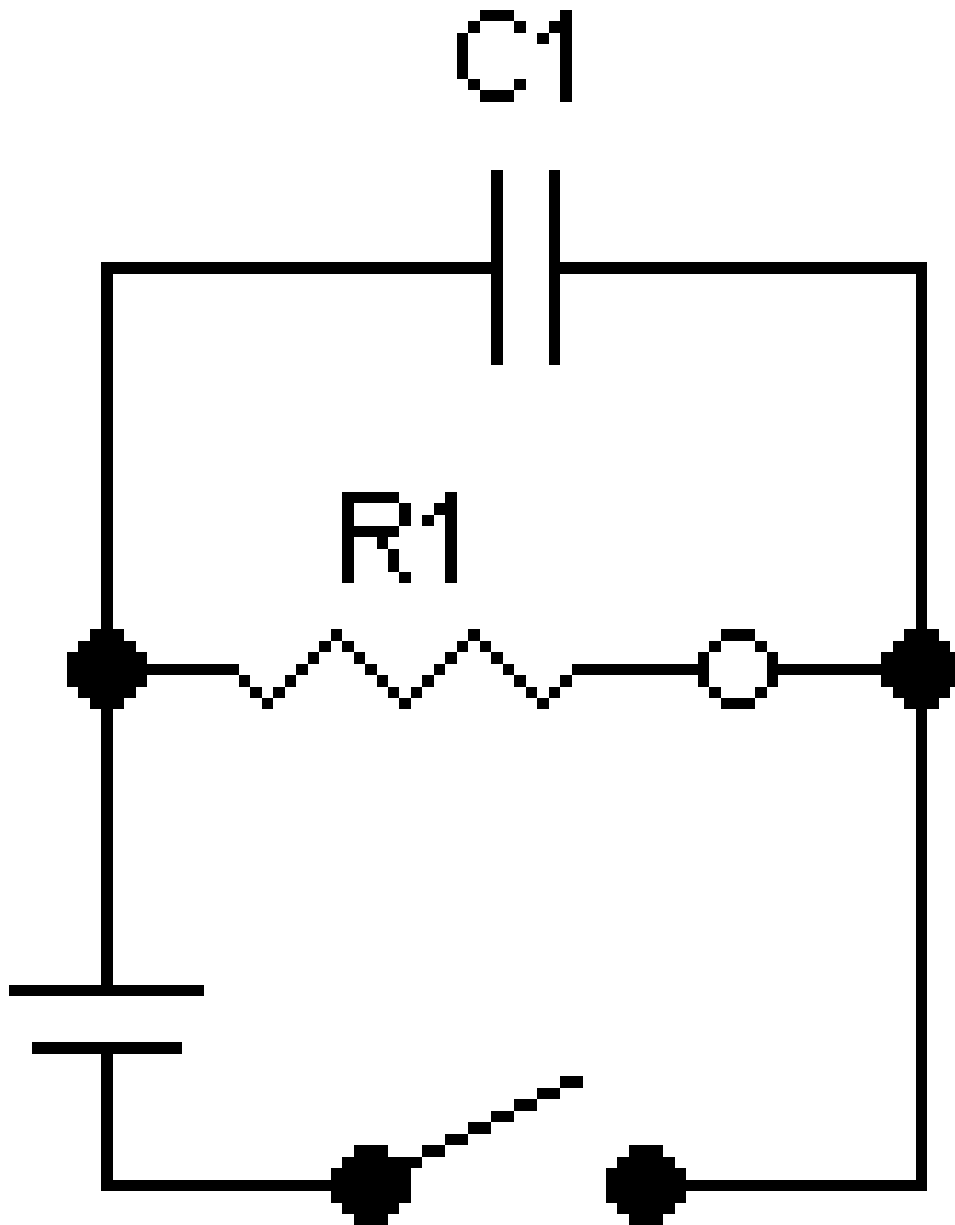
Figure 28

There is a capacitor in parallel with the resistor and current probe. The way the capacitor functions is by acting as a very low resistance **load** when the circuit is initially turned on. This is illustrated below:
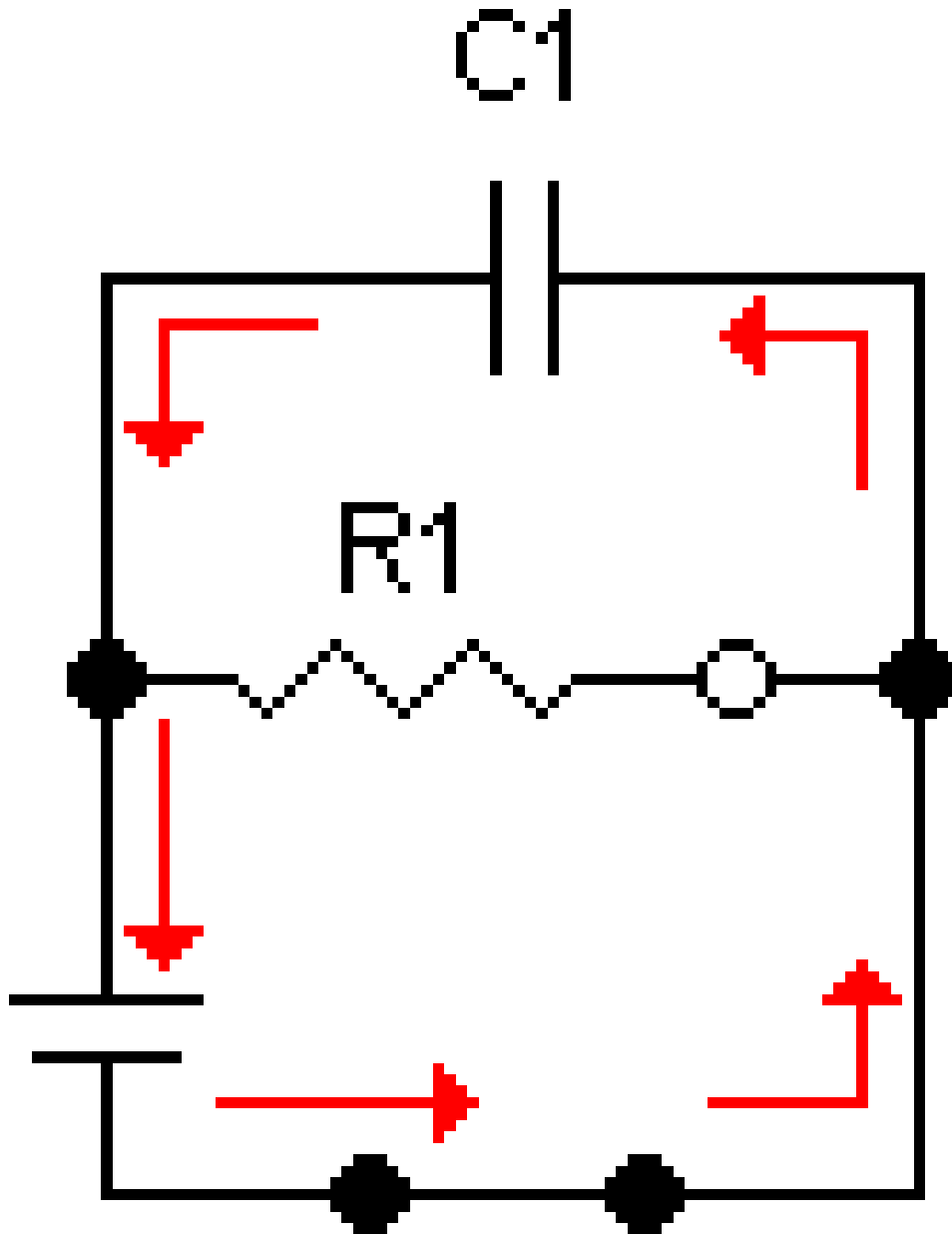
Figure 29

Initially, the capacitor has a very low resistance, almost 0. Since electricity takes the path of least resistance, almost all the electricity flows through the capacitor, not the resistor, as the resistor has considerably higher resistance.
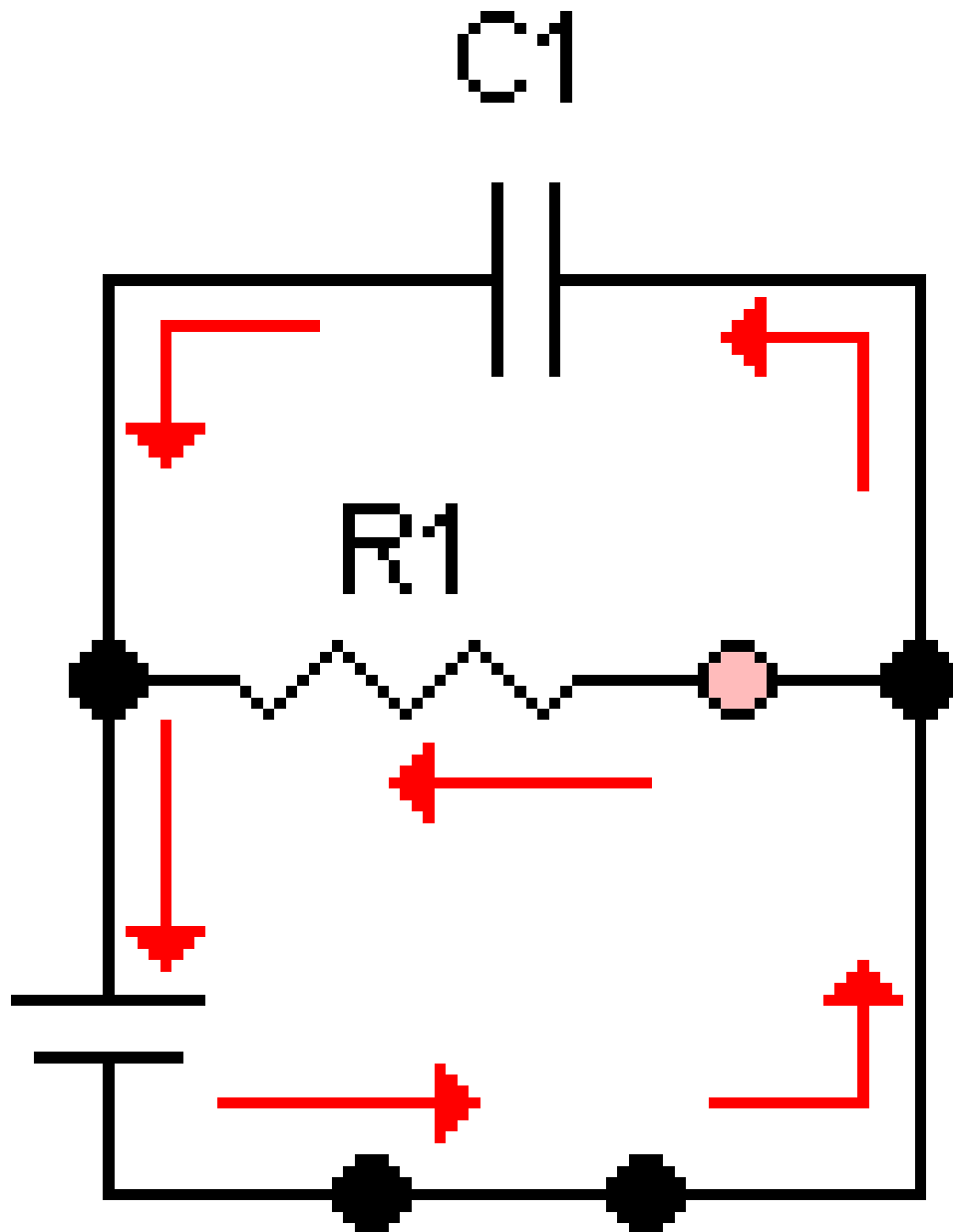
Figure 30

As a capacitor charges, its resistance increases as it gains more and more charge. As the resistance of the capacitor climbs, electricity begins to flow not only to the capacitor, but through the resistor as well:
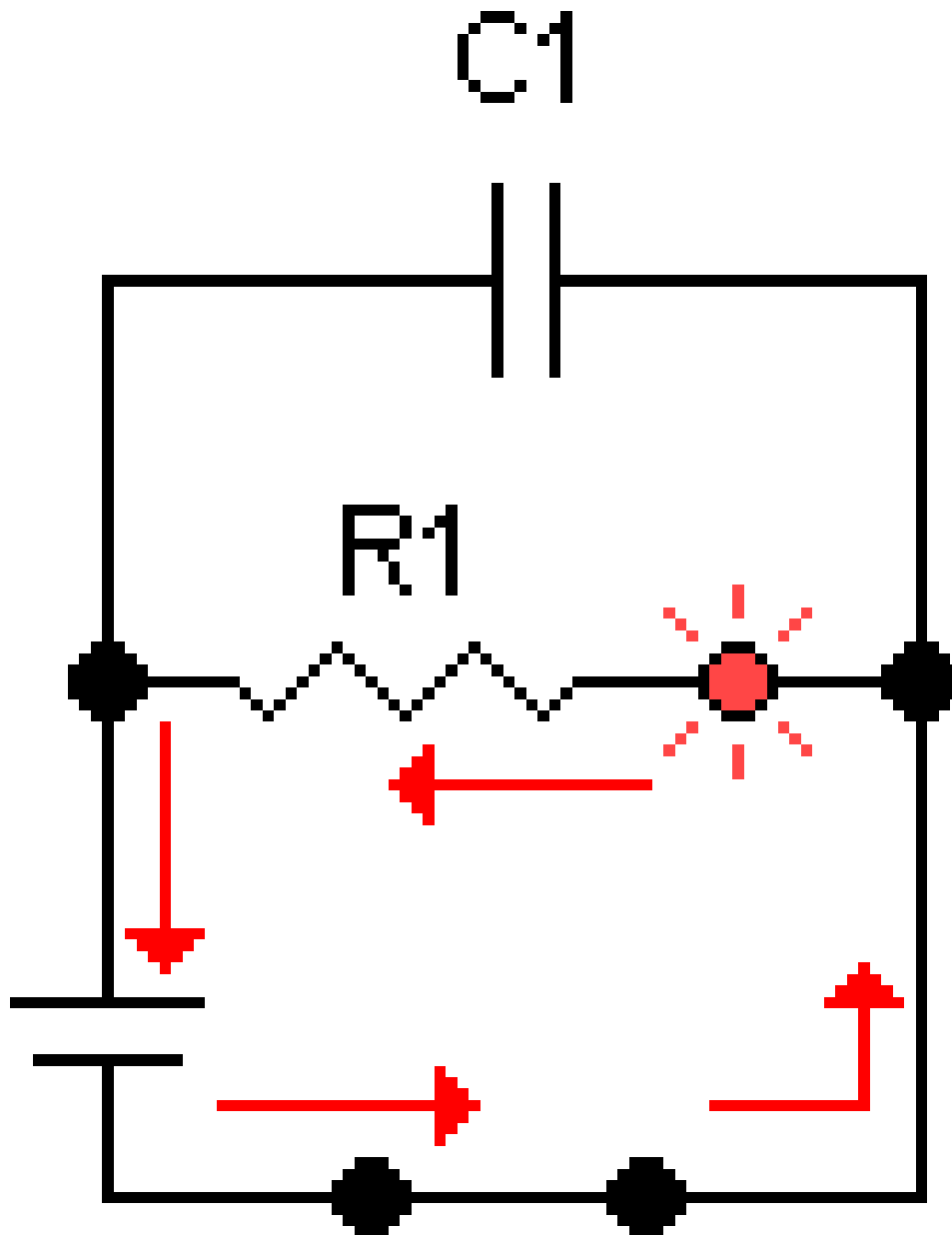
Figure 31

Once the capacitor's voltage equals that of the battery, meaning it is fully charged, it will not allow any current to pass through it. As a capacitor charges its resistance increases and becomes effectively infinite (open connection) and all the electricity flows through the resistor.
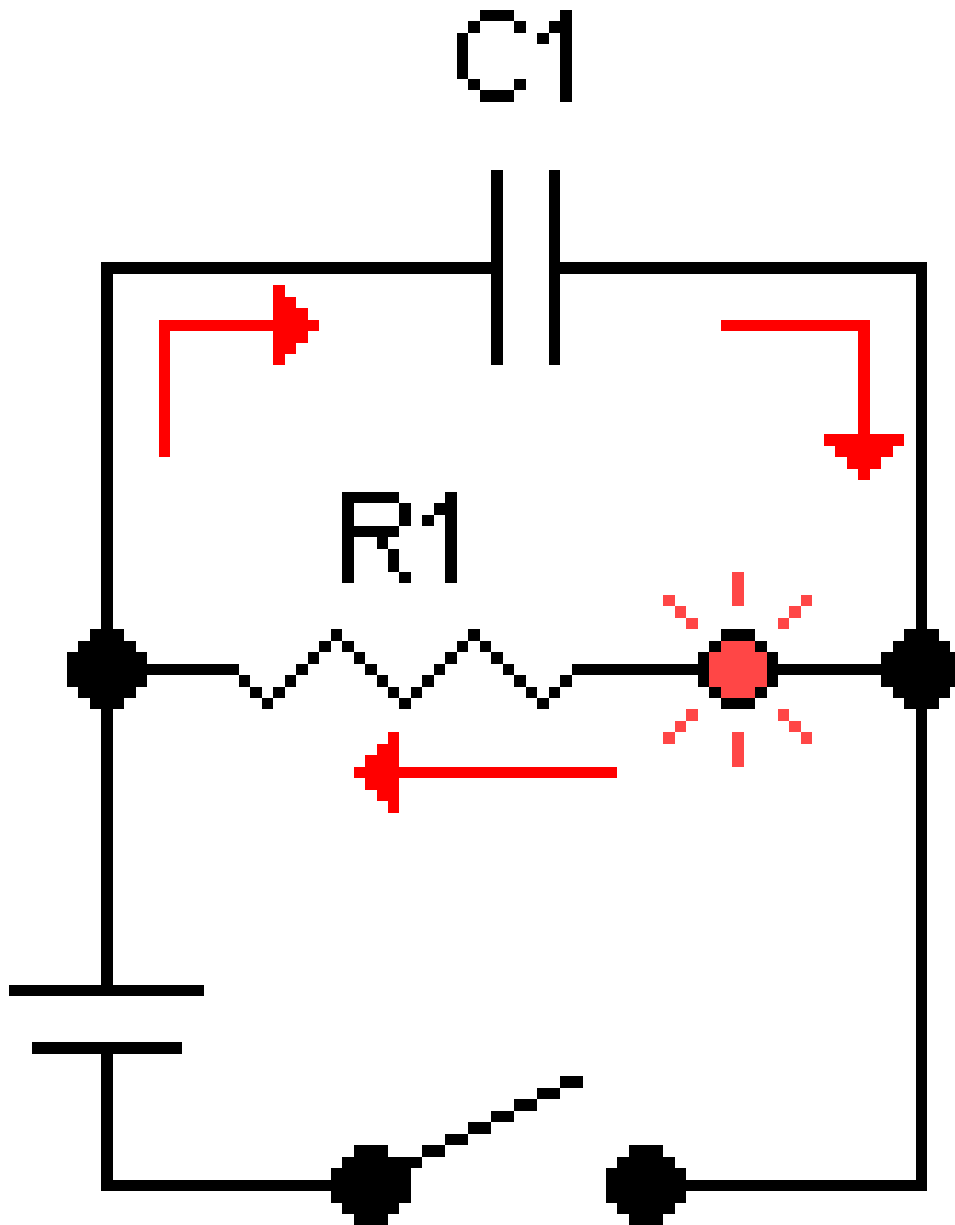
Figure 32

Once the voltage source is disconnected, however, the capacitor acts as a voltage source itself:
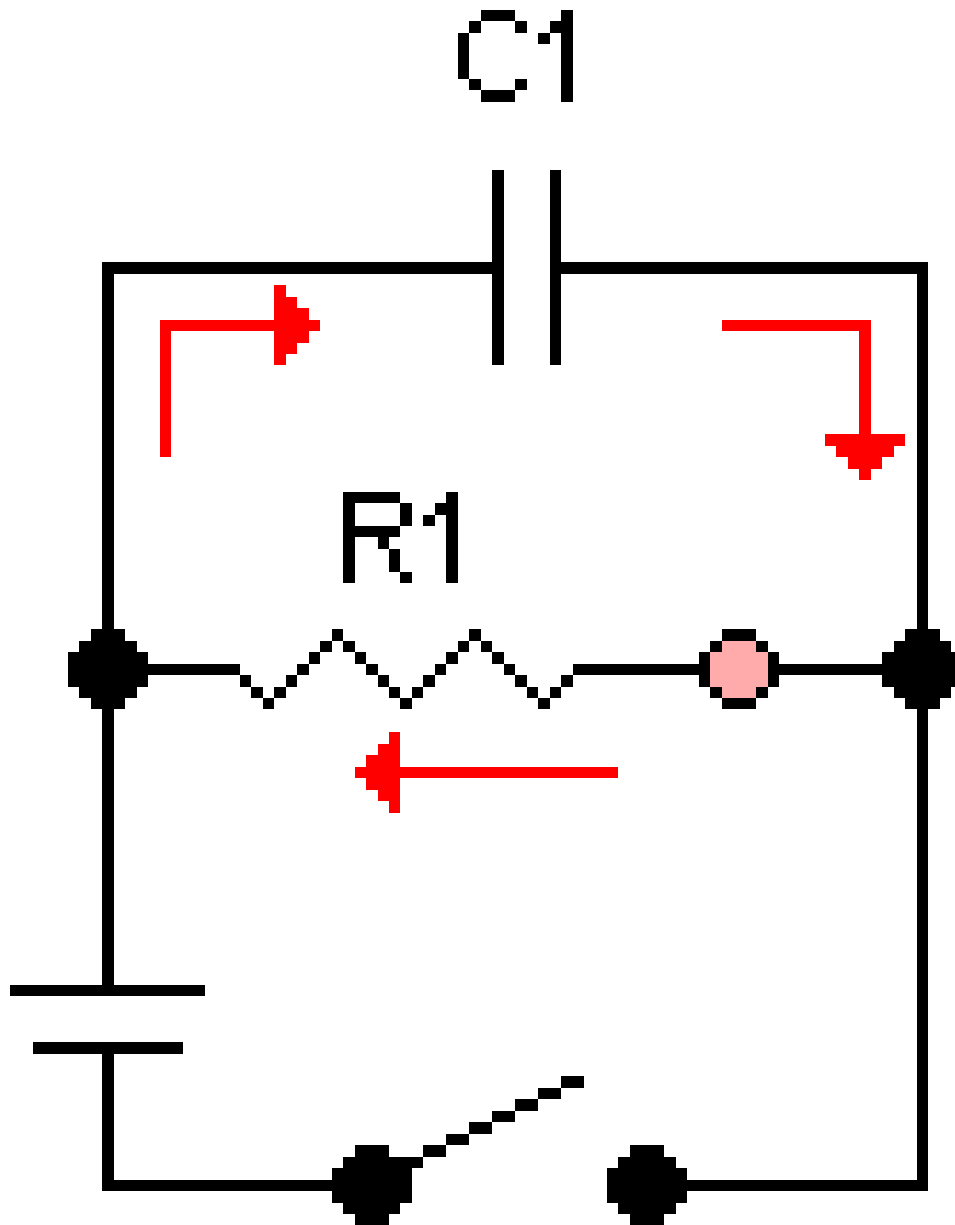
Figure 33

As time goes on, the capacitor's charge begins to drop, and so does its voltage. This means less current flowing through the resistor:
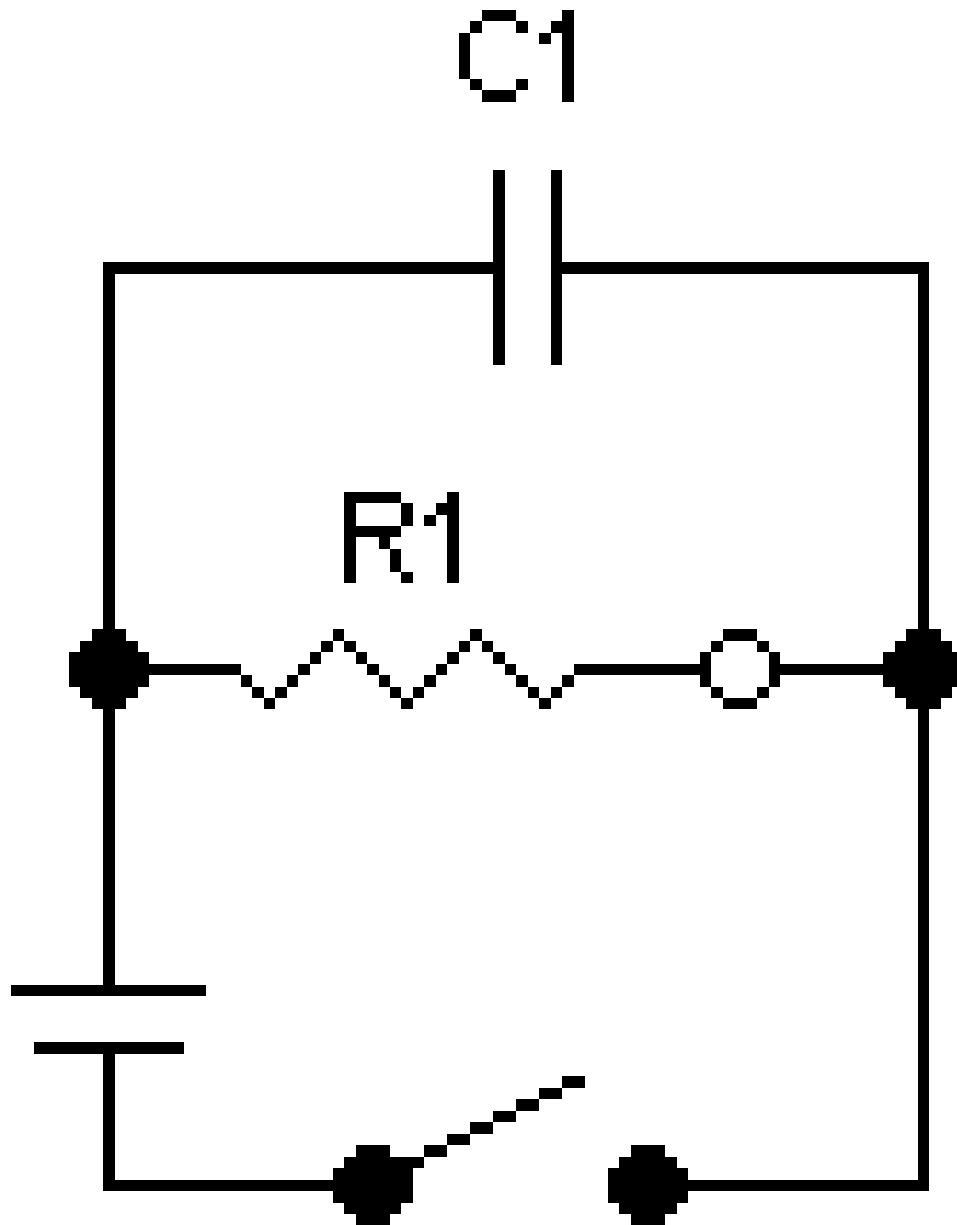
Figure 34

Once the capacitor is fully discharged, you are back to square one:

If one were to do this with a light and a capacitor connected to a battery, what you would see is the following:

1. Switch is closed. Light does not light up.
2. Light gradually becomes brighter and brighter...
3. Light is at full luminosity.
4. Switch is released. Light continues to shine.
5. Light begins to fade...

6. Light is off.

This is how a capacitor acts. However, what if you changed the values of R1? C1? The voltage of the battery? We will examine the mathematical relationship between the resistor, capacitor, and charging rate below.

7.7.3 Time Constant

In order to find out how long it takes for a capacitor to fully charge or discharge, or how long it takes for the capacitor to reach a certain voltage, you must know a few things. First, you must know the starting and finishing voltages. Secondly, you must know the **time constant** of the circuit you have. Time constant is denoted by the Greek letter 'tau' or τ . The formula to calculate this time constant is:

$$\tau = RC$$

Great, so what does this mean? The time constant is how long it takes for a capacitor to charge to 63% of its full charge. This time, in seconds, is found by multiplying the resistance in ohms and the capacitance in farads.

According to the formula above, there are two ways to lengthen the amount of time it takes to discharge. One would be to increase the resistance, and the other would be to increase the capacitance of the capacitor. This should make sense. It should be noted that the formula compounds, such that in the second time constant, it charges another 63%, based on the original 63%. This gives you about 86.5% charge in the second time constant. Below is a table.

Time Constant	Charge
1	63%
2	87%
3	95%
4	98%
5	99+%

For all practicality, by the 5th time constant it is considered that the capacitor is fully charged or discharged.

put some stuff in here about how discharging works the same way, and the function for voltage based on time

$v(t) = \frac{1}{C} \int i(t) dt$

Where $i(t)$ is the current flowing through the capacitor as a function of time.

This equation is often used in another form. By differentiating with respect to time:

$i(t) = C \frac{dv(t)}{dt}$

Substituting v/r for i(t) and integrating the above equation gives you an equation used to describe the charging and discharging characteristics of RC circuits. A charging character-

istic curve exponentially increases from 0% (0 volts) and approaches 100% full (maximum voltage), similarly, a discharge curve starts at the theoretical 100% (maximum voltage) and exponentially falls back to 0% (0 volts).

7.8 Capacitors - general remarks

7.8.1 Common capacitors and their names

Capacitors are divided into two mechanical groups: Fixed capacitors with fixed capacitance values and variable capacitors with variable (trimmer) or adjustable (tunable) capacitance values.

The most important group is the fixed capacitors. Many got their names from the dielectric. For a systematic classification these characteristics can't be used, because one of the oldest, the electrolytic capacitor, is named instead by its cathode construction. So the most-used names are simply historical.

The most common kinds of capacitors are:

- **Ceramic capacitors** have a ceramic dialectic.
- **Film** and **paper capacitors** are named for their dielectrics.
- **Aluminum, tantalum** and **niobium electrolytic capacitors** are named after the material used as the anode and the construction of the cathode
- **Supercapacitor** is the family name for:
  - **Double-layer capacitors** were named for the physical phenomenon of the Helmholtz double-layer
  - **Pseudocapacitors** were named for their ability to store electric energy electro-chemically with reversible faradaic charge-transfer
  - **Hybrid capacitors** combine double-layer and pseudocapacitors to increase power density
- Seldom-used **Silver mica, glass, silicon, air-gap and vacuum capacitors** were named for their dielectric.

Capacitors in each family have similar physical design features, but vary, for example, in the form of the terminals.
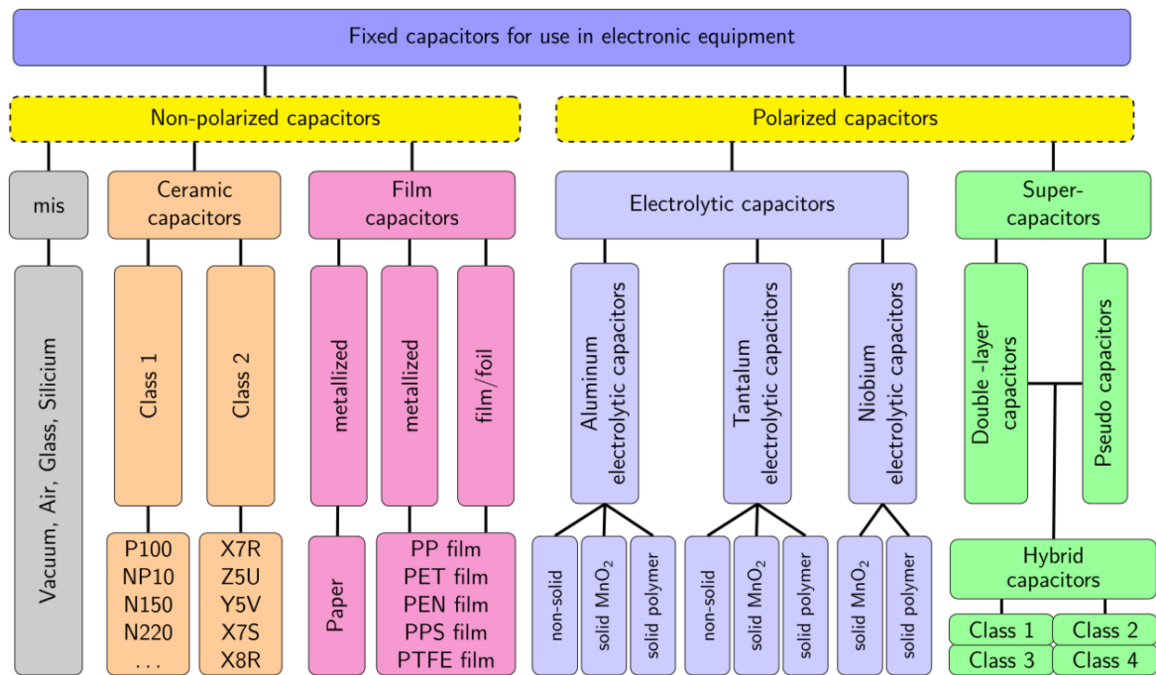
Figure 35 Overview over the most commonly used fixed capacitors in electronic equipment

In addition to the above shown capacitor types, which derived their name from historical development, there are many individual capacitors that have been named based on their application. They include:

- Power capacitors, motor capacitors, DC-link capacitors, suppression capacitors, audio crossover capacitors, lighting ballast capacitors, snubber capacitors, coupling, decoupling or bypassing capacitors.

Often, more than one capacitor family is employed for these applications, e.g. interference suppression can use ceramic capacitors or film capacitors.

Specialized devices such as built-in capacitors with metal conductive areas in different layers of a multi-layer printed circuit board and kludges such as twisting together two pieces of insulated wire also exist.

7.8.2 Dielectrics
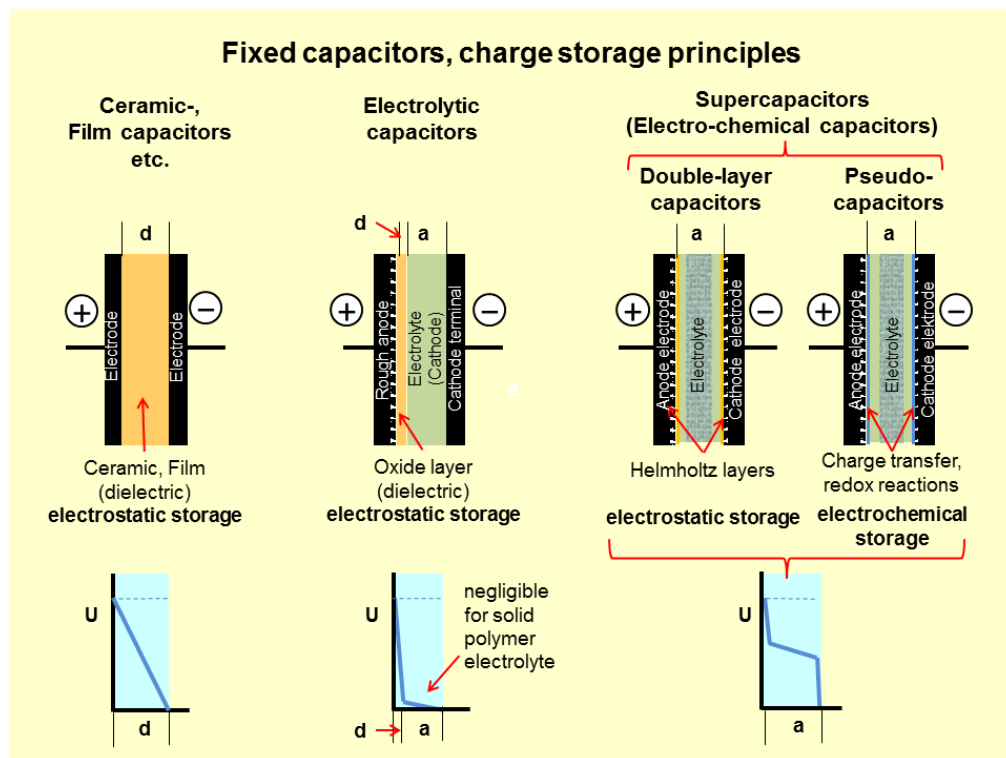
Figure 36 Principle charge storage of different capacitor types and their inherent voltage progression

The most common dielectrics are:

- Ceramics
- Plastic films
- Oxide[5] layer on metal (Aluminum[6], Tantalum[7], Niobium[8])
- Natural materials like mica[9], glass[10], paper[11], air[12], vacuum[13]

All of them store their electrical charge statically within an electric field[14] between two (parallel) electrodes.

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5   http://en.wikibooks.org/wiki/Oxide

6   http://en.wikibooks.org/wiki/Aluminum

7   http://en.wikibooks.org/wiki/Tantalum

8   http://en.wikibooks.org/wiki/Niobium

9   http://en.wikibooks.org/wiki/mica

10   http://en.wikibooks.org/wiki/glass

11   http://en.wikibooks.org/wiki/paper

12   http://en.wikibooks.org/wiki/air

13   http://en.wikibooks.org/wiki/vacuum

14   http://en.wikibooks.org/wiki/electric%20field

Beneath this conventional capacitors a family of electrochemical capacitors called Supercapacitor[15]s was developed. Supercapacitors don't have a conventional dielectric. They store their electrical charge statically in

- Helmholtz double-layers[16] (Double-layer capacitors)

and additional electrochemical with faradaic charge transfer

- with a pseudocapacitance[17] (Pseudocapacitors)
- or with both storage principles together (Hybrid capacitors).

The most important material parameters of the different dielectrics used and the appr. Helmholtz-layer thickness are given in the table below.

Key parameters[18][19][20][21][22]				
Capacitor style	Dielectric	Permittivity at 1 kHz	Maximum/realized. dielectric strength V/µm	Minimum thickness of the dielectric µm
Ceramic capacitor[23]s, Class 1	paraelectric[24]	12–40	< 100(?)	1
Ceramic capacitors, Class 2	ferroelectric[25]	200–14,000	< 25(?)	0.5
Film capacitor[26]s	Polypropylene[27] (PP)	2.2	650/450	1.9 – 3.0
Film capacitors	Polyethylen terephthalate, Polyester[28] (PET)	3.3	580/280	0.7–0.9
Film capacitors	Polyphenylene sulfide[29] (PPS)	3.0	470/220	1.2
Film capacitors	Polyethylene naphthalate[30] (PEN)	3.0	500/300	0.9–1.4
Film capacitors	Polytetrafluoroethylene[31] (PTFE)	2.0	450(?)/250	5.5
Paper capacitors	Paper	3.5–5.5	60	5–10
Aluminium electrolytic capacitors[32]	Aluminium oxide[33] Al_2O_3	9,6[34]	710	< 0.01 (6.3 V) < 0.8 (450 V)

15   http://en.wikibooks.org/wiki/Supercapacitor
16   http://en.wikibooks.org/wiki/Double%20layer%20%28interfacial%29
17   http://en.wikibooks.org/wiki/Pseudocapacitor
23   http://en.wikibooks.org/wiki/Ceramic%20capacitor
24   http://en.wikibooks.org/wiki/Paraelectricity
25   http://en.wikibooks.org/wiki/Ferroelectricity
26   http://en.wikibooks.org/wiki/Film%20capacitor
27   http://en.wikibooks.org/wiki/Polypropylene
28   http://en.wikibooks.org/wiki/Polyester
29   http://en.wikibooks.org/wiki/Poly%28p-phenylene%20sulfide%29
30   http://en.wikibooks.org/wiki/Polyethylene%20naphthalate
31   http://en.wikibooks.org/wiki/Polytetrafluoroethylene
32   http://en.wikibooks.org/wiki/Electrolytic%20capacitor
33   http://en.wikibooks.org/wiki/Aluminium%20oxide
34   . . ,

Key parameters[18][19][20][21][22]				
Capacitor style	Dielectric	Permittivity at 1 kHz	Maximum/realized. dielectric strength V/µm	Minimum thickness of the dielectric µm
Tantalum electrolytic capacitor[35]s	Tantalum pentoxide[36] Ta_2O_5	26^{37}	625	< 0.01 (6.3 V) < 0.08 (40 V)
Niobium electrolytic capacitors	Niobium pentoxide[38], Nb_2O_5	42	455	< 0.01 (6.3 V) < 0.10 (40 V)
Supercapacitors[39] Double-layer capacitors	Helmholtz double-layer[40]	-	-	< 0.001 (2.7 V)
Vacuum capacitors	Vacuum[41]	1	40	-
Air gap capacitors	Air[42]	1	3.3	-
Glass capacitors	Glass[43]	5–10	450	-
Mica capacitors	Mica[44]	5–8	118	4–50

The capacitor's plate area can be adapted to the wanted capacitance value. The permittivity and the dielectric thickness are the determining parameter for capacitors. Ease of processing is also crucial. Thin, mechanically flexible sheets can be wrapped or stacked easily, yielding large designs with high capacitance values. Razor-thin metallized sintered ceramic layers covered with metallized electrodes however, offer the best conditions for the miniaturization of circuits with SMD styles.

A short view to the figures in the table above gives the explanation for some simple facts:

- **Supercapacitor[45]s** have the highest capacitance density because of its special charge storage principles
- **Electrolytic capacitor[46]s** have lesser capacitance density than supercapacitors but the highest capacitance density of conventional capacitors because its thin dielectric.
- **Ceramic capacitor[47]s** class 2 have much higher capacitance values in a given case than class 1 capacitors because of their much higher permittivity.
- **Film capacitor[48]s** with their different plastic film material do have a small spread in the dimensions for a given capacitance/voltage value of a film capacitor because the minimum dielectric film thickness differs between the different film materials.

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35 http://en.wikibooks.org/wiki/Tantalum%20capacitor
36 http://en.wikibooks.org/wiki/Tantalum%20pentoxide
37 . . ,
38 http://en.wikibooks.org/wiki/Niobium%20pentoxide
39 http://en.wikibooks.org/wiki/Supercapacitors
40 http://en.wikibooks.org/wiki/Double%20layer%20%28interfacial%29
41 http://en.wikibooks.org/wiki/Vacuum
42 http://en.wikibooks.org/wiki/Air
43 http://en.wikibooks.org/wiki/Glass
44 http://en.wikibooks.org/wiki/Mica
45   http://en.wikibooks.org/wiki/Supercapacitor
46   http://en.wikibooks.org/wiki/Electrolytic%20capacitor
47   http://en.wikibooks.org/wiki/Ceramic%20capacitor
48   http://en.wikibooks.org/wiki/Film%20capacitor

7.8.3 Capacitance and voltage range
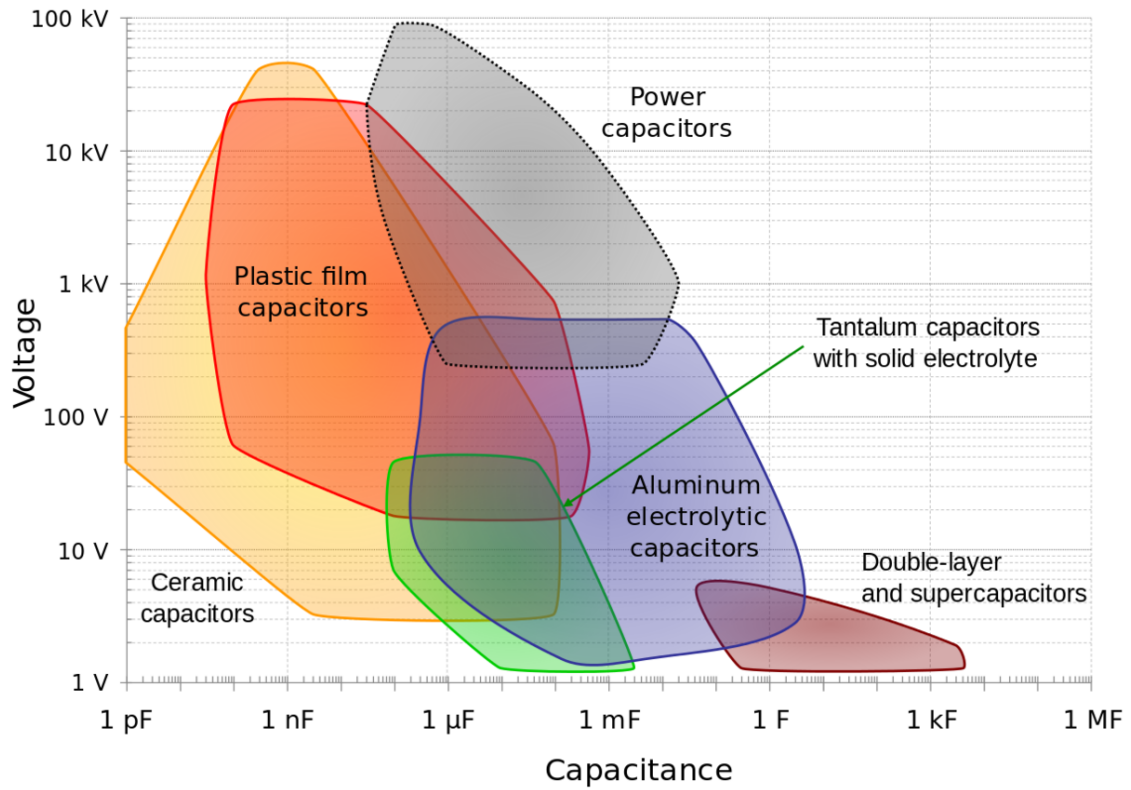
Figure 37 Capacitance ranges vs. voltage ranges of different capacitor types

Capacitance ranges from picofarad to more than hundreds of farad. Voltage ratings can reach 100 kilovolts. In general, capacitance and voltage correlates with physical size and cost.

7.8.4 Miniaturization
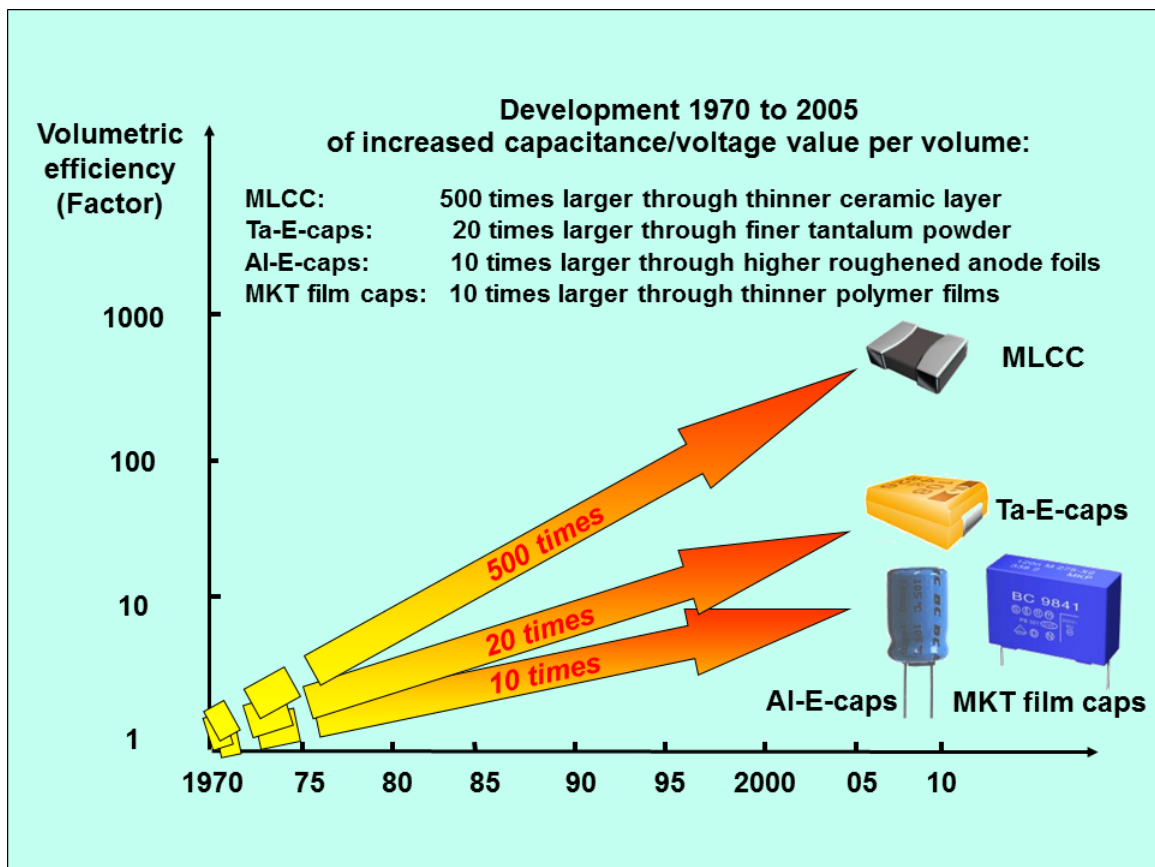
Figure 38   Capacitor volumetric efficiency increased from 1970 to 2005 (click image to enlarge)

As in other areas of electronics, volumetric efficiency[49] measures the performance of electronic function per unit volume. For capacitors, the volumetric efficiency is measured with the "CV product", calculated by multiplying the capacitance (C) by the maximum voltage rating (V), divided by the volume. From 1970 to 2005, volumetric efficiencies have improved dramatically.

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49   http://en.wikibooks.org/wiki/volumetric%20efficiency

Figure 39 Stacked paper capacitor (Block capacitor) from 1923 for noise decoupling (blocking) in telegraph lines

Figure 40 Wound metallized paper capacitor from the early 1930s in hardpaper case, capacitance value specified in "cm" in the cgs system[a]; 5,000 cm corresponds to 28 nF

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[a] http://en.wikibooks.org/wiki/Centimetre%20%E2%80%93%20gram%20%E2%80%93%20second%20system%20of%20units
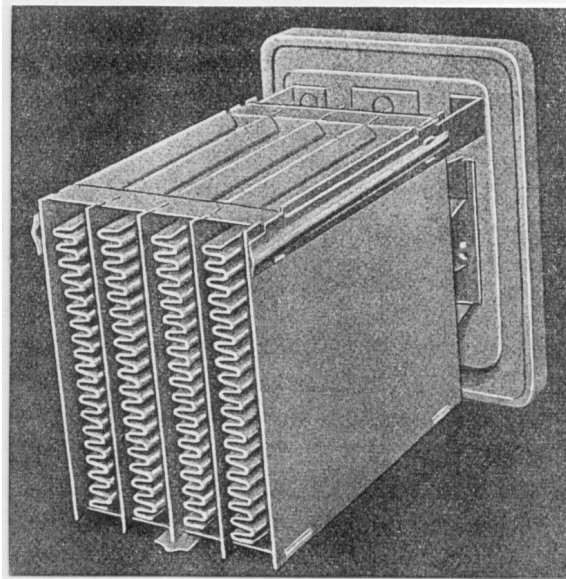
Figure 41   Folded wet aluminum electrolytic capacitor, Bell System 1929, view onto the folded anode, which was mounted in a squared housing (not shown) filled with liquid electrolyte

Figure 42   Two 8 μF, 525 V wound wet aluminum electrolytic capacitors in paper housing sealed with tar out of a 1930s radio.

7.8.5 Overlapping range of applications

These individual capacitors can perform their application independent of their affiliation to an above shown capacitor type, so that an overlapping range of applications between the different capacitor types exists.
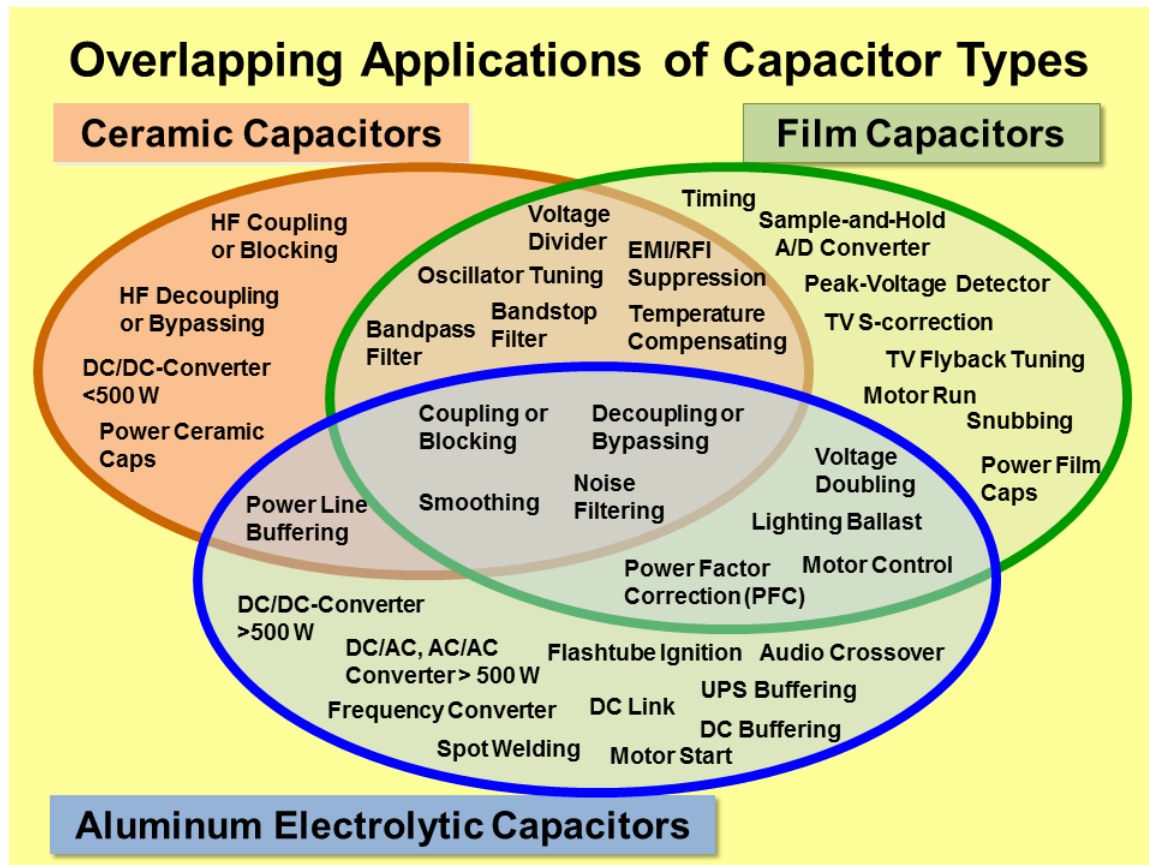
Figure 43 Comparing the three main capacitor types it shows, that a broad range of overlapping functions for many general-purpose and industrial applications exists in electronic equipment.

7.9 Capacitor - types and styles

7.9.1 Ceramic capacitors
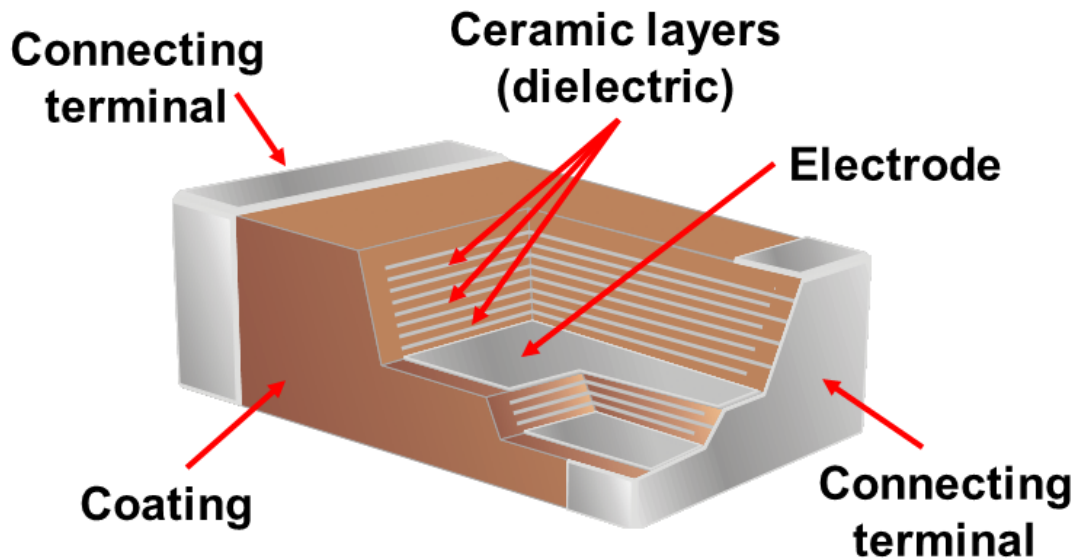
Figure 44   Construction of a **M** ulti-**L** ayer **C** eramic **C** apacitor (MLCC)

Main Page: Ceramic capacitor

A **ceramic capacitor**[50] is a non-polarized fixed capacitor made out of two or more alternating layers of ceramic and metal in which the ceramic material acts as the dielectric and the metal acts as the electrodes. The ceramic material is a mixture of finely ground granules of paraelectric[51] or ferroelectric[52] materials, modified by mixed oxides[53] that are necessary to achieve the capacitor's desired characteristics. The electrical behavior of the ceramic material is divided into two stability classes:

- Class 1[54] ceramic capacitors with high stability and low losses compensating the influence of temperature in resonant circuit application. Common EIA[55]/IEC[56] code abbreviations are C0G[57]/NP0, P2G/N150, R2G/N220, U2J/N750 etc.

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50   http://en.wikibooks.org/wiki/ceramic%20capacitor
51   http://en.wikibooks.org/wiki/paraelectric
52   http://en.wikibooks.org/wiki/ferroelectric
53   http://en.wikibooks.org/wiki/oxides
54   http://en.wikibooks.org/wiki/Ceramic%20capacitor%23Class%201
55   http://en.wikibooks.org/wiki/Electronic%20Industries%20Alliance
56   http://en.wikibooks.org/wiki/International%20Electrotechnical%20Commission
57   http://en.wikibooks.org/wiki/C0G

- Class 2[58] ceramic capacitors with high volumetric efficiency[59] for buffer, by-pass and coupling applications Common EIA/IEC code abbreviations are: X7R/2XI, Z5U/E26, Y5V/2F4, X7S/2C1, etc.

The great plasticity of ceramic raw material works well for many special applications and enables an enormous diversity of styles, shapes and great dimensional spread of ceramic capacitors. The smallest discrete capacitor, for instance, is a "01005" chip capacitor with the dimension of only 0.4 mm × 0.2 mm.

The construction of ceramic multilayer capacitors with mostly alternating layers results in single capacitors connected in parallel. This configuration increases capacitance and decreases all losses and parasitic inductance[60]s. Ceramic capacitors are well-suited for high frequencies and high current pulse loads.

Because the thickness of the ceramic dielectric layer can be easily controlled and produced by the desired application voltage, ceramic capacitors are available with rated voltages up to the 30 kV range.

Some ceramic capacitors of special shapes and styles are used as capacitors for special applications, including RFI/EMI suppression capacitors[61] for connection to supply mains, also known as safety capacitors,[62][63] X2Y® capacitors for bypassing and decoupling applications,[64] feed-through capacitors for noise suppression by low-pass filters[65] and ceramic power capacitors[66] for transmitters and HF applications.[67][68]

Figure 45 Multi-layer ceramic capacitors (MLCC chips) for SMD mounting

58   http://en.wikibooks.org/wiki/Ceramic%20capacitor%23Class%202
59   http://en.wikibooks.org/wiki/volumetric%20efficiency
60   http://en.wikibooks.org/wiki/inductance
61   http://en.wikibooks.org/wiki/Ceramic%20capacitor%23RFI%2FEMI%20suppression%20ceramic%20capacitor
62   General technical information of (RFI/EMI)Noise suppression capacitors on AC mains http://www.capakor.com/product/pdf/(21)General_technical_information.pdf
63   Vishay, Capacitors - RFI Class X/Y ^{http://www.vishay.com/capacitors/rfi-class-xy/}
64   X2Y® Technology ^{http://www.x2y.com/}
65   Murata, Three-terminal Capacitor Structure, No.TE04EA-1.pdf 98.3.20 ^{http://www.murata.com/products/emc/knowhow/pdf/20to22.pdf}
66   http://en.wikibooks.org/wiki/Ceramic%20capacitor%23Ceramic%20power%20capacitors
67   Vishay, Ceramic RF-Power Capacitors ^{http://www.vishay.com/docs/22071/geninfo.pdf}
68   Capacitors - RF Power [69]. Vishay . Retrieved 2013-03-09
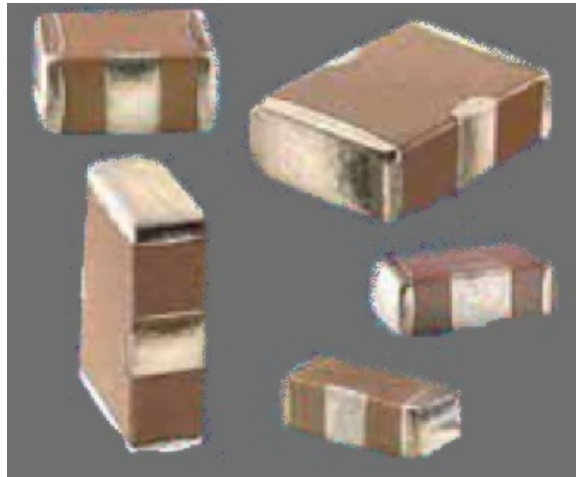
Figure 46 Ceramic X2Y® decoupling capacitors

Figure 47 Ceramic EMI suppression capacitors for connection to the supply mains (safety capacitor)

Figure 48 High voltage ceramic power capacitor

Features and applications as well as disadvantages of ceramic capacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Ceramic Class 1 capacitors	paraelectric[70] ceramic mixture of Titanium dioxide[71] modified by additives	Predictable linear[72] and low capacitance[73] change with operating temperature. Excellent high frequency[74] characteristics with low losses. For temperature compensation in resonant circuit[75] application. Available in voltages up to 15,000 V	Low permittivity[76] ceramic, capacitors with low volumetric efficiency[77], larger dimensions than Class 2 capacitors
Ceramic Class 2 capacitors	ferroelectric[78] ceramic mixture of barium titanate[79] and suitable additives	High permittivity, high volumetric efficiency, smaller dimensions than Class 1 capacitors. For buffer, by-pass and coupling applications. Available in voltages up to 50,000 V.	Lower stability and higher losses than Class 1. Capacitance changes with change in applied voltage, with frequency and with aging effects. Slightly microphonic[80]

70 http://en.wikibooks.org/wiki/Paraelectricity
71 http://en.wikibooks.org/wiki/Titanium%20dioxide
72 http://en.wikibooks.org/wiki/linear
73 http://en.wikibooks.org/wiki/capacitance
74 http://en.wikibooks.org/wiki/frequency
75 http://en.wikibooks.org/wiki/LC%20circuit
76 http://en.wikibooks.org/wiki/permittivity
77 http://en.wikibooks.org/wiki/volumetric%20efficiency
78 http://en.wikibooks.org/wiki/Ferroelectricity
79 http://en.wikibooks.org/wiki/barium%20titanate
80 http://en.wikibooks.org/wiki/Microphonics

7.9.2 Film capacitors

Main Page: Film capacitor

Plastic film,
Single-sided metallized
Standard pulse strength

Plastic film,
Double-sided metallized
High pulse strength

Film/foil construction
Very high pulse strength
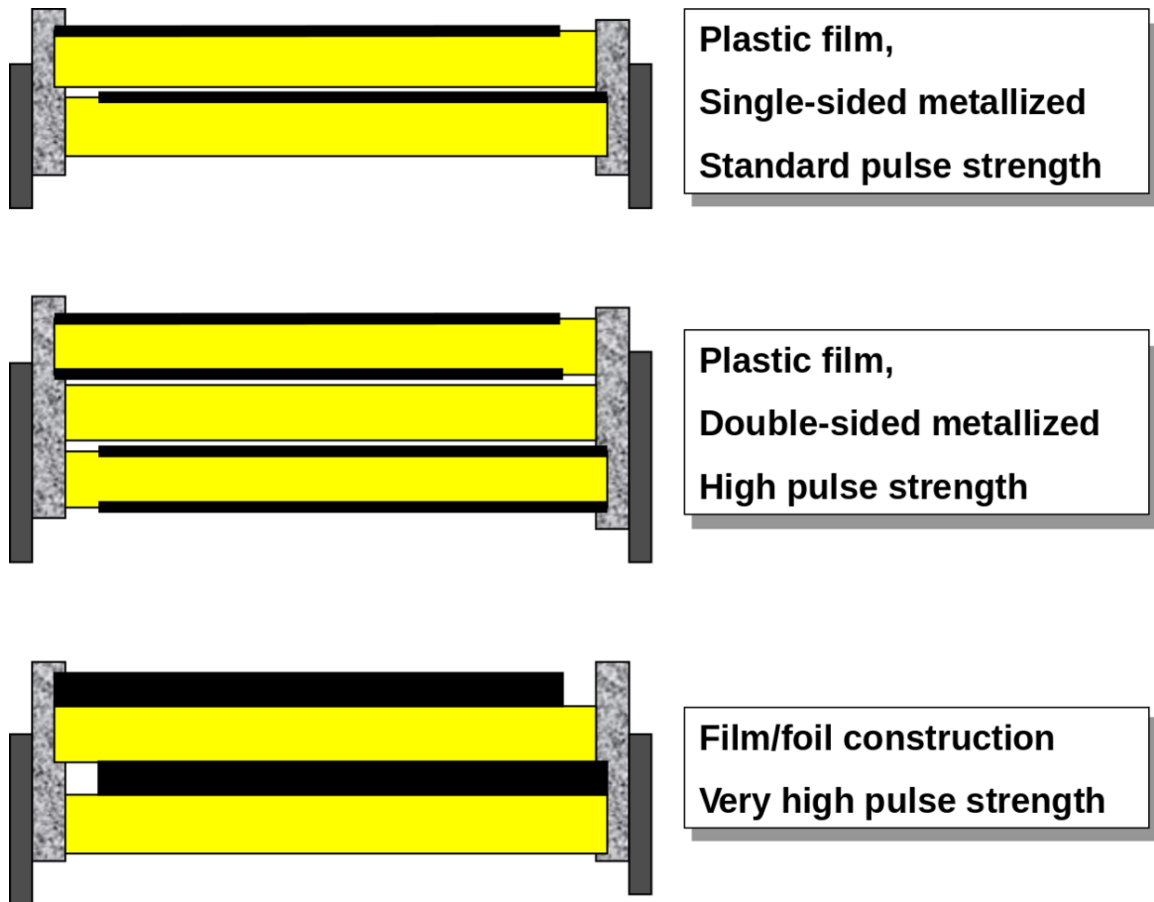
Figure 49   Three examples of different film capacitor configurations for increasing surge current ratings

Film capacitor[81]s or plastic film capacitors are non-polarized capacitors with an insulating plastic film as the dielectric. The dielectric films are drawn to a thin layer, provided with metallic electrodes and wound into a cylindrical winding. The electrodes of film capacitors may be metallized aluminum or zinc, applied on one or both sides of the plastic film, resulting in metallized film capacitors or a separate metallic foil overlying the film, called film/foil capacitors.

Metallized film capacitors offer self-healing properties. Dielectric breakdowns or shorts between the electrodes do not destroy the component. The metallized construction makes it possible to produce wound capacitors with larger capacitance values (up to 100 µF and larger) in smaller cases than within film/foil construction.

Film/foil capacitors or metal foil capacitors use two plastic films as the dielectric. Each film is covered with a thin metal foil, mostly aluminium, to form the electrodes. The advantage

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81   http://en.wikibooks.org/wiki/Film%20capacitor

of this construction is the ease of connecting the metal foil electrodes, along with an excellent current pulse strength.

A key advantage of every film capacitor's internal construction is direct contact to the electrodes on both ends of the winding. This contact keeps all current paths very short. The design behaves like a large number of individual capacitors connected in parallel, thus reducing the internal ohm[82]ic losses (ESR[83]) and parasitic inductance (ESL). The inherent geometry of film capacitor structure results in low ohmic losses and a low parasitic inductance, which makes them suitable for applications with high surge currents (snubber[84]s) and for AC power applications, or for applications at higher frequencies.

The plastic films used as the dielectric for film capacitors are Polypropylene[85] (PP), Polyester[86] (PET), Polyphenylene sulfide[87] (PPS), Polyethylene naphthalate[88] (PEN), and Polytetrafluoroethylene[89] or Teflon[90] (PTFE). Polypropylene film material with a market share of something about 50% and Polyester film with something about 40% are the most used film materials. The rest of something about 10% will be used by all other materials including PPS and paper with roughly 3%, each.[91][92]

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82   `http://en.wikibooks.org/wiki/ohm`
83   `http://en.wikibooks.org/wiki/Equivalent%20series%20resistance`
84   `http://en.wikibooks.org/wiki/snubber`
85   `http://en.wikibooks.org/wiki/Polypropylene`
86   `http://en.wikibooks.org/wiki/Polyester`
87   `http://en.wikibooks.org/wiki/Polyphenylene%20sulfide`
88   `http://en.wikibooks.org/wiki/Polyethylene%20naphthalate`
89   `http://en.wikibooks.org/wiki/Polytetrafluoroethylene`
90   `http://en.wikibooks.org/wiki/Teflon`
91   Passive component magazine, Nov./Dec. 2005, F. Jacobs, Polypropylene Capacitor Film Resin, p. 29 ff `http://old.passivecomponentmagazine.com/files/archives/2005/PCI_05_06Nov-Dec.pdf`
92   Paumanok Publications, PCInewsletterOct2007cmp Paumanok Publications, Inc. ^{`http://www.paumanokgroup.com/}`

Characteristics of plastic film materials for film capacitors

Film characteristics		Film material, abbreviated codes			
		PET	PEN	PPS	PP
Relative permittivity at 1 kHz		3.3	3.0	3.0	2.2
Minimum film thickness (µm)		0.7–0.9	0.9–1.4	1.2	2.4–3.0
Moisture absorption (%)		low	0.4	0.05	<0.1
Dielectric strength (V/µm)		580	500	470	650
Commercial realized voltage proof (V/µm)		280	300	220	400
DC voltage range (V)		50–1,000	16–250	16–100	40–2,000
Capacitance range		100 pF–22 µF	100 pF–1 µF	100 pF–0.47 µF	100 pF–10 µF
Application temperature range (°C)		−55 to +125 /+150	−55 to +150	−55 to +150	−55 to +105
ΔC/C versus temperature range (%)		±5	±5	±1.5	±2.5
Dissipation factor ($\bullet 10^{-4}$)	at 1 kHz	50–200	42–80	2–15	0.5–5
	at 10 kHz	110–150	54–150	2.5–25	2–8
	at 100 kHz	170–300	120–300	12–60	2–25
	at 1 MHz	200–350	–	18–70	4–40
Time constant $R_{Insul} \bullet C$	at 25 °C	≥10,000	≥10,000	≥10,000	≥100,000
(s)	at 85 °C	1,000	1,000	1,000	10,000
Dielectric absorption (%)		0.2–0.5	1–1.2	0.05–0.1	0.01–0.1
Specific capacitance (nF$\bullet$V/mm^3)		400	250	140	50

Some film capacitors of special shapes and styles are used as capacitors for special applications, including RFI/EMI suppression capacitors[93] for connection to the supply mains, also known as safety capacitors,[94] Snubber capacitors for very high surge currents,[95] Motor run capacitors, AC capacitors for motor-run applications[96]
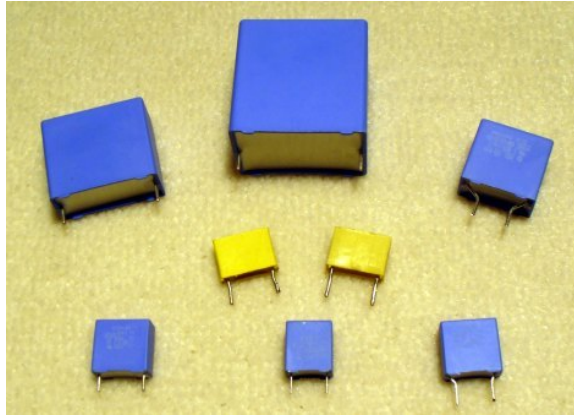
Figure 50 Radial style (single ended) for through-hole solder mounting on printed circuit boards
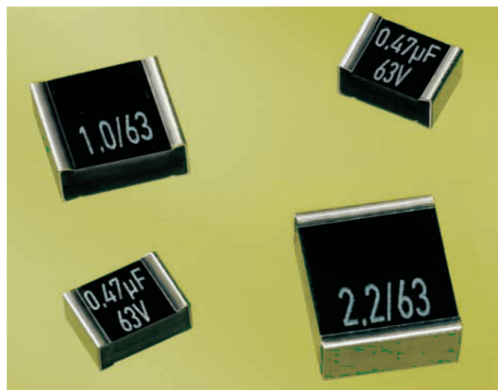
Figure 51 SMD style for printed circuit board surface mounting, with metallized contacts on two opposite edges

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93 http://en.wikibooks.org/wiki/Film%20capacitor%23Safety%20and%20EMI%2FRFI%20suppression%20film%20capacitors

94 WIMA, RFI Capacitors ^{http://www.wima.com/EN/products_rfi.htm}

95 WIMA Snubber Capacitors ^{http://www.wima.com/EN/products_snubber.htm}

96 Amrad Engeneering Inc., Motor run capacitors ^{http://www.motor-runcapacitorsonline.com/}
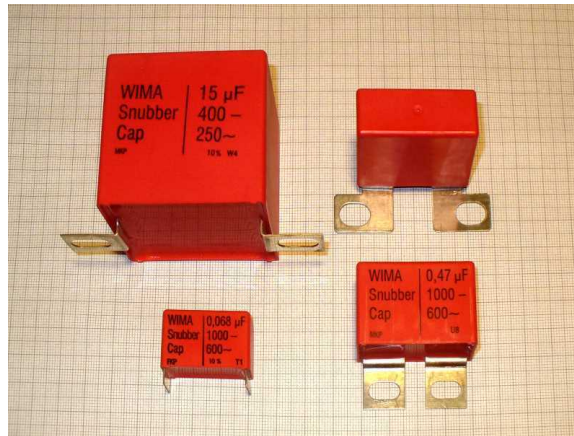
Figure 52   Radial style with heavy-duty solder terminals for snubber applications and high surge pulse loads

Figure 53   Heavy-duty snubber capacitor with screw terminals

Features and applications as well as disadvantages of film capacitors			
Capacitor type	Dielectric	Features/applications	Disadvantages
Metallized film capacitors	PP, PET, PEN, PPS, (PTFE)	Metallized film capacitors are significantly smaller in size than film/foil versions and have self-healing properties.	Thin metallized electrodes limit the maximum current[97] carrying capability respectively the maximum possible pulse voltage.
Film/foil film capacitors	PP, PET, PTFE	Film/foil film capacitors have the highest surge ratings/pulse voltage, respectively. Peak currents are higher than for metallized types.	No self-healing properties: internal short may be disabling. Larger dimensions than metallized alternative.
Polypropylene (PP) film capacitors	Polypropylene[98] (Treofan®)	Most popular film capacitor dielectric. Predictable linear and low capacitance change with operating temperature. Suitable for applications in Class-1 frequency-determining circuits and precision analog applications. Very narrow capacitances. Extremely low dissipation factor. Low moisture absorption, therefore suitable for "naked" designs with no coating. High insulation resistance. Usable in high power applications such as snubber or IGBT. Used also in AC[99] power applications, such as in motors or power factor correction[100]. Very low dielectric losses. High frequency and high power applications such as induction heating[101]. Widely used for safety/EMI suppression, including connection to power supply mains.	Maximum operating temperature of 105 °C. Relatively low permittivity of 2.2. PP film capacitors tend to be larger than other film capacitors. More susceptible to damage from transient over-voltages or voltage reversals than oil-impregnated MKV-capacitors for pulsed power[102] applications.

97   http://en.wikibooks.org/wiki/Electric%20current
98   http://en.wikibooks.org/wiki/Polypropylene
99   http://en.wikibooks.org/wiki/AC%20power
100 http://en.wikibooks.org/wiki/power%20factor%20correction
101 http://en.wikibooks.org/wiki/induction%20heating
102 http://en.wikibooks.org/wiki/pulsed%20power

Features and applications as well as disadvantages of film capacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Polyester (PET) film (Mylar) capacitors	Polyethylene terephthalate, Polyester[103] (Hostaphan®, Mylar®)	Smaller in size than functionally comparable polypropylene film capacitors. Low moisture absorption. Have almost completely replaced metallized paper and polystyrene film for most DC applications. Mainly used for general purpose applications or semi-critical circuits with operating temperatures up to 125 °C. Operating voltages up to 60.000 V DC.	Usable at low (AC power) frequencies. Limited use in power electronics due to higher losses with increasing temperature and frequency.
Polyethylene naphthalate (PEN) film capacitors	Polyethylene naphthalate[104] (Kaladex®)	Better stability at high temperatures than PET. More suitable for high temperature applications and for SMD packaging. Mainly used for non-critical filtering, coupling and decoupling, because temperature dependencies are not significant.	Lower relative permittivity and lower dielectric strength imply larger dimensions for a given capacitance and rated voltage than PET.
Polyphenylene Sulfide (PPS) film capacitors	Polyphenylene (Torelina®)	Small temperature dependence over the entire temperature range and a narrow frequency dependence in a wide frequency range. Dissipation factor is quite small and stable. Operating emperatures up to 270 °C. Suitable for SMD. Tolerate increased reflow soldering temperatures for lead-free soldering mandated by the RoHS 2002/95/European Union directive[105]	Above 100 °C, the dissipation factor increases, increasing component temperature, but can operate without degradation. Cost is usually higher than PP.
Polytetrafluoroethylene (PTFE) (Teflon[106] film) capacitors	Polytetrafluoroethylene[107] (Teflon®)	Lowest loss solid dielectric. Operating temperatures up to 250 °C. Extremely high insulation resistance. Good stability. Used in mission-critical applications.	Large size (due to low dielectric constant). Higher cost than other film capacitors.
Polycarbonate (PC) film capacitors	Polycarbonate[108]	Almost completely replaced by PP	Limited manufacturers
Polystyrene (PS) film capacitors	Polystyrene[109] (Styroflex)	Almost completely replaced by PET	Limited manufacturers
Polysulphone film capacitors	Polysulfone[110]	Similar to polycarbonate. Withstand full voltage at comparatively higher temperatures.	Only development, no series found (2012)
Polyamide film capacitors	Polyamide[111]	Operating temperatures of up to 200 °C. High insulation resistance. Good stability. Low dissipation factor.	Only development, no series found (2012)
Polyimide film (Kapton) capacitors	Polyimide[112] (Kapton)	Highest dielectric strength of any known plastic film dielectric.	Only development, no series found (2012)

103 http://en.wikibooks.org/wiki/Polyester

104 http://en.wikibooks.org/wiki/Polyethylene%20naphthalate

105 http://en.wikibooks.org/wiki/Restriction%20of%20Hazardous%20Substances%20Directive

106 http://en.wikibooks.org/wiki/Teflon

107 http://en.wikibooks.org/wiki/Polytetrafluoroethylene

108 http://en.wikibooks.org/wiki/Polycarbonate

109 http://en.wikibooks.org/wiki/Polystyrene

110 http://en.wikibooks.org/wiki/Polysulfone

111 http://en.wikibooks.org/wiki/Polyamide

112 http://en.wikibooks.org/wiki/Polyimide

7.9.3 Film power capacitors

MKV capacitor
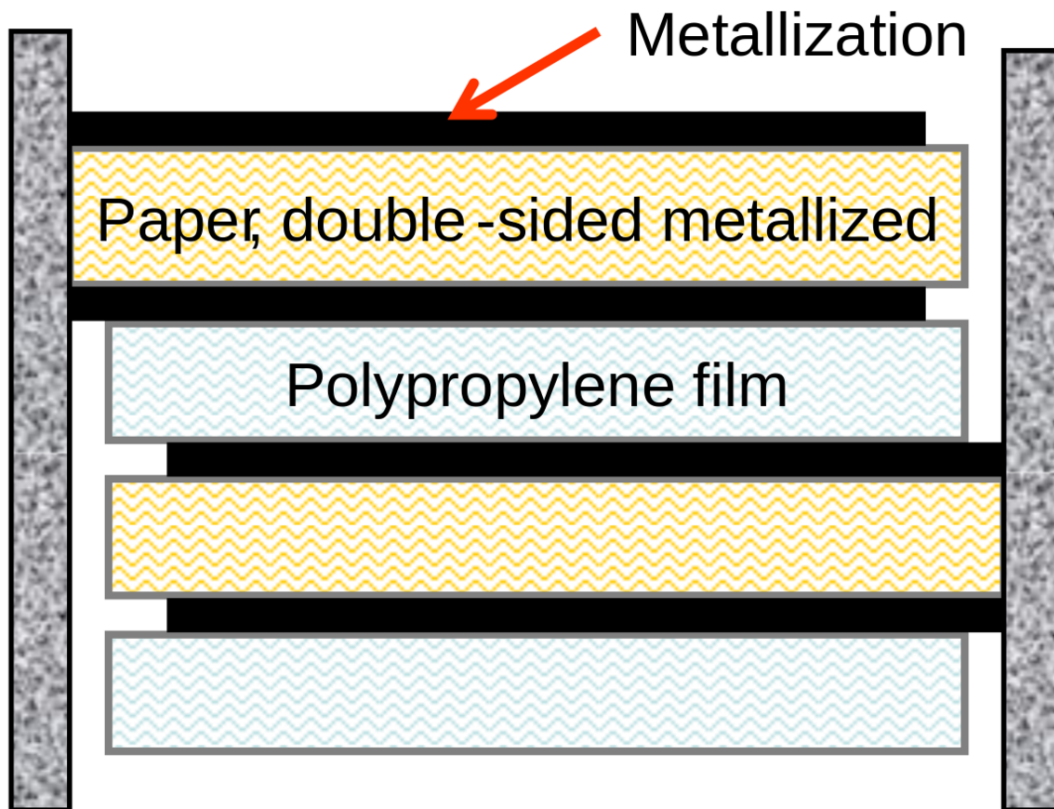
Figure 54 MKV power capacitor, double-sided metallized paper (field-free mechanical carrier of the electrodes), polypropylene film (dielectric), windings impregnated with insulating oil

A related type is the power film capacitor[113]. The materials and construction techniques used for large power film capacitors mostly are similar to those of ordinary film capacitors. However, capacitors with high to very high power ratings for applications in power systems and electrical installations are often classified separately, for historical reasons. The standardization of ordinary film capacitors is oriented on electrical and mechanical parameters. The standardization of power capacitors by contrast emphasizes the safety of personnel and equipment, as given by the local regulating authority.

As modern electronic equipment gained the capacity to handle power levels that were previously the exclusive domain of "electrical power" components, the distinction between the

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113 http://en.wikibooks.org/wiki/Film%20capacitor%23Power%20film%20capacitors

"electronic" and "electrical" power ratings blurred. Historically, the boundary between these two families was approximately at a reactive power of 200 volt-amps.

Film power capacitors mostly use polypropylene film as the dielectric. Other types include metallized paper capacitors (MP capacitors) and mixed dielectric film capacitors with polypropylene dielectrics. MP capacitors serve for cost applications and as field-free carrier electrodes (soggy foil capacitors) for high AC or high current pulse loads. Windings can be filled with an insulating oil or with epoxy resin[114] to reduce air bubbles, thereby preventing short circuits.

They find use as converters to change voltage, current or frequency, to store or deliver abruptly electric energy or to improve the power factor. The rated voltage range of these capacitors is from approximately120 V AC (capacitive lighting ballasts) to 100 kV.[115]

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114 `http://en.wikibooks.org/wiki/epoxy%20resin`

115 Epcos, Capacitors for power electronics, General technical information ˆ{`http://web.archive.org/web/20081114082811/http://www.epcos.com/web/generator/Web/Sections/ProductCatalog/Capacitors/PDF/PDF__GeneralTechnicalInformation,property=Data__en.pdf;/PDF_GeneralTechnicalInformation.pdf`}

Figure 55 Power film capacitor for AC
Power factor correction[a] (PFC), packaged in
a cylindrical metal can

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[a] http://en.wikibooks.org/wiki/Power%20factor%23Power%20factor%20correction%20in%20non-linear%20loads
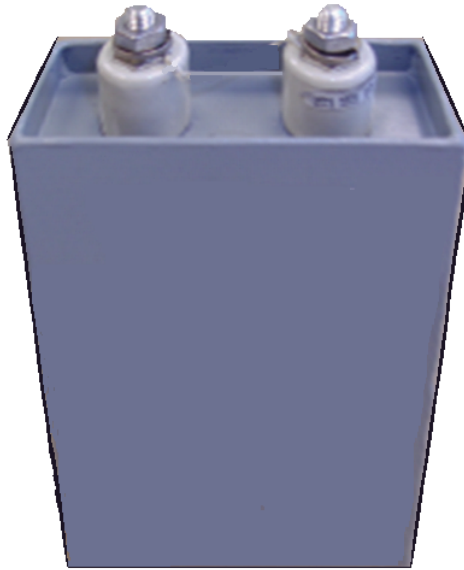
Figure 56 Power film capacitor in rectangular housing

Figure 57 One of several energy storage power film capacitor banks, for magnetic field generation at the Hadron-Electron Ring Accelerator (HERA[a]), located on the DESY[b] site in Hamburg[c]

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a   http://en.wikibooks.org/wiki/Hadron%20Elektron%20Ring%20Anlage
b   http://en.wikibooks.org/wiki/DESY
c   http://en.wikibooks.org/wiki/Hamburg

Figure 58 75MVAR substation capacitor bank at 150kV

Features and applications as well as disadvantages of film-based power capacitors			
Capacitor type	Dielectric	Features/applications	Disadvantages
Metallized paper power capacitors	Paper[116] impregnated with insulating oil or epoxy resin	Self-healing properties. Originally impregnated with wax, oil or epoxy. Oil-Kraft paper version used in certain high voltage[117] applications. Mostly replaced by PP.	Large size. Highly hygroscopic[118], absorbing moisture[119] from the atmosphere[120] despite plastic enclosures and impregnates. Moisture increases dielectric losses and decreases insulation[121] resistance.
Paper film/foil power capacitors	Kraft paper[122] impregnated with oil	Paper covered with metal foils as electrodes. Low cost. Intermittent duty, high discharge applications.	Physically large and heavy. Significantly lower energy density than PP dielectric. Not self-healing. Potential catastrophic failure due to high stored energy.

116 http://en.wikibooks.org/wiki/Paper
117 http://en.wikibooks.org/wiki/high%20voltage
118 http://en.wikibooks.org/wiki/Hygroscopy
119 http://en.wikibooks.org/wiki/moisture
120 http://en.wikibooks.org/wiki/atmosphere
121 http://en.wikibooks.org/wiki/Insulator%20%28electricity%29
122 http://en.wikibooks.org/wiki/Kraft%20paper

Features and applications as well as disadvantages of film-based power capacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
PP dielectric, field-free paper power capacitors (MKV power capacitors)	Double-sided (field-free) metallized paper as electrode carrier. PP as dielectric, impregnated with insulating oil, epoxy resin or insulating gas	Self-healing. Very low losses. High insulation resistance. High inrush current strength. High thermal stability. Heavy duty applications such as commutating with high reactive power, high frequencies and a high peak current load and other AC applications.	Physically larger than PP power capacitors.
Single- or double-sided metallized PP power capacitors	PP as dielectric, impregnated with insulating oil, epoxy resin or insulating gas	Highest capacitance per volume power capacitor. Self-healing. Broad range of applications such as general-purpose, AC capacitors, motor capacitor[123]s, smoothing or filtering, DC links, snubbing or clamping, damping AC, series resonant DC circuits, DC discharge, AC commutation, AC power factor correction.	critical for reliable high voltage operation and very high inrush current loads, limited heat resistance (105 °C)
PP film/foil power capacitors	Impregnated PP or insulating gas, insulating oil, epoxy resin or insulating gas	Highest inrush current strength	Larger than the PP metallized versions. Not self-healing.

7.9.4 Electrolytic capacitors

Main Page: Electrolytic capacitor[124]

Electrolytic capacitor[125]s have a metallic anode covered with an oxidized layer used as dielectric. The second electrode is a non-solid (wet) or solid electrolyte. Electrolytic capacitors are polarized. Three families are available, categorized according to their dielectric.

- Aluminum electrolytic capacitors with aluminum oxide[126] as dielectric
- Tantalum electrolytic capacitors with tantalum pentoxide[127] as dielectric
- Niobium electrolytic capacitors with niobium pentoxide[128] as dielectric.

The anode is highly roughened to increase the surface area. This and the relatively high permittivity of the oxide layer gives these capacitors very high capacitance per unit volume compared with film- or ceramic capacitors.

The permittivity of tantalum pentoxide is approximately three times higher than aluminium dioxide, producing significantly smaller components. However, permittivity determines only the dimensions. Electrical parameters, especially conductivity[129], are established by the electrolyte's material and composition. Three general types of electrolytes are used:

- non solid (wet, liquid)—conductivity approximately 10 mS/cm and are the lowest cost
- solid manganese oxide—conductivity approximately 100 mS/cm offer high quality and stability

123 http://en.wikibooks.org/wiki/motor%20capacitor
124 http://en.wikibooks.org/wiki/Electrolytic%20capacitor
125 http://en.wikibooks.org/wiki/Electrolytic%20capacitor
126 http://en.wikibooks.org/wiki/aluminum%20oxide
127 http://en.wikibooks.org/wiki/tantalum%20pentoxide
128 http://en.wikibooks.org/wiki/niobium%20pentoxide
129 http://en.wikibooks.org/wiki/Conductivity%20%28electrolytic%29

- solid conductive polymer (Polypyrrole[130])—conductivity approximately 10,000 mS/cm,[131] offer ESR values as low as <10 mΩ

Internal losses of electrolytic capacitors, prevailing used for decoupling and buffering applications, are determined by the kind of electrolyte.

130 http://en.wikibooks.org/wiki/Polypyrrole
131 Sanyo, Capacitor lecture POSCAP (Ta) (Basic), Polymerized electrolyte ^{http://web.archive.org/web/20090521013917/http://www.edc.sanyo.com/pdf/e_poscap/E_poscap_basic.pdf}

Some important values of the different electrolytic capacitors

Anode material	Electrolyte	Capacitance range (µF)	Max. rated voltage at 85 °C (V)	Upper categorie temperature (°C)	Specific ripple current (mA/mm^3) [1]
Aluminum (roughned foil)	non solid, e.g. Ethylene glycol[132], DMF[133], DMA[134], GBL[135]	0.1–2,700,000	600	150	0.05–2.0
	solid, Manganese dioxide[136] (MnO_2)	0.1–1,500	40	175	0.5–2.5
	solid conductive polymere (e.g. Polypyrrole[137])	10–1,500	25	125	10–30
Tantalum (roughned foil)	non solid Sulfuric acid[138]	0.1–1,000	630	125	–
Tantalum (sintered)	non solid sulfuric acid	0.1–15,000	150	200	–
	solid Manganese dioxide (MnO_2)	0.1–3,300	125	150	1.5–15
	solid conductive polymere (e.g. Polypyrrole)	10–1,500	35	125	10–30

132 http://en.wikibooks.org/wiki/Ethylene%20glycol
133 http://en.wikibooks.org/wiki/Dimethylformamide
134 http://en.wikibooks.org/wiki/Dimethylacetamide
135 http://en.wikibooks.org/wiki/gamma-Butyrolactone
136 http://en.wikibooks.org/wiki/Manganese%20dioxide
137 http://en.wikibooks.org/wiki/Polypyrrole
138 http://en.wikibooks.org/wiki/Sulfuric%20acid

Some important values of the different electrolytic capacitors

Anode material	Electrolyte	Capacitance range (µF)	Max. rated voltage at 85 °C (V)	Upper categorie temperature (°C)	Specific ripple current (mA/mm^3) [1]
Niobium (sintered)	solid Manganese dioxide (MnO_2)	1–1,500	10	125	5–20
	solid conductive polymere (e.g. Polypyrrole)	2.2–1,000	25	105	10–30

[1] Ripple current at 100 kHz and 85 °C / volumen (nominal dimensions)

The large capacitance per unit volume of electrolytic capacitors make them valuable in relatively high-current and low-frequency electrical circuits[139], e.g. in power supply[140] filters for decoupling unwanted AC components from DC power connections or as coupling capacitors in audio amplifiers, for passing or bypassing low-frequency signals and storing large amounts of energy. The relatively high capacitance value of an electrolytic capacitor combined with the very low ESR of the polymer electrolyte of polymer capacitor[141]s, especially in SMD styles, makes them a competitor to MLC chip capacitors in personal computer power supplies.

Bipolar electrolytics (also called Non-Polarized capacitors) contain two anodized aluminium foils, behaving like two capacitors connected in series opposition.

Electolytic capacitors for special applications include motor start capacitors,[142] flashlight capacitors[143] and audio frequency capacitors.[144]
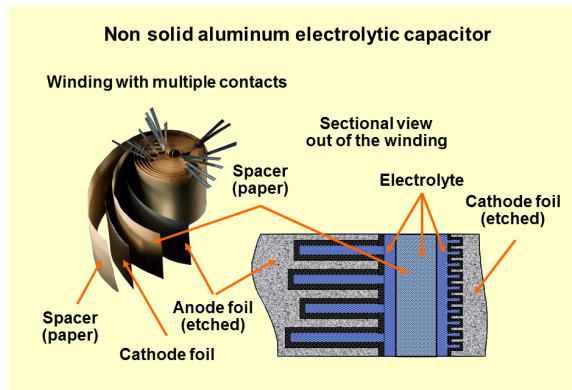
Figure 59 Schematic representation of the structure of a wound aluminum electrolytic capacitor with non solid (liquid) electrolyte

139 http://en.wikibooks.org/wiki/electrical%20network
140 http://en.wikibooks.org/wiki/power%20supply
141 http://en.wikibooks.org/wiki/polymer%20capacitor
142 CDE, Motor Start Capacitors ^{http://www.cde.com/catalogs/PSU.pdf}
143 Rubycon, Aluminum Electrolytic Capacitors for Strobe Flash ^{http://www.rubycon.co.jp/en/catalog/e_pdfs/aluminum/e_CDF.pdf}
144 Fischer & Tausche, Electrolytic capacitor for audio frequency ^{http://www.ftcap.de/index.php/audio-frequency-archiv.html}
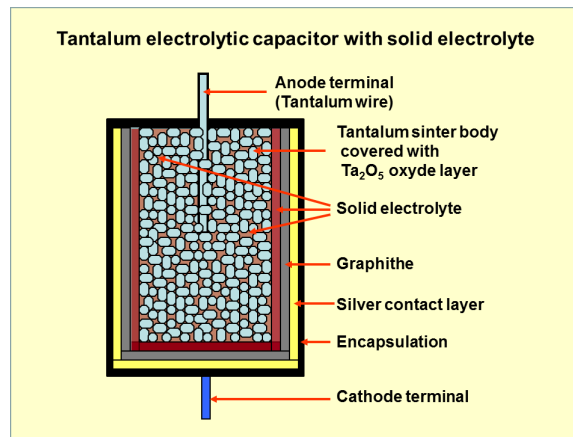
Figure 60 Schematic representation of the structure of a sintered tantalum electrolytic capacitor with solid electrolyte
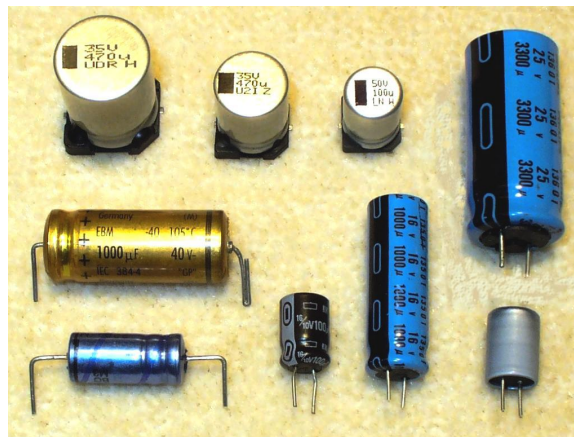
Figure 61 Axial, radial (single ended) anv V-chip styles of aluminum electrolytic capacitors

Figure 62 Snap-in style of aluminum electrolytic capacitors for power applications
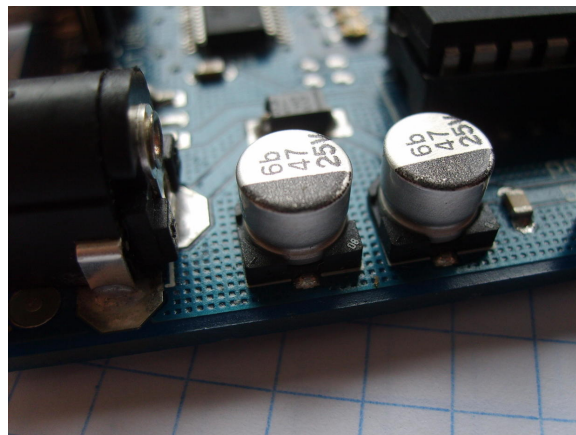
Figure 63 SMD style for surface mounting of aluminum electrolytic capacitors with polymer electrolyte
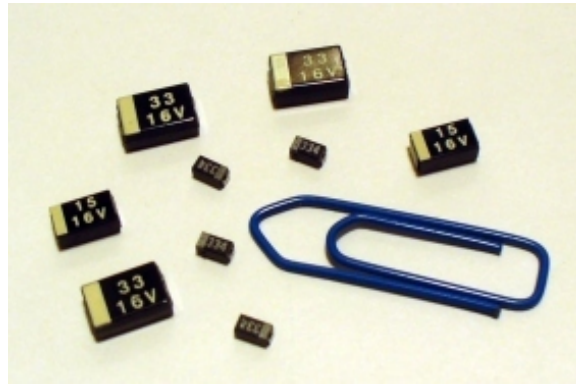
Figure 64 Tantalum electrolytic chip capacitors for surface mounting

Features and applications as well as disadvantages of electrolytic capacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Electrolytic capacitors with non solid (wet, liquid) electrolyte	Aluminum dioxide Al_2O_3	Very large capacitance to volume ratio. Capacitance values up to 2,700,000 μF/6.3 V. Voltage up to 550 V. Lowest cost per capacitance/voltage values. Used where low losses and high capacitance stability are not of major importance, especially for lower frequencies, such as by-pass, coupling, smoothing and buffer applications in power supplies and DC-links.	Polarized. Significant leakage. Relatively high ESR[145] and ESL[146] values, limiting high ripple current and high frequency applications. Lifetime calculation required because drying out phenomenon. Vent or burst when overloaded, overheated or connected wrong polarized. Water based electrolyte may vent at end-of-life, showing failures like "capacitor plague[147]"
	Tantalum pentoxide Ta_2O_5	Wet tantalum electrolytic capacitors (wet slug)[148] Lowest leakage among electrolytics. Voltage up to 630 V (tantalum film) or 125 V (tantalum sinter body). Hermetically sealed. Stable and reliable. Military and space applications.	Polarized. Violent explosion when voltage, ripple current or slew rates are exceeded, or under reverse voltage. Expensive.

145 http://en.wikibooks.org/wiki/ESR

146 http://en.wikibooks.org/wiki/ESL

147 http://en.wikibooks.org/wiki/capacitor%20plague

148 Vishay, Wet Electrolyte Tantalum Capacitors, Introduction ^{http://www.vishay.com/docs/40021/wtintro.pdf}

Features and applications as well as disadvantages of electrolytic capacitors			
Capacitor type	Dielectric	Features/applications	Disadvantages
[Electrolytic capacitors with solid [Manganese dioxide]] electrolyte	Aluminum dioxide $Al2O3$ Tantalum pentoxide Ta_2O_5, Niobium pentoxide $Nb2O5$	Tantalum and niobium with smaller dimensions for a given capacitance/voltage vs aluminum. Stable electrical parameters. Good long-term high temperature performance. Lower ESR lower than non-solid (wet) electrolytics.	Polarized. About 125 V. Low voltage and limited, transient, reverse or surge voltage tolerance. Possible combustion upon failure. ESR much higher than conductive polymer electrolytics. Manganese expected to be replaced by polymer.
Electrolytic capacitors with solid Polymer[149] electrolyte (Polymer capacitor[150]s)	Aluminum dioxide $Al2O3$, Tantalum pentoxide Ta_2O_5, Niobium pentoxide $Nb2O5$	Greatly reduced ESR compared with manganese or non-solid (wet) elelectrolytics. Higher ripple current ratings. Extended operational life. Stable electrical parameters. Self-healing.[151] Used for smoothing and buffering in smaller power supplies especially in SMD.	Polarized. Highest leakage current among electrolytics. Higher prices than non-solid or manganese dioxide. Voltage limited to about 100 V. Explodes when voltage, current, or slew rates are exceeded or under reverse voltage.

7.9.5 Supercapacitors

Main Page: Supercapacitor[152]

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149 http://en.wikibooks.org/wiki/Polymer

150 http://en.wikibooks.org/wiki/Polymer%20capacitor

151 Self-healing Characteristics of Solid Electrolytic Capacitor with Polypyrrole Electrolyte, Yamamoto Hideo http://sciencelinks.jp/j-east/article/199920/000019992099A0753223.php

152 http://en.wikibooks.org/wiki/Supercapacitor
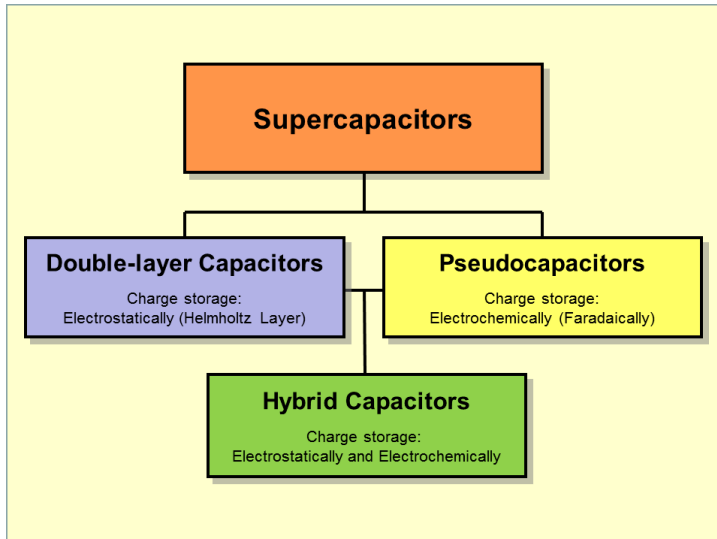
Figure 65 Hierarchical classification of supercapacitors and related types
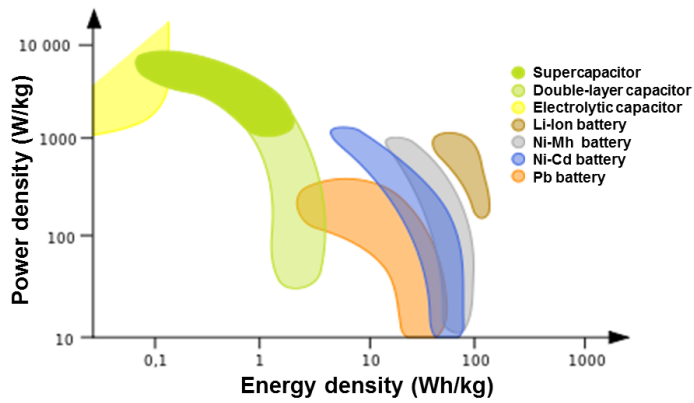
Figure 66 Ragone chart showing power density vs. energy density of various capacitors and batteries
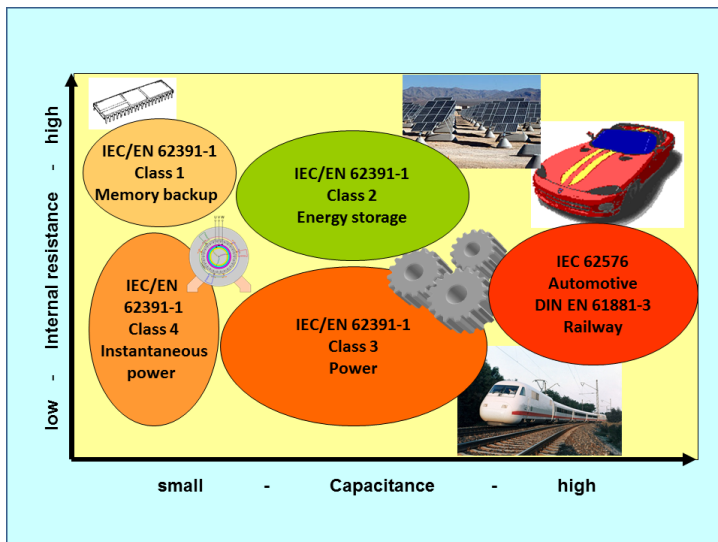
Figure 67 Classification of supercapacitors into classes regarding to IEC 62391-1, IEC 62567and DIN EN 61881-3 standards

Supercapacitors (SC) ,[153] comprise a family of electrochemical[154] capacitor[155]s. Supercapacitor, sometimes called **ultracapacitor** is a generic term for electric double-layer capacitor[156]s (EDLC), pseudocapacitor[157]s and hybrid capacitors. They don't have a conventional solid dielectric[158]. The capacitance value of an electrochemical capacitor is determined by two storage principles, both of which contribute to the total capacitance of the capacitor:[159][160][161]

153 B. E. Conway Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications. Springer, , 1999 see also Brian E. Conway in Electrochemistry Encyclopedia: *Electrochemical Capacitors — Their Nature, Function and Applications* ^{http://electrochem.cwru.edu/encycl/art-c03-elchem-cap.htm}

154 http://en.wikibooks.org/wiki/Electrochemistry

155 http://en.wikibooks.org/wiki/capacitor

156 http://en.wikibooks.org/wiki/electric%20double-layer%20capacitor

157 http://en.wikibooks.org/wiki/pseudocapacitor

158 http://en.wikibooks.org/wiki/dielectric

159 Marin S. Halper, James C. Ellenbogen . Supercapacitors: A Brief Overview Supercapacitors: A Brief Overview ^{www.mitre.org/work/tech_papers/tech_papers_06/06_0667/06_0667.pdf} . , (MITRE Nanosystems Group)

160 Elzbieta Frackowiak, Francois Beguin, PERGAMON, Carbon 39 (2001) 937–950, Carbon materials for the electrochemical storage of energy in Capacitors ^{http://www.sciencedirect.com/science/article/pii/S0008622300001834}

161 Yu.M. Volfkovich, A.A. Mikhailin, D.A. Bograchev, V.E. Sosenkin and V.S. Bagotsky, Studies of Supercapacitor Carbon Electrodes with High Pseudocapacitance ^{http://cdn.intechopen.com/pdfs/26963/InTech-Studies_of_supercapacitor_carbon_electrodes_with_high_pseudocapacitance.pdf} , A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow, Russia, Dr. Ujjal Kumar Sur (Ed.), ISBN 978-953-307-830-4

- Double-layer capacitance[162] – Storage is achieved by separation of charge in a Helmholtz[163] double layer[164] at the interface[165] between the surface of a conductor and an electrolytic solution. The distance of separation of charge in a double-layer is on the order of a few Angstrom[166]s (0.3–0.8 nm[167]). This storage is electrostatic[168] in origin.[169]
- Pseudocapacitance[171] – Storage is achieved by redox reactions[172], electrosorbtion or intercalation[173] on the surface of the electrode or by specifically adsorbed ion[174]s that results in a reversible faradaic[175] charge-transfer[176]. The pseudocapacitance is faradaic in origin.[177]

The ratio of the storage resulting from each principle can vary greatly, depending on electrode design and electrolyte composition. Pseudocapacitance can increase the capacitance value by as much as an order of magnitude over that of the double-layer by itself.[179]

Supercapacitors are divided into three families, based on the design of the electrodes:

- **Double-layer capacitors** – with carbon[180] electrodes or derivates with much higher static double-layer capacitance than the faradaic pseudocapacitance
- **Pseudocapacitors** – with electrodes out of metal oxides or conducting polymers with a high amount of faradaic pseudocapacitance
- **Hybrid capacitors** – capacitors with special and asymmetric electrodes that exhibit both significant double-layer capacitance and pseudocapacitance, such as lithium-ion capacitor[181]s

Supercapacitors bridge the gap between conventional capacitors and rechargeable batteries[182]. They have the highest available capacitance values per unit volume and the greatest energy density[183] of all capacitors. They support up to 12,000 Farad[184]s/1.2 Volt,[185] with

162 http://en.wikibooks.org/wiki/Double%20layer%20%28interfacial%29
163 http://en.wikibooks.org/wiki/Hermann%20von%20Helmholtz
164 http://en.wikibooks.org/wiki/Double%20layer%20%28interfacial%29
165 http://en.wikibooks.org/wiki/Interface%20%28chemistry%29
166 http://en.wikibooks.org/wiki/Angstrom
167 http://en.wikibooks.org/wiki/Nanometre
168 http://en.wikibooks.org/wiki/Electrostatics
169 A Survey of Electrochemical Supercapacitor Technology [170]. . Retrieved 2011-06-24
171 http://en.wikibooks.org/wiki/Pseudocapacitor
172 http://en.wikibooks.org/wiki/Redox
173 http://en.wikibooks.org/wiki/Intercalation%20%28chemistry%29
174 http://en.wikibooks.org/wiki/ion
175 http://en.wikibooks.org/wiki/Faradaic%20current
176 http://en.wikibooks.org/wiki/Charge-transfer%20complex
177 A Survey of Electrochemical Supercapacitor Technology [178]. . Retrieved 2011-06-24
179 B. E. Conway Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications. Springer, , 1999 see also Brian E. Conway in Electrochemistry Encyclopedia: *Electrochemical Capacitors — Their Nature, Function and Applications* ^{http://electrochem.cwru.edu/encycl/art-c03-elchem-cap.htm}
180 http://en.wikibooks.org/wiki/carbon
181 http://en.wikibooks.org/wiki/lithium-ion%20capacitor
182 http://en.wikibooks.org/wiki/Rechargeable%20battery
183 http://en.wikibooks.org/wiki/energy%20density
184 http://en.wikibooks.org/wiki/Farad
185 Elton ^{http://www.elton-cap.com/products/capacitor-cells/}

capacitance values up to 10,000 times that of electrolytic capacitor[186]s.[187] While existing supercapacitors have energy densities that are approximately 10% of a conventional battery, their power density[188] is generally 10 to 100 times greater. Power density is defined as the product of energy density, multiplied by the speed at which the energy is delivered to the load[189]. The greater power density results in much shorter charge/discharge cycles than a battery is capable, and a greater tolerance for numerous charge/discharge cycles. This makes them well-suited for parallel connection with batteries, and may improve battery performance in terms of power density.

Within electrochemical capacitors, the electrolyte is the conductive connection between the two electrodes, distinguishing them from electrolytic capacitors, in which the electrolyte only forms the cathode, the second electrode.

Supercapacitors are polarized and must operate with correct polarity. Polarity is controlled by design with asymmetric electrodes, or, for symmetric electrodes, by a potential applied during the manufacturing process.

Supercapacitors support a broad spectrum of applications for power and energy requirements, including:

- Low supply current during longer times for memory backup in (SRAM[190]s) in electronic equipment
- Power electronics that require very short, high current, as in the KERS[191]system in Formula 1[192] cars
- Recovery of braking energy for vehicles such as buses and trains

Supercapacitors are rarely interchangeable, especially those with higher energy densities. IEC standard 62391-1 *Fixed electric double layer capacitors for use in electronic equipment* identifies four application classes:

- Class 1, Memory backup, discharge current in mA = 1 • C (F)
- Class 2, Energy storage, discharge current in mA = 0.4 • C (F) • V (V)
- Class 3, Power, discharge current in mA = 4 • C (F) • V (V)
- Class 4, Instantaneous power, discharge current in mA = 40 • C (F) • V (V)

Exceptional for electronic components like capacitors are the manifold different trade or series names used for supercapacitors like: *APowerCap, BestCap, BoostCap, CAP-XX, DL-CAP, EneCapTen, EVerCAP, DynaCap, Faradcap, GreenCap, Goldcap, HY-CAP, Kapton capacitor, Super capacitor, SuperCap, PAS Capacitor, PowerStor, PseudoCap, Ultracapacitor* making it difficult for users to classify these capacitors.

186 http://en.wikibooks.org/wiki/electrolytic%20capacitor

187 B. E. Conway Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications. Springer, , 1999 see also Brian E. Conway in Electrochemistry Encyclopedia: *Electrochemical Capacitors — Their Nature, Function and Applications* ^{http://electrochem.cwru.edu/encycl/art-c03-elchem-cap.htm}

188 http://en.wikibooks.org/wiki/power%20density

189 http://en.wikibooks.org/wiki/Electric%20load

190 http://en.wikibooks.org/wiki/Static%20random-access%20memory

191 http://en.wikibooks.org/wiki/Kinetic%20energy%20recovery%20system

192 http://en.wikibooks.org/wiki/Formula%201

Figure 68 Double-layer capacitor with 1 F at 5.5 V for data buffering

Figure 69 Radial (single ended) style of lithium ion capacitors for high energy density

Figure 70 Supercapacitor/Ultracapacitor cells and modules for high current loads

Features and applications as well as disadvantages of supercapacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Supercapacitors Pseudocapacitors	Helmholtz double-layer plus faradaic pseudo-capacitance	Energy density typically tens to hundreds of times greater than conventional electrolytics. More comparable to batteries than to other capacitors. Large capacitance/volume ratio. Relatively low ESR. Thousands of farads. RAM memory backup. Temporary power during battery replacement. Rapidly absorbs/delivers much larger currents than batteries. Hundreds of thousands of charge/discharge cycles. Hybrid vehicles. Recuperation	Polarized. Low operating voltage per cell. (Stacked cells provide higher operating voltage.) Relatively high cost.
Hybrid capacitors Lithium ion capacitor[193]s (LIC)	Helmholtz double-layer plus faradaic pseudo-capacitance. Anode doped with lithium[194] ions.	Higher operating voltage. Higher energy density than common EDLCs, but smaller than lithium ion batteries[195] (LIB). No thermal runaway reactions.	Polarized. Low operating voltage per cell. (Stacked cells provide higher operating voltage.) Relatively high cost.

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193 http://en.wikibooks.org/wiki/Lithium%20ion%20capacitor

194 http://en.wikibooks.org/wiki/lithium

195 http://en.wikibooks.org/wiki/Lithium-ion%20battery

7.9.6 Miscellaneous capacitors

Beneath the above described capacitors covering more or less nearly the total market of discrete capacitors some new developments or very special capacitor types as well as older types can be found in electronics.

Integrated capacitors

- Integrated capacitors—in integrated circuits[196], nano-scale capacitors can be formed by appropriate patterns of metallization on an isolating substrate. They may be packaged in multiple capacitor arrays with no other semiconductive parts as discrete components.[197]
- Glass capacitors—First Leyden jar[198] capacitor was made of glass, as of 2012 glass capacitors were in use as SMD version for applications requiring ultra-reliable and ultra-stable service.

Power capacitors

- Vacuum capacitor[199]s—used in high power RF[200] transmitters
- SF$_6$[201] gas filled capacitors—used as capacitance standard in measuring bridge circuits

Special capacitors

- Printed circuit board[202]s—metal conductive areas in different layers of a multi-layer printed circuit board can act as a highly stable capacitor. It is common industry practice to fill unused areas of one PCB layer with the ground conductor and another layer with the power conductor, forming a large distributed capacitor between the layers.
- Wire—2 pieces of insulated wire twisted together. Capacitance alues usually range from 3 pF to 15 pF. Used in homemade VHF[203] circuits for oscillation feedback.

Obsolete capacitors

- Mica capacitor[204]s—the first capacitors with stable frequency behavior and low losses, used for military radio applications during World War II[205]
- Air[206]-gap capacitors—used by the first spark-gap transmitter[207]s

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196 http://en.wikibooks.org/wiki/integrated%20circuits
197 IPDiA, 3D Silicon Capacitors ^{http://www.ipdia.com/index.php?page=our_products&cat_id=2}
198 http://en.wikibooks.org/wiki/Leyden%20jar
199 http://en.wikibooks.org/wiki/Vacuum%20capacitor
200 http://en.wikibooks.org/wiki/radio%20frequency
201 http://en.wikibooks.org/wiki/Sulfur%20hexafluoride
202 http://en.wikibooks.org/wiki/Printed%20circuit%20board
203 http://en.wikibooks.org/wiki/VHF
204 http://en.wikibooks.org/wiki/Silver%20mica%20capacitor
205 http://en.wikibooks.org/wiki/World%20War%20II
206 http://en.wikibooks.org/wiki/Air
207 http://en.wikibooks.org/wiki/spark-gap%20transmitter

Figure 71 Some 1nF × 500VDC rated silver mica capacitors

Figure 72 Vacuum capacitor with uranium glass encapsulation

Features and applications as well as disadvantages of miscellaneous capacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Air gap capacitors	Air[208]	Low dielectric loss. Used for resonating HF circuits for high power HF welding.	Physically large. Relatively low capacitance.
Vacuum capacitors	Vacuum[209]	Extremely low losses. Used for high voltage, high power RF applications, such as transmitters and induction heating. Self-healing if arc-over[210] current is limited.	Very high cost. Fragile. Large. Relatively low capacitance.
SF6-gas filled capacitors	SF6[211] gas	High precision.[212] Extremely low losses. Very high stability. Up to 1600 kV rated voltage. Used as capacitance standard in measuring bridge circuits.	Very high cost

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208 http://en.wikibooks.org/wiki/Air

209 http://en.wikibooks.org/wiki/Vacuum

210 http://en.wikibooks.org/wiki/Electric%20arc

211 http://en.wikibooks.org/wiki/Sulfur%20hexafluoride

212 Tettex instruments, SF_6 Gas insulated Standard Capacitors ^{http://www.electrico.drilco.net/pdf/Capacidad%20-%20NKStdCaps_flyer.pdf}

Features and applications as well as disadvantages of miscellaneous capacitors			
Capacitor type	Dielectric	Features/applications	Disadvantages
Metallized mica (Silver mica) capacitors	Mica[213]	Very high stability. No aging. Low losses. Used for HF and low VHF RF circuits and as capacitance standard in measuring bridge circuits. Mostly replaced by Class 1 ceramic capacitors	Higher cost than class 1 ceramic capacitors
Glass capacitors	Glass[214]	Better stability and frequency than silver mica. Ultra-reliable. Ultra-stable. Resistant to nuclear radiation. Operating temperature: -75 °C to $+200$ °C and even short overexposure to $+250$ °C.[215]	Higher cost than class 1 ceramic
Integrated capacitors	oxide-nitride-oxide (ONO)[216]	Thin (down to 100 µm). Smaller footprint than most MLCC. Low ESL. Very high stability up to 200 °C. High reliability	Customized production

7.9.7 Variable capacitors

Variable capacitors may have their capacitance changed by mechanical motion. Generally two versions of variable capacitors has to be to distinguished

- Tuning capacitor – variable capacitor for intentionally and repeatedly tuning an oscillator circuit in a radio or another tuned circuit
- Trimmer capacitor – small variable capacitor usually for one-time oscillator circuit internal adjustment

Variable capacitors include capacitors that use a mechanical construction to change the distance between the plates, or the amount of plate surface area which overlaps. They mostly use air as dielectric medium.

Semiconductive variable capacitance diodes[217] are not capacitors in the sense of passive components but can change their capacitance as a function of the applied reverse bias voltage and are used like a variable capacitor. They have replaced much of the tuning and trimmer capacitors.

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213 http://en.wikibooks.org/wiki/Silver%20mica%20capacitor

214 http://en.wikibooks.org/wiki/Glass

215 AVX, Performance Characteristics of Multilayer Glass Capacitors ^{http://www.avx.com/docs/techinfo/perform_gl.pdf}

216 http://en.wikibooks.org/wiki/SONOS

217 http://en.wikibooks.org/wiki/Varicap
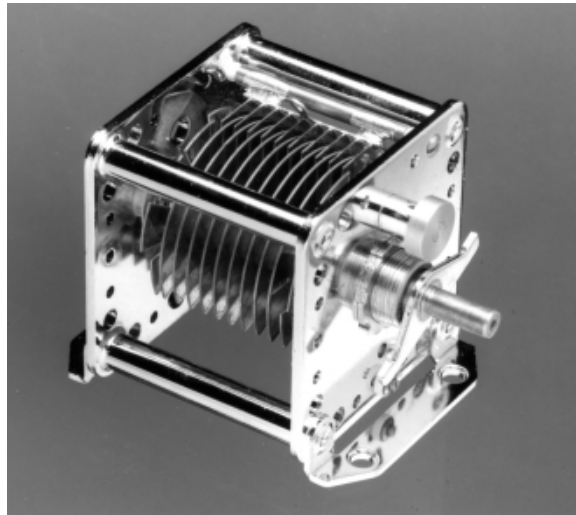
Figure 73   Air gap tuning capacitor

Figure 74   Vacuum tuning capacitor
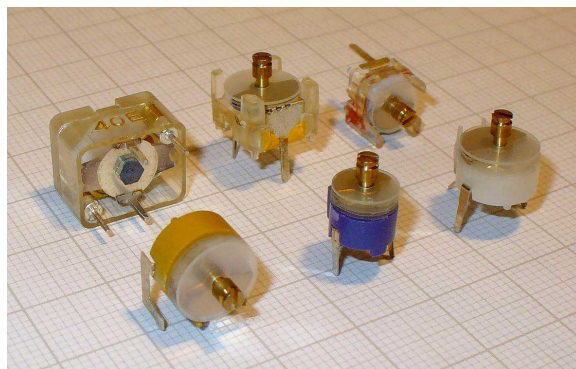
Figure 75   Trimmer capacitor for through hole mounting
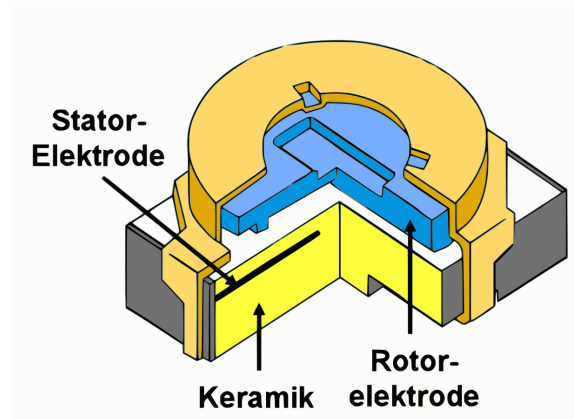
Figure 76 Trimmer capacitor for surface mounting

Features and applications as well as disadvantages of variable capacitors			
Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Air gap tuning capacitors	Air	Circular or various logarithmic cuts of the rotor electrode for different capacitance curves. Split rotor or stator cut for symmetric adjustment. Ball bearing[218] axis for noise reduced adjustment. For high professional devices.	Large dimensions. High cost.
Vacuum tuning capacitors	Vacuum	Extremely low losses. Used for high voltage, high power RF applications, such as transmitters and induction heating. Self-healing if arc-over current is limited.	Very high cost. Fragile. Large dimensions.
SF6 gas filled tuning capacitor	SF6	Extremely low losses. Used for very high voltage high power RF applications.	Very high cost, fragile, large dimensions

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218 `http://en.wikibooks.org/wiki/Ball%20bearing`

Features and applications as well as disadvantages of variable capacitors			
Capacitor type	Dielectric	Features/applications	Disadvantages
Air gap trimmer capacitors	Air	Mostly replaced by semiconductive variable capacitance diodes	High cost
Ceramic trimmer capacitors	Class 1 ceramic	Linear and stable frequency behavior over wide temperature range	High cost

7.9.8 Market

Discrete capacitors today are industrial products produced in very large quantities for use in electronic and in electrical equipment. Globally, the market for fixed capacitors was estimated at approximately US$18 billion in 2008 for 1,400 billion (1.4×10^{12}) pieces.[219] This market is dominated by ceramic capacitors with estimate of approximately one trillion (1×10^{12}) items per year.[220]

Detailed estimated figures in value for the main capacitor families are:

- Ceramic capacitor[221]s—US$8.3 billion (46%);
- Aluminum electrolytic capacitors[222]—US$ 3.9 billion (22%);
- Film capacitor[223]s and Paper capacitors—US$ 2.6 billion, (15%);
- Tantalum electrolytic capacitors[224]—US$ 2.2 billion (12%);
- Super capacitor[225]s (Double-layer capacitor[226]s)—US$ 0.3 billion (2%); and
- Others like silver mica[227] and vacuum capacitors[228]—US$ 0.7 billion (3%).

All other capacitor types are negligible in terms of value and quantity compared with the above types.

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219 highbeam business, Electronic Capacitors SIC 3675, Industry report ^{http://business.highbeam.com/industry-reports/equipment/electronic-capacitors}

220 J. Ho, T. R. Jow, S. Boggs, Historical Introduction to Capacitor Technology, PDF http://www.ifre.re.kr/board/filedown.php?seq=179

221 http://en.wikibooks.org/wiki/Ceramic%20capacitor

222 http://en.wikibooks.org/wiki/Electrolytic%20capacitor

223 http://en.wikibooks.org/wiki/Film%20capacitor

224 http://en.wikibooks.org/wiki/Tantalum%20capacitor

225 http://en.wikibooks.org/wiki/Super%20capacitor

226 http://en.wikibooks.org/wiki/Double-layer%20capacitor

227 http://en.wikibooks.org/wiki/silver%20mica%20capacitor

228 http://en.wikibooks.org/wiki/Vacuum%20variable%20capacitor

7.10 Capacitor - Electrical characteristics

7.10.1 Series-equivalent circuit
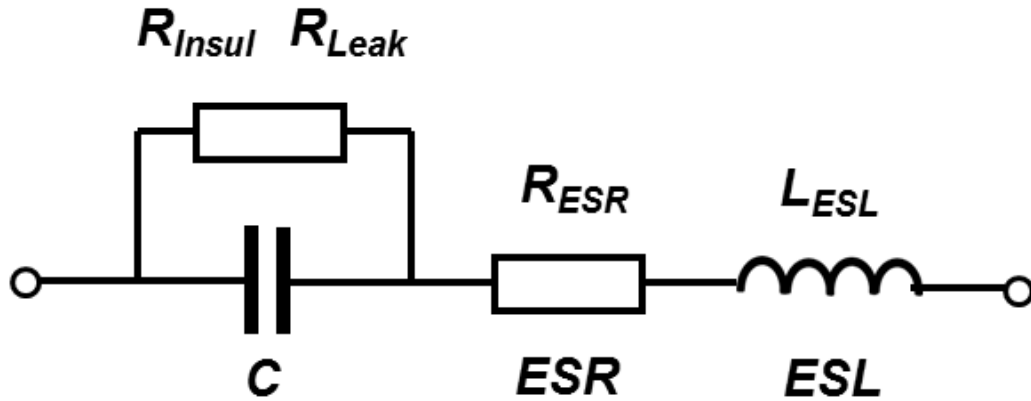
Figure 77 Series-equivalent circuit model of a capacitor

Discrete capacitors deviate from the ideal capacitor. An ideal capacitor only stores and releases electrical energy, with no dissipation. Capacitor components have losses and parasitic inductive parts. These imperfections in material and construction can have positive implications such as linear frequency and temperature behavior in class 1 ceramic capacitors. Conversely, negative implications include the non-linear, voltage-dependent capacitance in class 2 ceramic capacitors or the insufficient dielectric insulation of capacitors leading to leakage currents.

All properties can be defined and specified by a series equivalent circuit composed out of an idealized capacitance and additional electrical components which model all losses and inductive parameters of a capacitor. In this series-equivalent circuit the electrical characteristics are defined by:

- C , the capacitance of the capacitor
- R_{insul}, the insulation resistance[229] of the dielectric, not to be confused with the insulation of the housing
- R_{leak}, the resistance representing the leakage current[230] of the capacitor
- R_{ESR}, the equivalent series resistance[231] which summarizes all ohmic losses of the capacitor, usually abbreviated as "ESR"
- L_{ESL}, the equivalent series inductance[232] which is the effective self-inductance of the capacitor, usually abbreviated as "ESL".

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229 http://en.wikibooks.org/wiki/Insulator%20%28electricity%29
230 http://en.wikibooks.org/wiki/Leakage%20%28electronics%29
231 http://en.wikibooks.org/wiki/equivalent%20series%20resistance
232 http://en.wikibooks.org/wiki/equivalent%20series%20inductance

Using a series equivalent circuit instead of a parallel equivalent circuit is specified by IEC[233]/EN 60384-1.

7.10.2 Standard values and tolerances

The "rated capacitance" C_R or "nominal capacitance" C_N is the value for which the capacitor has been designed. Actual capacitance depends on the measured frequency and ambient temperature. Standard measuring conditions are a low-voltage AC measuring method at a temperature of 20 °C with frequencies of

- 100 kHz, 1 MHz (preferred) or 10 MHz for non-electrolytic capacitors with $C_R \leq 1$ nF:
- 1 kHz or 10 kHz for non-electrolytic capacitors with 1 nF $< C_R \leq 10$ μF
- 100/120 Hz for electrolytic capacitors
- 50/60 Hz or 100/120 Hz for non-electrolytic capacitors with $C_R > 10$ μF

For supercapacitors a voltage drop method is applied for measuring the capacitance value.
.

Capacitors are available in geometrically increasing preferred values[234] (E series[235] standards) specified in IEC/EN 60063. According to the number of values per decade, these were called the E3, E6, E12, E24 etc. series. The range of units used to specify capacitor values has expanded to include everything from pico- (pF), nano- (nF) and microfarad (μF) to farad (F). Millifarad and kilofarad are uncommon.

The percentage of allowed deviation from the rated value is called tolerance[236]. The actual capacitance value should be within its tolerance limits, or it is out of specification. IEC/EN 60062 specifies a letter code for each tolerance.

Tolerances of capacitors and their letter codes				
E series	**Tolerance**			
	$C_R > 10$ pF	**Letter code**	$C_R < 10$ pF	**Letter code**
E 96	1%	F	0.1 pF	B
E 48	2%	G	0.25 pF	C
E 24	5%	J	0.5 pF	D
E 12	10%	K	1 pF	F
E 6	20%	M	2 pF	G
E3	−20/+50%	S	-	-
	−20/+80%	Z	-	-

The required tolerance is determined by the particular application. The narrow tolerances of E24 to E96 are used for high-quality circuits such as precision oscillators and timers. General applications such as non-critical filtering or coupling circuits employ E12 or E6.

233 http://en.wikibooks.org/wiki/International%20Electrotechnical%20Commission
234 http://en.wikibooks.org/wiki/Preferred%20number
235 http://en.wikibooks.org/wiki/E48%20series
236 http://en.wikibooks.org/wiki/Engineering%20tolerance

Electrolytic capacitors, which are often used for filtering[237] and bypassing[238] capacitors mostly have a tolerance range of $\pm 20\%$ and need to conform to E6 (or E3) series values.

7.10.3 Temperature dependence

Capacitance typically varies with temperature. The different dielectrics express great differences in temperature sensitivity. The temperature coefficient is expressed in parts per million[239] (ppm) per degree Celsius for class 1 ceramic capacitors or in % over the total temperature range for all others.

Temperature coefficients of some common capacitors		
Type of capacitor, dielectric material	**Temperature coefficient ΔC/C**	**Application temperature range**
Ceramic capacitor class 1 paraelectric[240] NP0	$\pm$ 30 ppm/K ($\pm$0.5 %)	−55 to +125 °C
Ceramic capacitor class 2 ferroelectric[241] X7R	$\pm$15 %	−55 to +125 °C
Ceramic capacitor class 2, ferroelectric Y5V	+22 % / −82 %	−30 to +85 °C
Film capacitor Polypropylene[242] (PP)	$\pm$2.5 %	−55 to +85/105 °C
Film capacitor Polyethylen terephthalate, Polyester[243] (PET)	+5 %	−55 to +125/150 °C
Film capacitor Polyphenylene sulfide[244] (PPS)	$\pm$1.5 %	−55 to +150 °C
Film capacitor Polyethylene naphthalate[245] (PEN)	$\pm$5 %	−40 to +125/150 °C
Film capacitor Polytetrafluoroethylene[246] (PTFE)	?	−40 to +130 °C
Metallized paper capacitor (impregnated)	$\pm$10 %	−25 to +85 °C
Aluminum electrolytic capacitor Al_2O_3	$\pm$20 %	−40 to +85/105/125 °C
Tantalum electrolytic capacitor Ta_2O_5	$\pm$20 %	−40 to +125 °C

237 http://en.wikibooks.org/wiki/Electronic%20filter
238 http://en.wikibooks.org/wiki/Decoupling%20capacitor
239 http://en.wikibooks.org/wiki/parts%20per%20million
240 http://en.wikibooks.org/wiki/Paraelectricity
241 http://en.wikibooks.org/wiki/Ferroelectricity
242 http://en.wikibooks.org/wiki/Polypropylene
243 http://en.wikibooks.org/wiki/Polyester
244 http://en.wikibooks.org/wiki/Poly%28p-phenylene%20sulfide%29
245 http://en.wikibooks.org/wiki/Polyethylene%20naphthalate
246 http://en.wikibooks.org/wiki/Polytetrafluoroethylene

7.10.4 Frequency dependence

Most discrete capacitor types have more or less capacitance changes with increasing frequencies. The dielectric strength of class 2 ceramic and plastic film diminishes with rising frequency. Therefore their capacitance value decreases with increasing frequency. This phenomenon for ceramic class 2 and plastic film dielectrics is related to dielectric relaxation[247] in which the time constant of the electrical dipoles is the reason for the frequency dependence of permittivity[248]. The graphs below show typical frequency behavior of the capacitance for ceramic and film capacitors.
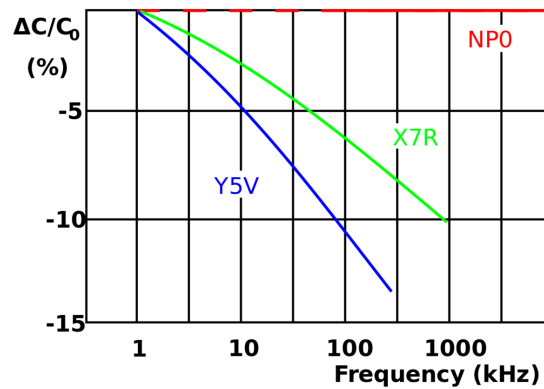
Figure 78 Frequency dependence of capacitance for ceramic class 2 capacitors (NP0 class 1 for comparisation)
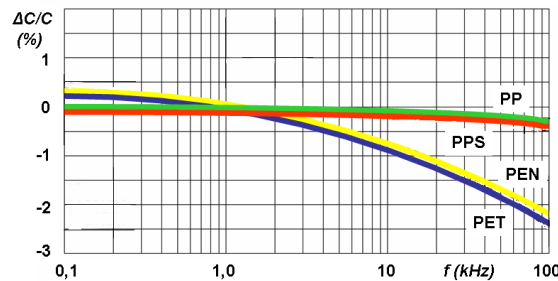
Figure 79 Frequency dependence of capacitance for film capacitors with different film materials

For electrolytic capacitors with non-solid electrolyte, mechanical motion of the ion[249]s occurs. Their movability is limited so that at higher frequencies not all areas of the roughened anode structure are covered with charge-carrying ions. As higher the anode structure is roughned as more the capacitance value decreases with increasing frequency. Low voltage

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247 http://en.wikibooks.org/wiki/dielectric%20relaxation
248 http://en.wikibooks.org/wiki/permittivity
249 http://en.wikibooks.org/wiki/ion

types with highly-roughened anodes display capacitance at 100 kHz approximately 10 to 20% of the value measured at 100 Hz.

7.10.5 Voltage dependence

Capacitance may also change with applied voltage. This effect is more prevalent in class 2 ceramic capacitors. The permittivity of ferroelectric class 2 material depends on the applied voltage. Higher applied voltage lowers permittivity. The change of capacitance can drop to 80% of the value measured with the standardized measuring voltage of 0.5 or 1.0 V. This behavior is a small source of non-linearity in low-distortion filters and other analog applications. In audio applications this can be the reason for harmonic distortion[250].

Film capacitors and electrolytic capacitors have no significant voltage dependence.
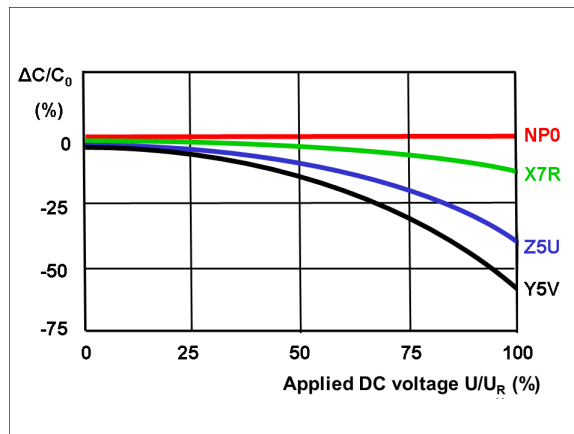
Figure 80   Simplified diagram of the change in capacitance as a function of the applied voltage for 25-V capacitors in different kind of ceramic grades
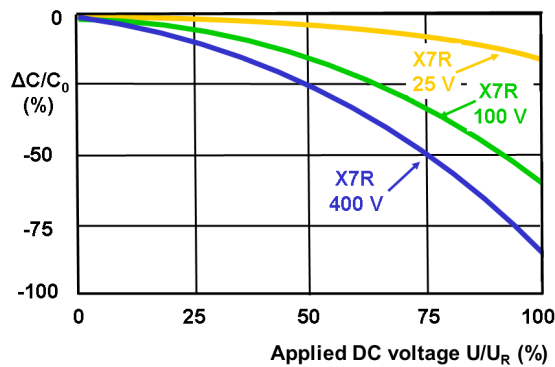
Figure 81   Simplified diagram of the change in capacitance as a function of applied voltage for X7R ceramics with different rated voltages

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250 http://en.wikibooks.org/wiki/Total%20harmonic%20distortion

7.10.6 Rated and category voltage
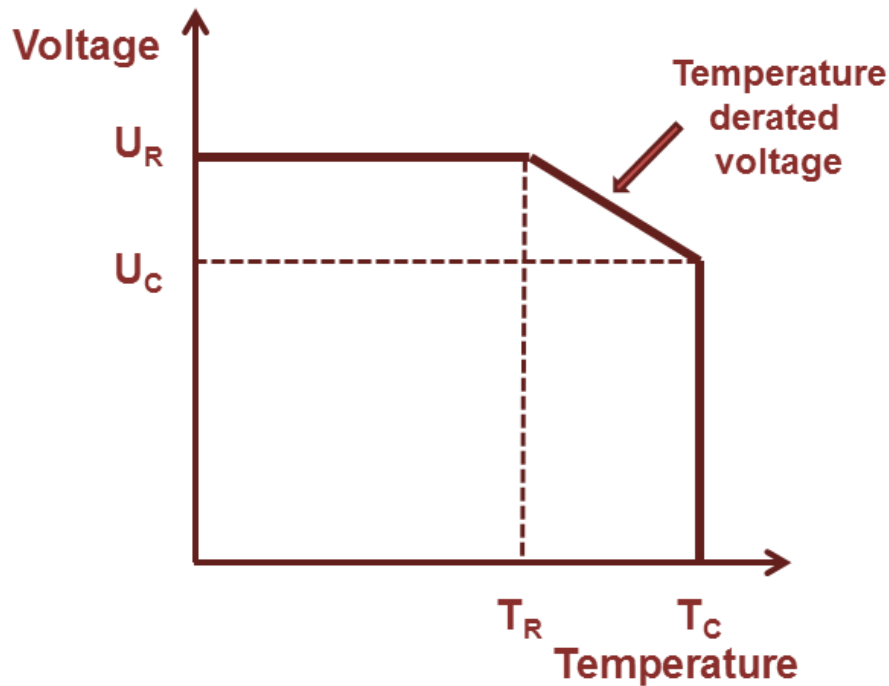
Figure 82   Relation between rated and category temperature range and applied voltage

The voltage at which the dielectric becomes conductive is called the breakdown voltage, and is given by the product of the dielectric strength and the separation between the electrodes. The dielectric strength depends on temperature, frequency, shape of the electrodes, etc. Because a breakdown in a capacitor normally is a short circuit and destroys the component, the operating voltage is lower than the breakdown voltage. The operating voltage is specified such that the voltage may be applied continuously throughout the life of the capacitor.

In IEC/EN 60384-1 the allowed operating voltage is called "rated voltage" or "nominal voltage". The rated voltage (UR) is the maximum DC voltage or peak pulse voltage that may be applied continuously at any temperature within the rated temperature range.

The voltage proof of nearly all capacitors decreases with increasing temperature. For some applications it is important to use a higher temperature range. Lowering the voltage applied at a higher temperature maintains safety margins. For some capacitor types therefore the IEC standard specify a second "temperature derated voltage" for a higher temperature range, the "category voltage". The category voltage (UC) is the maximum DC voltage or

peak pulse voltage that may be applied continuously to a capacitor at any temperature within the category temperature range.

The relation between both voltages and temperatures is given in the picture right.

7.10.7 Impedance
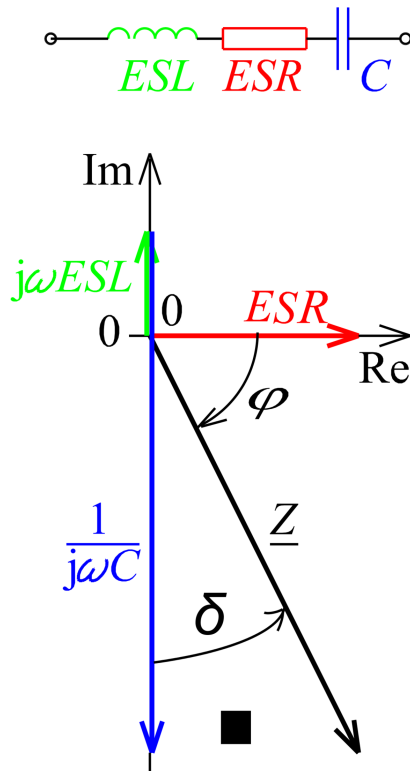
Figure 83 Simplified series-equivalent circuit of a capacitor for higher frequencies (above); vector diagram with electrical reactances X_{ESL} and X_C and resistance ESR and for illustration the impedance Z and dissipation factor tan δ

In general, a capacitor is seen as a storage component for electric energy. But this is only one capacitor function. A capacitor can also act as an AC[251] resistor[252]. In many cases the capacitor is used as a decoupling capacitor[253] to filter or bypass undesired biased

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251 http://en.wikibooks.org/wiki/Alternating%20current
252 http://en.wikibooks.org/wiki/resistor
253 http://en.wikibooks.org/wiki/decoupling%20capacitor

AC frequencies to the ground. Other applications use capacitors for capacitive coupling[254] of AC signals; the dielectric is used only for blocking DC. For such applications the AC resistance[255] is as important as the capacitance value.

The frequency dependent AC resistance is called impedance[256] z and is the complex[257] ratio of the voltage to the current in an AC circuit. Impedance extends the concept of resistance to AC circuits and possesses both magnitude and phase[258] at a particular frequency. This is unlike resistance, which has only magnitude.

$$Z = |Z|e^{j\theta}$$

The magnitude $|z|$ represents the ratio of the voltage difference amplitude to the current amplitude, j is the imaginary unit[259], while the argument θ gives the phase difference between voltage and current.

In capacitor data sheets, only the impedance magnitude |Z| is specified, and simply written as "Z" so that the formula for the impedance can be written in Cartesian form[260]

$$Z = R + jX$$

where the real part[261] of impedance is the resistance R (for capacitors ESR) and the imaginary part[262] is the reactance[263] X.

As shown in a capacitor's series-equivalent circuit, the real component includes an ideal capacitor C, an inductance $L(ESL)$ and a resistor $R(ESR)$. The total reactance at the angular frequency ω therefore is given by the geometric (complex) addition of a capacitive reactance (Capacitance[264]) $X_C = -\frac{1}{\omega C}$ and an inductive reactance (Inductance[265]): $X_L = \omega L_{\text{ESL}}$.

To calculate the impedance z the resistance has to be added geometrically and then Z is given by

$Z = \sqrt{ESR^2 + (X_{\text{C}} + (-X_{\text{L}}))^2}$. The impedance is a measure of the capacitor's ability to pass alternating currents. In this sense the impedance can be used like Ohms law

$Z = \frac{\hat{u}}{\hat{\imath}} = \frac{U_{\text{eff}}}{I_{\text{eff}}}$.

to calculate either the peak or the effective value of the current or the voltage.

254 http://en.wikibooks.org/wiki/capacitive%20coupling
255 http://en.wikibooks.org/wiki/Electrical%20resistance
256 http://en.wikibooks.org/wiki/Electrical%20impedance
257 http://en.wikibooks.org/wiki/Complex%20number
258 http://en.wikibooks.org/wiki/Phasor
259 http://en.wikibooks.org/wiki/imaginary%20unit
260 http://en.wikibooks.org/wiki/Cartesian%20plane
261 http://en.wikibooks.org/wiki/real%20part
262 http://en.wikibooks.org/wiki/imaginary%20part
263 http://en.wikibooks.org/wiki/Reactance%20%28electronics%29
264 http://en.wikibooks.org/wiki/Capacitance
265 http://en.wikibooks.org/wiki/Inductance

In the special case of resonance[266], in which the both reactive resistances

$X_C = -\frac{1}{\omega C}$ and $X_L = \omega L_{\text{ESL}}$

have the same value ($X_C = X_L$), then the impedance will only be determined by ESR.
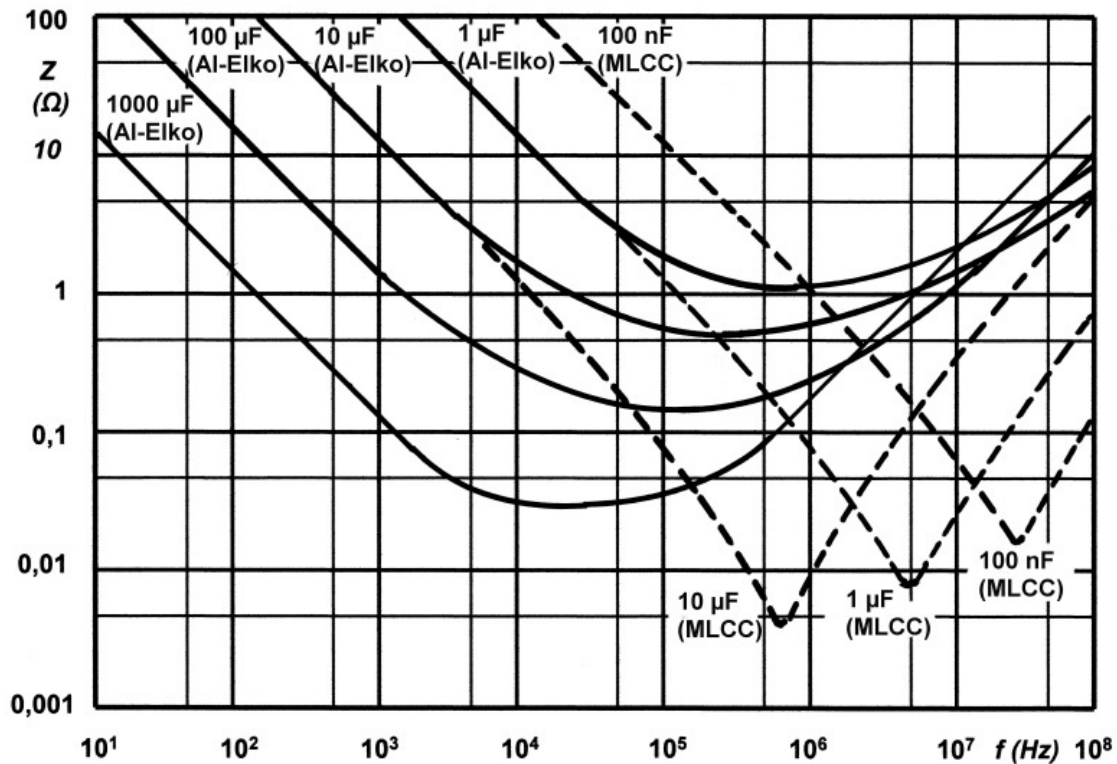
Figure 84 Typical impedance curves for different capacitance values over frequency showing the typical form with a decreasing impedance values below resonance and increasing values above resonance. As higher the capacitance as lower the resonance.

The impedance specified in the datasheets often show typical curves for the different capacitance values. With increasing frequency as the impedance decreases down to a minimum. The lower the impedance, the more easily alternating currents can be passed through the capacitor. At the apex[267], the point of resonance, where XC has the same value than XL, the capacitor has the lowest impedance value. Here only the ESR determines the impedance. With frequencies above the resonance the impedance increases again due to the ESL of the capacitor. The capacitor becomes to an inductance.

As shown in the graph, the higher capacitance values can fit the lower frequencies better while the lower capacitance values can fit better the higher frequencies.

Aluminum electrolytic capacitors have relatively good decoupling properties in the lower frequency range up to about 1 MHz due to their large capacitance values. This is the reason

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266 http://en.wikibooks.org/wiki/resonance
267 http://en.wikibooks.org/wiki/Apex%20%28geometry%29

for using electrolytic capacitors in standard or switched-mode power supplies[268] behind the rectifier[269] for smoothing application.

Ceramic and film capacitors are already out of their smaller capacitance values suitable for higher frequencies up to several 100 MHz. They also have significantly lower parasitic inductance, making them suitable for higher frequency applications, due to their construction with end-surface contacting of the electrodes. To increase the range of frequencies, often an electrolytic capacitor is connected in parallel with a ceramic or film capacitor.[270]

Many new developments are targeted at reducing parasitic inductance (ESL). This increases the resonance frequency of the capacitor and, for example, can follow the constantly increasing switching speed of digital circuits. Miniaturization, especially in the SMD multilayer ceramic chip capacitors (MLCC[271]), increases the resonance frequency. Parasitic inductance is further lowered by placing the electrodes on the longitudinal side of the chip instead of the lateral side. The "face-down" construction associated with multi-anode technology in tantalum electrolytic capacitors further reduced ESL. Capacitor families such as the so-called MOS capacitor or silicon capacitors offer solutions when capacitors at frequencies up to the GHz range are needed.

7.10.8 Inductance (ESL) and self-resonant frequency

ESL in industrial capacitors is mainly caused by the leads and internal connections used to connect the capacitor plates to the outside world. Large capacitors tend to have higher ESL than small ones because the distances to the plate are longer and every mm counts as an inductance.

For any discrete capacitor, there is a frequency above DC at which it ceases to behave as a pure capacitor. This frequency, where X_C is as high as X_L, is called the self-resonant frequency. The self-resonant frequency is the lowest frequency at which the impedance passes through a minimum. For any AC application the self-resonant frequency is the highest frequency at which capacitors can be used as a capacitive component.

This is critically important for decoupling[272] high-speed logic circuits from the power supply. The decoupling capacitor supplies transient[273] current to the chip. Without decouplers, the IC demands current faster than the connection to the power supply can supply it, as parts of the circuit rapidly switch on and off. To counter this potential problem, circuits frequently use multiple bypass capacitors—small (100 nF or less) capacitors rated for high frequencies, a large electrolytic capacitor rated for lower frequencies and occasionally, an intermediate value capacitor.

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268 http://en.wikibooks.org/wiki/Switched-mode%20power%20supply
269 http://en.wikibooks.org/wiki/rectifier
270 Murata: Basics of capacitors, lesson 2 ^{http://www.murata.com/products/emicon_fun/2011/04/cap_en14.html} Includes graph showing impedance as a function of frequency for different capacitor types; electrolytics are the only ones with a large component due to ESR
271 http://en.wikibooks.org/wiki/Multi-Layer%20Ceramic%20Capacitor
272 http://en.wikibooks.org/wiki/decoupling
273 http://en.wikibooks.org/wiki/Transient%20%28oscillation%29

7.10.9 Ohmic losses, ESR, dissipation factor, and quality factor

The summarized losses in discrete capacitors are ohmic AC[274] losses. DC[275] losses are specified as "leakage current[276]" or "insulating resistance" and are negligible for an AC specification. AC losses are non-linear, possibly depending on frequency, temperature, age or humidity. The losses result from two physical conditions:

- line losses including internal supply line resistances, the contact resistance of the electrode contact, line resistance of the electrodes, and in "wet" aluminum electrolytic capacitors and especially supercapacitors, the limited conductivity of liquid electrolytes and
- dielectric losses[277] from dielectric polarization[278].

The largest share of these losses in larger capacitors is usually the frequency dependent ohmic dielectric losses. For smaller components, especially for wet electrolytic capacitors, conductivity of liquid electrolytes may exceed dielectric losses. To measure these losses, the measurement frequency must be set. Since commercially available components offer capacitance values cover 15 orders of magnitude, ranging from pF (10^{-12} F) to some 1000 F in supercapacitors, it is not possible to capture the entire range with only one frequency. IEC 60384-1 states that ohmic losses should be measured at the same frequency used to measure capacitance. These are:

- 100 kHz, 1 MHz (preferred) or 10 MHz for non-electrolytic capacitors with $C_R \leq 1$ nF:
- 1 kHz or 10 kHz for non-electrolytic capacitors with 1 nF $< C_R \leq 10$ µF
- 100/120 Hz for electrolytic capacitors
- 50/60 Hz or 100/120 Hz for non-electrolytic capacitors with $C_R > 10$ µF

A capacitor's summarized resistive losses may be specified either as ESR, as a dissipation factor[279](DF, tan δ), or as quality factor[280] (Q), depending on application requirements.

Capacitors with higher ripple current I_R loads, such as electrolytic capacitors, are specified with equivalent series resistance[281] ESR. ESR can be shown as an ohmic part in the above vector diagram. ESR values are specified in datasheets per individual type.

The losses of film capacitors and some class 2 ceramic capacitors are mostly specified with the dissipation factor tan δ. These capacitors have smaller losses than electrolytic capacitors and mostly are used at higher frequencies up to some hundred MHz. However the numeric value of the dissipation factor, measured at the same frequency, is independent on the capacitance value and can be specified for a capacitor series with a range of capacitance. The dissipation factor is determined as the tangent of the reactance ($X_C - X_L$) and the ESR, and can be shown as the angle δ between imaginary and the impedance axis.

If the inductance ESL is small, the dissipation factor can be approximated as:

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274 http://en.wikibooks.org/wiki/Alternating%20current
275 http://en.wikibooks.org/wiki/Direct%20current
276 http://en.wikibooks.org/wiki/leakage%20current
277 http://en.wikibooks.org/wiki/Loss%20tangent
278 http://en.wikibooks.org/wiki/Dipolar%20polarization
279 http://en.wikibooks.org/wiki/dissipation%20factor
280 http://en.wikibooks.org/wiki/quality%20factor
281 http://en.wikibooks.org/wiki/equivalent%20series%20resistance

$$\tan\delta = ESR \cdot \omega C$$

Capacitors with very low losses, such as ceramic Class 1 and Class 2 capacitors, specify resistive losses with a quality factor[282] (Q). Ceramic Class 1 capacitors are especially suitable for LC resonant circuits with frequencies up to the GHz range, and precise high and low pass filters. For an electrically resonant system, Q represents the effect of electrical resistance[283] and characterizes a resonator's bandwidth[284] B relative to its center or resonant frequency f_0. Q is defined as the reciprocal value of the dissipation factor.

$$Q = \frac{1}{tan\delta} = \frac{f_0}{B}$$

A high Q value is for resonant circuits a mark of the quality of the resonance.

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282 http://en.wikibooks.org/wiki/Q%20factor%23Electrical%20systems
283 http://en.wikibooks.org/wiki/Electrical%20resistance%20and%20conductance
284 http://en.wikibooks.org/wiki/Bandwidth%20%28signal%20processing%29

Comparization of ohmic losses for different capacitor types for resonant circuits (Reference frequency 1 MHz)

Capacitor type	Capacitance (pF)	ESR at 100 kHz (mΩ)	ESR at 1 MHz (mΩ)	tan δ at 1 MHz (10^{-4})	Quality factor
Silicon capacitor[285]	560	400	—	2,5	4000
Mica capacitor[286]	1000	650	65	4	2500
Class 1 ceramic capacitor (NP0)[287]	1000	1600	160	10	1000

285 Siliziumkondensator, Vishay, HPC0603A ^{http://www.vishay.com/company/press/releases/2004/040915capacitor/de}
286 Simic Electronics, Chip Mica Capacitors ^{http://www.simicelectronics.com/chip_mica_capacitors.html}
287 AVX, NP0, 1000 pF 100 V, 0805, Q >= 1000 (1 MHz), http://www.avx.com/docs/Catalogs/ccog.pdf

7.10.10 Limiting current loads

A capacitor can act as an AC resistor, coupling AC voltage and AC current between two points. Every AC current flow through a capacitor generates heat inside the capacitor body. These dissipation power loss P is caused by ESR and is the squared value of the effective (RMS) current I

$$P = I^2 \cdot ESR$$

The same power loss can be written with the dissipation factor $tan\delta$ as

$$P = \frac{U^2 \cdot tan\delta}{2\pi f \cdot C}$$

The internal generated heat has to be distributed to the ambient. The temperature of the capacitor, which is established on the balance between heat produced and distributed, shall not exceed the capacitors maximum specified temperature. Hence, the ESR or dissipation factor is a mark for the maximum power (AC load, ripple current, pulse load, etc.) a capacitor is specified for.

AC currents may be a:

- ripple current—an effective (RMS) AC current, coming from an AC voltage superimposed of an DC bias, a
- pulse current—an AC peak current, coming from an voltage peak, or an
- AC current—an effective (RMS) sinusoidal current

Ripple and AC currents mainly warms the capacitor body. By this currents internal generated temperature influences the breakdown voltage of the dielectric. Higher temperature lower the voltage proof of all capacitors. In wet electrolytic capacitors higher temperatures force the evaporation of electrolytes, shortening the life time of the capacitors. In film capacitors higher temperatures may shrink the plastic film changing the capacitor's properties.

Pulse currents, especially in metallized film capacitors, heat the contact areas between end spray (schoopage) and metallized electrodes. This may reduce the contact to the electrodes, heightening the dissipation factor.

For safe operation, the maximal temperature generated by any AC current flow through the capacitor is a limiting factor, which in turn limits AC load, ripple current, pulse load, etc.

Ripple current

A "ripple current" is the RMS[288] value of a superimposed AC current of any frequency and any waveform of the current curve for continuous operation at a specified temperature. It

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288 http://en.wikibooks.org/wiki/Root%20mean%20square

arises mainly in power supplies (including switched-mode power supplies[289]) after rectifying an AC voltage and flows as charge and discharge current through the decoupling or smoothing capacitor. The "rated ripple current" shall not exceed a temperature rise of 3, 5 or 10 °C, depending on the capacitor type, at the specified maximum ambient temperature.

Ripple current generates heat within the capacitor body due to the ESR of the capacitor. The ESR, composed out of the dielectric losses caused by the changing field strength in the dielectric and the losses resulting out of the slightly resistive supply lines or the electrolyte depends on frequency and temperature. Higher frequencies heighten the ESR and higher temperatures lower the ESR slightly.

The types of capacitors used for power applications have a specified rated value for maximum ripple current. These are primarily aluminum electrolytic capacitors, and tantalum as well as some film capacitors and Class 2 ceramic capacitors.

Aluminium electrolytic capacitors, the most common type for power supplies, experience shorter life expectancy at higher ripple currents. Exceeding the limit tends to result in explosive failure.

Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are also limited by ripple current. Exceeding their ripple limits tends to shorts and burning components.

For film and ceramic capacitors, normally specified with a loss factor tan δ, the ripple current limit is determined by temperature rise in the body of approximately 10 °C. Exceeding this limit may destroy the internal structure and cause shorts.

Pulse current

The rated pulse load for a certain capacitor is limited by the rated voltage, the pulse repetition frequency, temperature range and pulse rise time. The "pulse rise time" dv/dt, represents the steepest voltage gradient of the pulse (rise or fall time) and is expressed in volts per μs (V/μs).

The rated pulse rise time is also indirectly the maximum capacity of an applicable peak current I_p. The peak current is defined as:

$$I_p = C \cdot dv/dt$$

where: I_p is in A; C in μF; dv/dt in V/μs

The permissible pulse current capacity of a metallized film capacitor generally allows an internal temperature rise of 8 to 10 °K.

In the case of metallized film capacitors, pulse load depends on the properties of the dielectric material, the thickness of the metallization and the capacitor's construction, especially the construction of the contact areas between the end spray and metallized electrodes. High peak currents may lead to selective overheating of local contacts between end spray and metallized electrodes which may destroy some of the contacts, leading to increasing ESR.

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289 http://en.wikibooks.org/wiki/Switched-mode%20power%20supply

For metallized film capacitors, so-called pulse tests simulate the pulse load that might occur during an application, according to a standard specification. IEC 60384 part 1, specifies that the test circuit is charged and discharged intermittently. The test voltage corresponds to the rated DC voltage and the test comprises 10000 pulses with a repetition frequency of 1 Hz. The pulse stress capacity is the pulse rise time. The rated pulse rise time is specified as 1/10 of the test pulse rise time.

The pulse load must be calculated for each application. A general rule for calculating the power handling of film capacitors is not available because of vendor-related internal construction details. To prevent the capacitor from overheating the following operating parameters have to be considered:

- peak current per µF
- Pulse rise or fall time dv/dt in V/µs
- relative duration of charge and discharge periods (pulse shape)
- maximum pulse voltage (peak voltage)
- peak reverse voltage;
- Repetition frequency of the pulse
- Ambient temperature
- Heat dissipation (cooling)

Higher pulse rise times are permitted for pulse voltage lower than the rated voltage.

Examples for calculations of individual pulse loads are given by many manufactures, e.g. WIMA[290] and Kemet.[291]

290 WIMA, Selection of Capacitors for Pulse Applications ^{http://www.wima.de/EN/pulseselection.htm}

291 Kemet, General information DC Film Capacitors ^{http://www.kemet.com/kemet/web/homepage/kechome.nsf/weben/CF9A77B25D8A4E0F852576AE007F3F0B/\protect\char"0024\relax{}file/F9000_GenInfo_DCFilm.pdf}

AC current
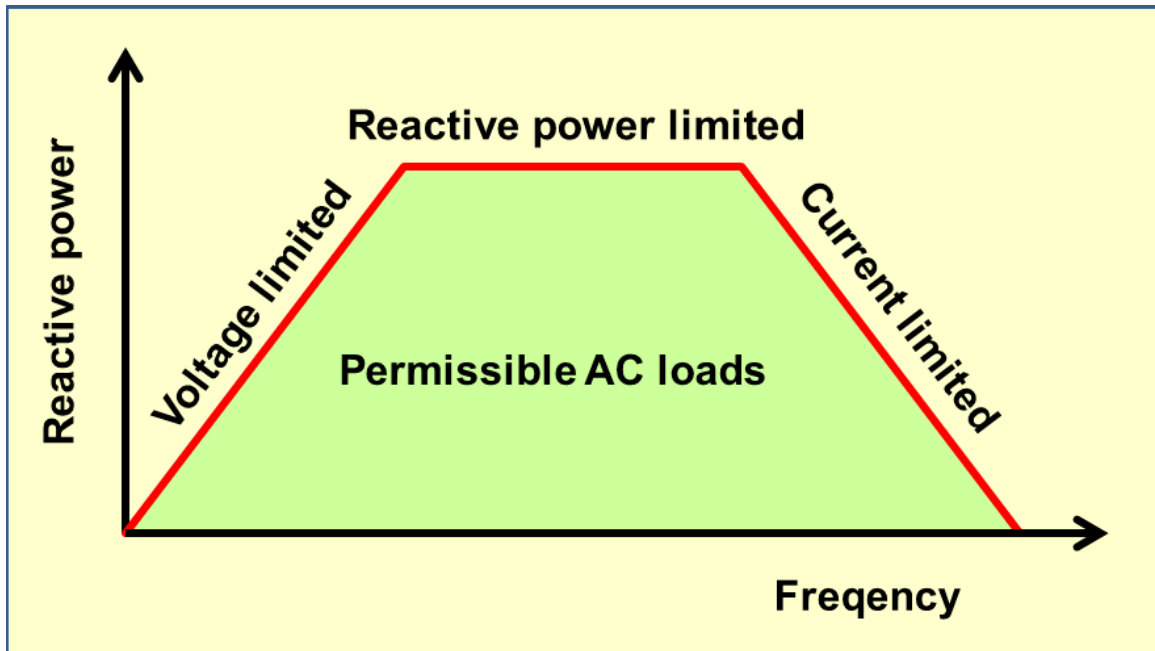
Figure 85   Limiting conditions for capacitors operating with AC loads

An AC load only can be applied to a non-polarized capacitor. Capacitors for AC applications are primarily film capacitors, metallized paper capacitors, ceramic capacitors and bipolar electrolytic capacitors.

The rated AC load for an AC capacitor is the maximum sinusoidal effective AC current (rms) which may be applied continuously to a capacitor within the specified temperature range. In the datasheets the AC load may be expressed as

- rated AC voltage at low frequencies,
- rated reactive power at intermediate frequencies,
- reduced AC voltage or rated AC current at high frequencies.
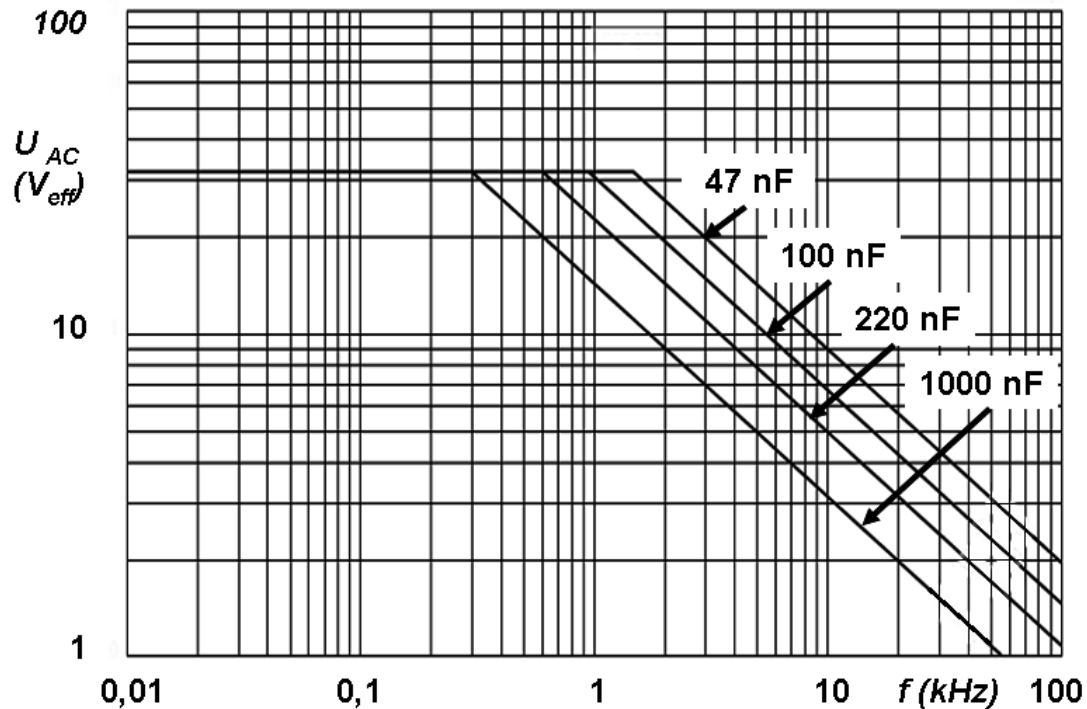
Figure 86   Typical rms AC voltage curves as a function of frequency, for 4 different capacitance values of a 63 V DC film capacitor series

The rated AC voltage for film capacitors is generally calculated so that an internal temperature rise of 8 to 10 °K is the allowed limit for safe operation. Because dielectric losses increase with increasing frequency, the specified AC voltage has to be derated at higher frequencies. Datasheets for film capacitors specify special curves for derating AC voltages at higher frequencies.

If film capacitors or ceramic capacitors only have a DC specification, the peak value of the AC voltage applied has to be lower than the specified DC voltage.

AC loads can occur in AC Motor run capacitors, for voltage doubling, in snubber[292]s, lighting ballast and for power factor correction[293] PFC for phase shifting to improve transmission network stability and efficiency, which is one of the most important applications for large power capacitors. These mostly large PP film or metallized paper capacitors are limited by the rated reactive power VAr.

Bipolar electrolytic capacitors, to which an AC voltage may be applicable, are specified with a rated ripple current.

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292   http://en.wikibooks.org/wiki/snubber
293   http://en.wikibooks.org/wiki/power%20factor%20correction

7.10.11 Insulation resistance and self-discharge constant

The resistance of the dielectric is finite, leading to some level of DC "leakage current"[294] that causes a charged capacitor to lose charge over time. For ceramic and film capacitors, this resistance is called "insulation resistance R_{ins}". This resistance is represented by the resistor R_{ins} in parallel with the capacitor in the series-equivalent circuit of capacitors. Insulation resistance must not be confused with the outer isolation of the component with respect to the environment.

The time curve of self-discharge over insulation resistance with decreasing capacitor voltage follows the formula

$$u(t) = U_0 \cdot \mathrm{e}^{-t/\tau_{\mathrm{s}}},$$

With stored DC voltage U_0 and self-discharge constant

$$\tau_{\mathrm{s}} = R_{\mathrm{ins}} \cdot C$$

Thus, after τ_{s} voltage U_0 drops to 37% of the initial value.

The self-discharge constant is an important parameter for the insulation of the dielectric between the electrodes of ceramic and film capacitors. For example, a capacitor can be used as the time-determining component for time relays or for storing a voltage value as in a sample and hold[295] circuits or operational amplifier[296]s.

Class 1 ceramic capacitors have an insulation resistance of at least 10 GΩ, while class 2 capacitors have at least 4 GΩ or a self-discharge constant of at least 100 s. Plastic film capacitors typically have an insulation resistance of 6 to 12 GΩ. This corresponds to capacitors in the uF range of a self-discarge constant of about 2000–4000 s.[297]

Insulation resistance respectively the self-discharge constant can be reduced if humidity penetrates into the winding. It is partially strongly temperature dependent and decreases with increasing temperature. Both decrease with increasing temperature.

In electrolytic capacitors, the insulation resistance is defined as leakage current.

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294 http://en.wikibooks.org/wiki/Direct%20current
295 http://en.wikibooks.org/wiki/sample%20and%20hold
296 http://en.wikibooks.org/wiki/operational%20amplifier
297 Wima,Insulation Resistance ^{http://www.wima.de/EN/insulation.htm}

7.10.12 Leakage current
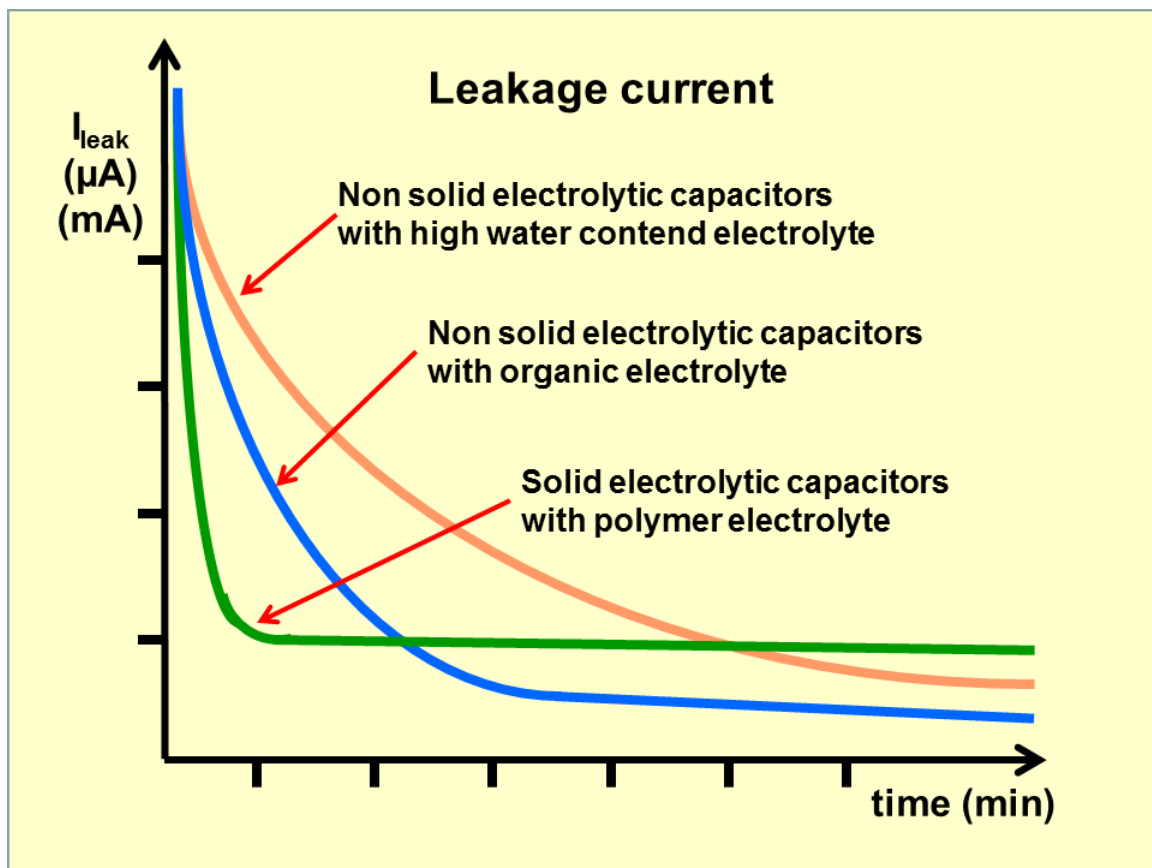
Figure 87 The general leakage current behavior of electrolytic capacitors depend on the kind of electrolyte

For electrolytic capacitors the insulation resistance of the dielectric is termed "leakage current". This DC current[298] is represented by the resistor R_{leak} in parallel with the capacitor in the series-equivalent circuit of electrolytic capacitors. This resistance between the terminals of a capacitor is also finite. R_{leak} is lower for electrolytics than for ceramic or film capacitors.

The leakage current includes all weak imperfections of the dielectric caused by unwanted chemical processes and mechanical damage. It is also the DC current that can pass through the dielectric after applying a voltage. It depends on the interval without voltage applied (storage time), the thermic stress from soldering, on voltage applied, on temperature of the capacitor, and on measuring time.

The leakage current drops in the first minutes after applying DC voltage. In this period the dielectric oxide layer can self-repair weaknesses by building up new layers. The time required depends generally on the electrolyte. Solid electrolytes drop faster than non-solid electrolytes but remain at a slightly higher level.

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298   http://en.wikibooks.org/wiki/Direct%20current

The leakage current in non-solid electrolytic capacitors as well as in manganese oxide solid tantalum capacitors decreases with voltage-connected time due to self-healing effects. Although electrolytics leakage current is higher than current flow over insulation resistance in ceramic or film capacitors, the self-discharge of modern non solid electrolytic capacitors takes several weeks.

A particular problem with electrolytic capacitors is storage time. Higher leakage current can be the result of longer storage times. These behaviors are limited to electrolytes with a high percentage of water. Organic solvents such as GBL[299] do not have high leakage with longer storage times.

Leakage current is normally measured 2 or 5 minutes after applying rated voltage.

7.10.13 Microphonics

All ferroelectric materials exhibit piezoelectricity[300] a piezoelectric effect. Because Class 2 ceramic capacitors use ferroelectric ceramics dielectric, these types of capacitors may have electrical effects called microphonics[301]. Microphonics (microphony) describes how electronic components transform mechanical vibration[302]s into an undesired electrical signal (noise[303]).[304] The dielectric may absorb mechanical forces from shock or vibration by changing thickness and changing the electrode separation, affecting the capacitance, which in turn induces an AC current. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording.

In the reverse microphonic effect, varying the electric field between the capacitor plates exerts a physical force, turning them into an audio speaker. High current impulse loads or high ripple currents can generate audible sound from the capacitor itself, draining energy and stressing the dielectric.[305]

7.10.14 Dielectric absorption (soakage)

Main Page: Dielectric absorption[306]

Dielectric absorption occurs when a capacitor that has remained charged for a long time discharges only incompletely when briefly discharged. Although an ideal capacitor would reach zero volts after discharge, real capacitors develop a small voltage from time-delayed

299 http://en.wikibooks.org/wiki/gamma-Butyrolactone
300 http://en.wikibooks.org/wiki/piezoelectricity
301 http://en.wikibooks.org/wiki/microphonics
302 http://en.wikibooks.org/wiki/vibration
303 http://en.wikibooks.org/wiki/Noise%20%28electronics%29
304 http://www.kemet.com/kemet/web/homepage/kfbk3.nsf/vaFeedbackFAQ/
     118EBDDDFA5D532C852572BF0046B776/\protect\char"0024\relax{}file/2007%20CARTS%20-%
     20Reduced%20Microphonics%20and%20Sound%20Emissions.pdf, Capacitors for reduced sound emissions.
305 Kemet, Are your military ceramic capacitors subject to the piezoelectric effect? http://www.kemet.com/
     kemet/web/homepage/kfbk3.nsf/vaFeedbackFAQ/242F5F2E69DCEC7485256EDF004CA495
306 http://en.wikibooks.org/wiki/Dielectric%20absorption

dipole discharging, a phenomenon that is also called dielectric relaxation[307], "soakage" or "battery action".

Values of dielectric absorption for some often used capacitors	
Type of capacitor	Dielectric Absorption
Air and vacuum capacitors	Not measurable
Class-1 ceramic capacitors, NP0	0.6%
Class-2 ceramic capacitors, X7R	2.5%
Polypropylene film capacitors (PP)	0.05 to 0.1%
Polyester film capacitors (PET)	0.2 to 0.5%
Polyphenylene sulfide film capacitors (PPS)	0.05 to 0.1%
Polyethylene naphthalate film capacitors (PEN)	1.0 to 1.2%
Tantalum electrolytic capacitors with solid electrolyte	2 to 3%,[308] 10%[309]
Aluminium electrolytic capacitor with non solid electrolyte	10 to 15%
Double-layer capacitor or super capacitors	data not available

In many applications of capacitors dielectric absorption is not a problem but in some applications, such as long-time-constant[310] integrator[311]s, sample-and-hold[312] circuits, switched-capacitor analog-to-digital converter[313]s, and very low-distortion filter[314]s, it is important that the capacitor does not recover a residual charge after full discharge, and capacitors with low absorption are specified.[315] The voltage at the terminals generated by the dielectric absorption may in some cases possibly cause problems in the function of an electronic circuit or can be a safety risk to personnel. In order to prevent shocks most very large capacitors are shipped with shorting wires that need to be removed before they are used.[316]

7.10.15 Energy density

The capacitance value depends on the dielectric material (ε), the surface of the electrodes (A) and the distance (d) separating the electrodes and is given by the formula of a plate capacitor:

$$C \approx \frac{\varepsilon A}{d}$$

307 http://en.wikibooks.org/wiki/dielectric%20relaxation

308 Kemet, Polymer Tantalum Chip Capacitors ^{http://d0server1.fnal.gov/users/bagby/www/L1_Cal/ORC_Docs/Final_Orc/ADF_CAPS/KEMET_F3102PolTaPerChar.pdf}

309 AVX, ANALYSIS OF SOLID TANTALUM CAPACITOR LEAKAGE CURRENT ^{http://www.avx.com/docs/techinfo/soltant.pdf}

310 http://en.wikibooks.org/wiki/time%20constant

311 http://en.wikibooks.org/wiki/integrator

312 http://en.wikibooks.org/wiki/sample-and-hold

313 http://en.wikibooks.org/wiki/analog-to-digital%20converter

314 http://en.wikibooks.org/wiki/Electronic%20filter

315 "Understand Capacitor Soakage to Optimize Analog Systems" by Bob Pease 1982 http://www.national.com/rap/Application/0,1570,28,00.html

316 * "Modeling Dielectric Absorption in Capacitors", by Ken Kundert ^{http://www.designers-guide.org/Modeling/da.pdf}

The separation of the electrodes and the voltage proof of the dielectric material defines the breakdown voltage of the capacitor. The breakdown voltage is proportional to the thickness of the dielectric.

Theoretically, given two capacitors with the same mechanical dimensions and dielectric, but one of them have half the thickness of the dielectric. With the same dimensions this one could place twice the parallel-plate area inside. This capacitor has theoretically 4 times the capacitance as the first capacitor but half of the voltage proof.

Since the energy density stored in a capacitor is given by:

$$E_{\text{stored}} = \frac{1}{2} C V^2,$$

thus a capacitor having a dielectric half as thick as another has 4 times higher capacitance but $\frac{1}{2}$ voltage proof, yielding an equal maximum energy density.

Therefore, dielectric thickness does not affect energy density within a capacitor of fixed overall dimensions. Using a few thick layers of dielectric can support a high voltage, but low capacitance, while thin layers of dielectric produce a low breakdown voltage, but a higher capacitance.

This assumes that neither the electrode surfaces nor the permittivity of the dielectric change with the voltage proof. A simple comparison with two existing capacitor series can show whether reality matches theory. The comparison is easy, because the manufacturers use standardized case sizes or boxes for different capacitance/voltage values within a series.

Comparison of energy stored in capacitors with the same dimensions but with different rated voltages and capacitance values			
Electrolytic capacitors NCC, KME series Ǿ D × H = 16.5 mm × 25 mm[317]		**Metallized PP film capacitors** KEMET; PHE 450 series W × H × L = 10.5 mm × 20.5 mm × 31.5 mm[318]	
Capacitance/Voltage	**Stored Energy**	**Capacitance/Voltage**	**Stored Energy**
4700 µF/10 V	**235 mWs**	1.2 µF/250 V	**37.5 mWs**
2200 µF/25 V	**688 mWs**	0.68 µF/400 V	**54.4 mWs**
220 µF/100 V	**1100 mWs**	0.39 µF/630 V	**77.4 mWs**
22 µF/400 V	**1760 mWs**	0.27 µF/1000 V	**135 mWs**

In reality modern capacitor series do not fit the theory. For electrolytic capacitors the sponge-like rough surface of the anode foil gets smoother with higher voltages, decreasing the surface area of the anode. But because the energy increases squared with the voltage, and the surface of the anode decreases lesser than the voltage proof, the energy density

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317 NCC, KME series ^{http://www.chemi-con.co.jp/catalog/pdf/bulletin/al-kme-bulleti512e-e-050712.pdf}

318 KEMET, series PHE450 ^{http://www.kemet.com/kemet/web/homepage/kechome.nsf/file/KEM_F3033_PHE450.pdf/\protect\char"0024\relax{}file/KEM_F3033_PHE450.pdf}

increases clearly. For film capacitors the permittivity changes with dielectric thickness and other mechanical parameters so that the deviation from the theory has other reasons.[319]

Comparing the capacitors from the table with a supercapacitor, the highest energy density capacitor family. For this, the capacitor 25 F/2.3 V in dimensions D × H = 16 mm × 26 mm from Maxwell HC Series, compared with the electrolytic capacitor of approximately equal size in the table. This supercapacitor has roughly 5000 times higher capacitance than the 4700/10 electrolytic capacitor but $\frac{1}{4}$ of the voltage and has about 66,000 mWs (0.018 Wh) stored electrical energy,[320] approximately 100 times higher energy density (40 to 280 times) than the electrolytic capacitor.

7.10.16 Long time behavior, aging

Electrical parameters of capacitors may change over time during storage and application. The reasons for parameter changings are different, it may be a property of the dielectric, environmental influences, chemical processes or drying-out effects for non-solid materials.

Aging

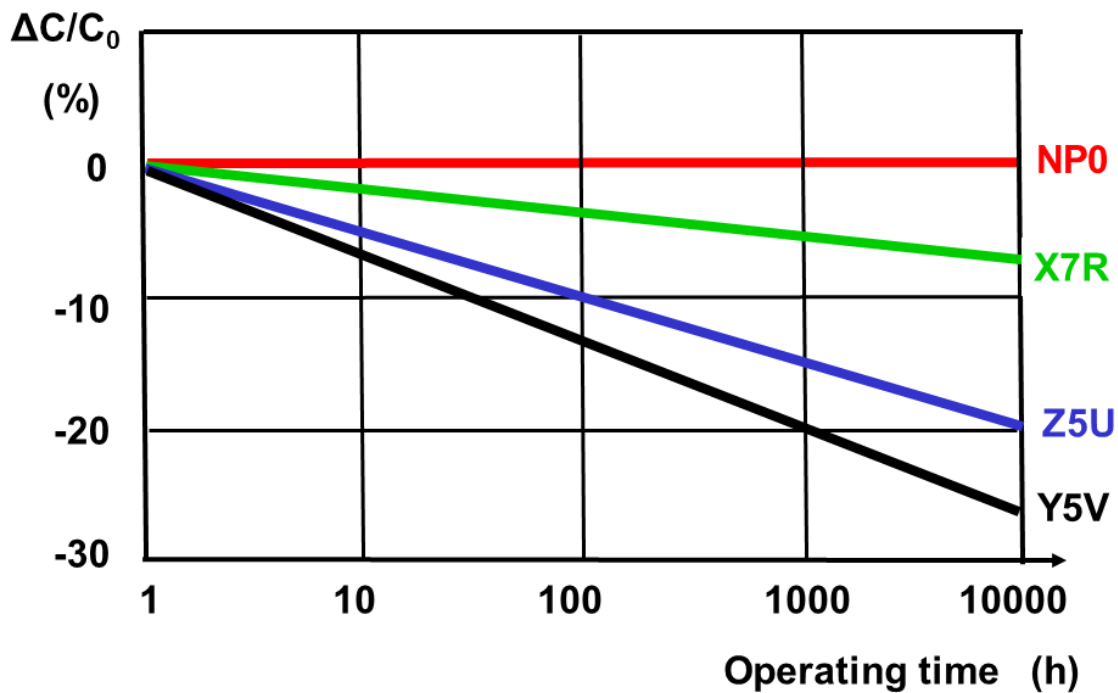
Figure 88 Aging of different Class 2 ceramic capacitors compared with NP0-Class 1 ceramic capacitor

319 Metallized Polypropylene Film Energy Storage Capacitors For Low Pulse Duty, Ralph M. Kerrigan, NWL Capacitor Division http://ecadigitallibrary.com/pdf/CARTSUSA07/2_4097.pdf

320 Maxwell HC Series / docs/datasheet_hc_series_1013793.pdf ^{http://www.maxwell.com/products/ultracapacitors}

In ferroelectric[321] Class 2 ceramic capacitors, capacitance decreases over time. This behavior is called "aging". This aging occurs in ferroelectric dielectrics, where domains of polarization in the dielectric contribute to the total polarization. Degradation of polarized domains in the dielectric decreases permittivity and therefore capacitance over time.[322][323] The aging follows a logarithmic law. This defines the decrease of capacitance as constant percentage for a time decade after the soldering recovery time at a defined temperature, for example, in the period from 1 to 10 hours at 20 °C. As the law is logarithmic, the percentage loss of capacitance will twice between 1 h and 100 h and 3 times between 1 h and 1,000 h and so on. Aging is fastest near the beginning, and the absolute capacitance value stabilizes over time.

The rate of aging of Class 2 ceramic capacitors depends mainly on its materials. Generally, the higher the temperature dependence of the ceramic, the higher the aging percentage. The typical aging of X7R ceramic capacitors is about 2.5&nbs;% per decade.[324] The aging rate of Z5U ceramic capacitors is significantly higher and can be up to 7% per decade.

The aging process of Class 2 ceramic capacitors may be reversed by heating the component above the Curie point[325].

Class 1 ceramic capacitors and film capacitors do not have ferroelectric-related aging. Environmental influences such as higher temperature, high humidity and mechanical stress can, over a longer period, lead to a small irreversible change in the capacitance value sometimes called aging, too.

The change of capacitance for P 100 and N 470 Class 1 ceramic capacitors is lower than 1%, for capacitors with N 750 to N 1500 ceramics it is ≤ 2%. Film capacitors may lose capacitance due to self-healing processes or gain it due to humidity influences. Typical changes over 2 years at 40 °C are, for example, ±3 % for PE film capacitors and ±1 % PP film capacitors.

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321 http://en.wikibooks.org/wiki/Ferroelectricity

322 . . ,

323 Takaaki Tsurumi & Motohiro Shono & Hirofumi Kakemoto & Satoshi Wada & Kenji Saito & Hirokazu Chazono, Mechanism of capacitance aging under DC-bias field in X7R-MLCCs Published online: 23 March 2007, # Springer Science + Business Media, LLC 2007 http://link.springer.com/article/10.1007%2Fs10832-007-9071-0?LI=true#page-1

324 Christopher England, Johanson dielectrics, Ceramic Capacitor Aging Made Simple http://www.johansondielectrics.com/technical-notes/general/ceramic-capacitor-aging-made-simple.html

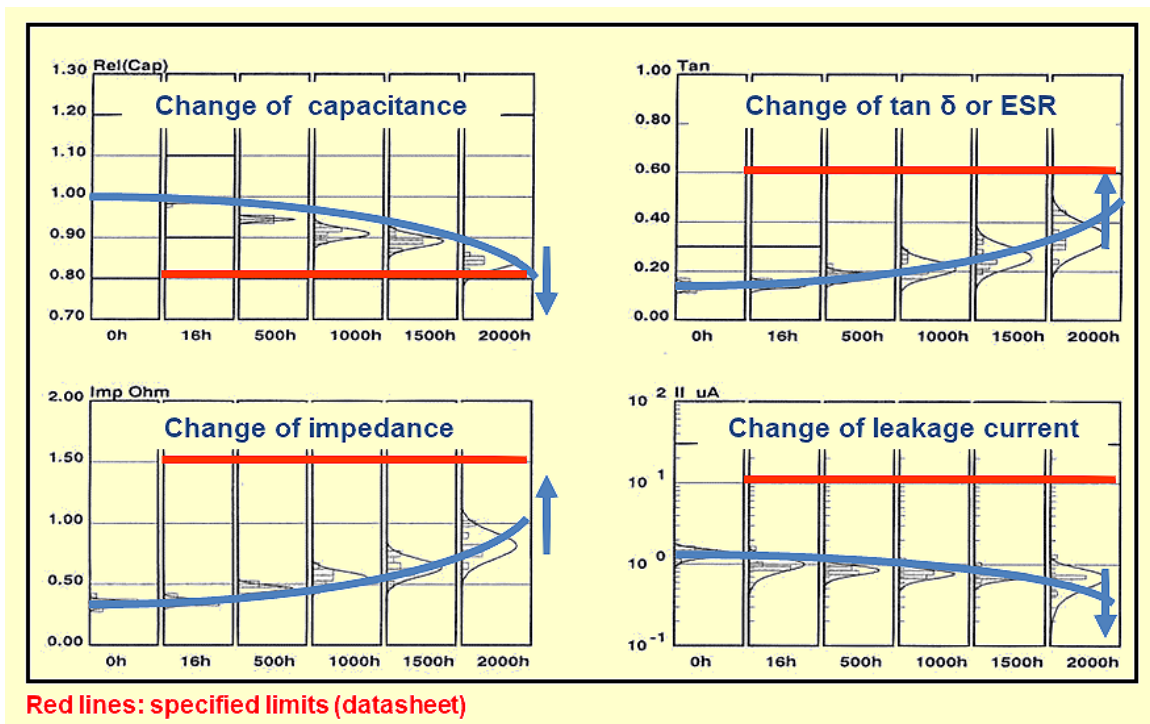325 http://en.wikibooks.org/wiki/Curie%20point

Life time

Figure 89 The electrical values of electrolytic capacitors with non-solid electrolyte changes over the time due to evaporation of electrolyte. Reaching specified limits of the parameters the capacitors will be count as "wear out failure".

Electrolytic capacitors with non-solid electrolyte age as the electrolyte evaporates. This evaporation depends on temperature and the current load the capacitors experience. Electrolyte escape influences capacitance and ESR. Capacitance decreases and the ESR increases over time. In contrast to ceramic, film and electrolytic capacitors with solid electrolytes, "wet" electrolytic capacitors reach a specified "end of life" reaching a specified maximum change of capacitance or ESR. End of life, "load life" or "lifetime" can be estimated either by formula or diagrams[326] or roughly by a so-called "10-degree-law". A typical specification for an electrolytic capacitor states a lifetime of 2,000 hours at 85 °C, doubling for every 10 degrees lower temperature, achieving lifespan of approximately 15 years at room temperature.

Supercapacitors also experience electrolyte evaporation over time. Estimation is similar to wet electrolytic capacitors. Additional to temperature the voltage and current load influence the life time. Lower voltage than rated voltage and lower current loads as well as lower temperature extend the life time.

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326 Electrolytic Capacitor Lifetime Estimation, Dr. Arne Albertsen, Jianghai Europe, http://jianghai-europe.com/wp-content/uploads/1-Jianghai-Europe-E-Cap-Lifetime-Estimation-long-AAL-2012-10-30.pdf
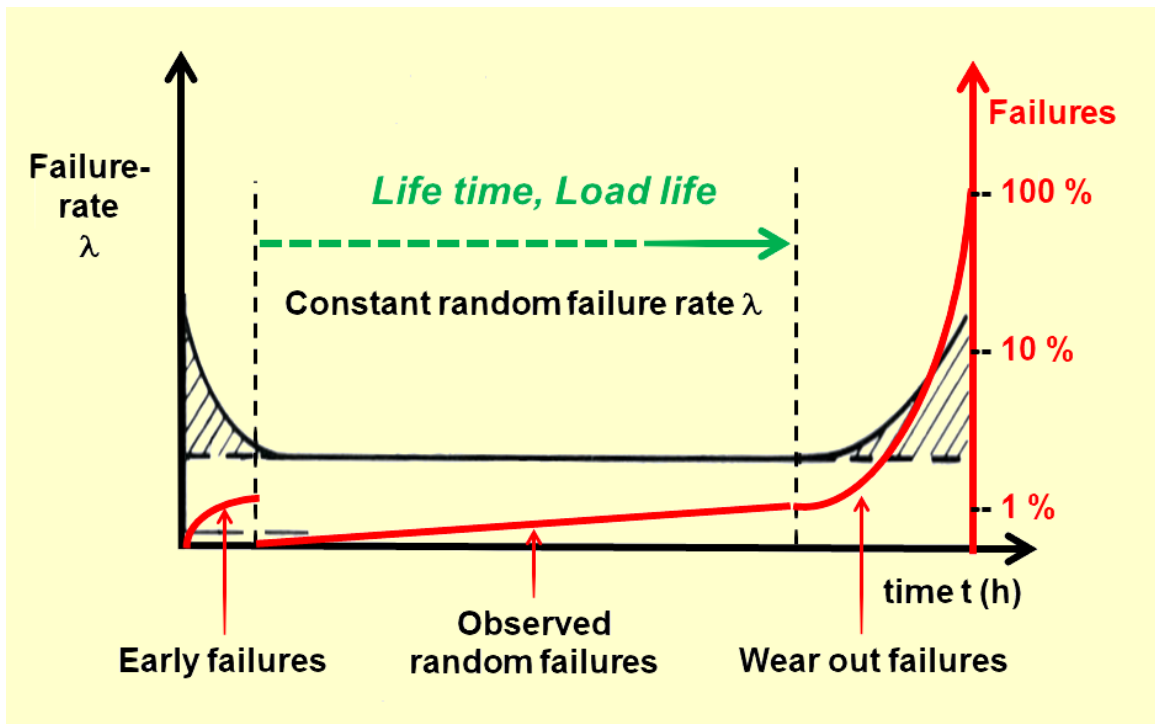
7.10.17 Failure rate

Figure 90 The life time (load life) of capacitors correspondents with the time of constant random failure rate shown in the bathtub curve[a]. For electrolytic capacitors with non-solid electrolyte and supercapacitors ends this time with the beginning of wear out failures due to evaporation of electrolyte

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a   http://en.wikibooks.org/wiki/bathtub%20curve

Capacitors are reliable[327] components with low failure rate[328]s, achieving life expectancies of decades under normal conditions. Most capacitors pass a test at the end of production similar to a "burn in[329]", so that early failures are found during production, reducing the number of post-shipment failures.

Reliability for capacitors is usually specified in numbers of Failures In Time[330] (FIT) during the period of constant random failures. FIT is the number of failures that can be expected in one billion (10^9) component-hours of operation at fixed working conditions (e.g. 1000 devices for 1 million hours, or 1 million devices for 1000 hours each, at 40 °C and 0.5 U_R). For other conditions of applied voltage, current load, temperature, mechanical influences and

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327   http://en.wikibooks.org/wiki/Reliability%20engineering
328   http://en.wikibooks.org/wiki/failure%20rate
329   http://en.wikibooks.org/wiki/burn%20in
330   http://en.wikibooks.org/wiki/Failure%20rate

humidity the FIT can recalculated with terms standardized for industrial[331] or military[332] contexts.

7.11 Additional information

7.11.1 Soldering

Capacitors may experience changes to electrical parameters due to environmental influences like soldering, mechanical stress factors (vibration, shock) and humidity. The greatest stress factor is soldering. The heat of the solder bath, especially for SMD capacitors, can cause ceramic capacitors to change contact resistance between terminals and electrodes; in film capacitors, the film may shrink, and in wet electrolytic capacitors the electrolyte may boil. A recovery period enables characteristics to stabilize after soldering; some types may require up to 24 hours. Some properties may change irreversibly by a few per cent from soldering.

7.11.2 Electrolytic behavior from storage or disuse

Electrolytic capacitors with non-solid electrolyte are "aged" during manufacturing by applying rated voltage at high temperature for a sufficient time to repair all cracks and weaknesses that may have occurred during production. Some electrolytes with a high water content react quite aggressively or even violently with unprotected aluminum. This leads to a "storage" or "disuse" problem of electrolytic capacitors manufactured before the 1980s. Chemical processes weaken the oxide layer when these capacitors are not used for too long. New electrolytes with "inhibitors" or "passivators" were developed during the 1980s to solve this problem.[333][334] As of 2012 the standard storage time for electronic components of two years at room temperature substantiates (cased) by the oxidation of the terminals will be specified for electrolytic capacitors with non-solid electrolytes, too. Special series for 125 °C with organic solvents like GBL[335] are specified up to 10 years storage time ensure without pre-condition the proper electrical behavior of the capacitors.[336]

For antique radio equipment, "pre-conditioning" of older electrolytic capacitors may be recommended. This involves applying the operating voltage for some 10 minutes over a current

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331 IEC/EN 61709, Electric components. Reliability. Reference conditions for failure rates and stress models for conversion

332 MIL-HDBK-217F Reliability Prediction of Electronic Equipment

333 J. L. Stevens, T. R. Marshall, A. C. Geiculescu M., C. R. Feger, T. F. Strange, Carts USA 2006, The Effects of Electrolyte Composition on the Deformation Characteristics of Wet Aluminum ICD Capacitors, `http://ecadigitallibrary.com/pdf/CARTS06/5_2zxm.pdf`

334 Alfonso Berduque, Zongli Dou, Rong Xu, BHC Components Ltd (KEMET), Electrochemical Studies for Aluminium Electrolytic Capacitor Applications: Corrosion Analysis of Aluminium in Ethylene Glycol-Based Electrolytes pdf `^{http://www.kemet.com/kemet/web/homepage/kfbk3.nsf/vaFeedbackFAQ/ 9A3F15E8C67C5305852576F80076DBA3/\protect\char"0024\relax{}file/2009-10%20CARTS%20-% 20Al-Electrolytic%20Corrosion%20of%20Al%20in%20Ethylen-Glycol%20Electrolytes.pdf}`

335 `http://en.wikibooks.org/wiki/gamma-Butyrolactone`

336 Vishay BCcomponents, Introduction Aluminum Capacitors, paragraph "Storage", Revision: 10-May-12, Document Number: 28356, pdf `^{http://www.vishay.com/docs/28356/alucapsintroduction.pdf}`

limiting resistor to the terminals of the capacitor. Applying a voltage through a safety resistor repairs the oxide layers.

7.11.3 IEC/EN standards

The tests and requirements to be met by capacitors for use in electronic equipment for approval as standardized types are set out in the generic specification IEC[337]/EN[338] 60384-1 in the following sections.[339]

Ceramic capacitors

- IEC/EN 60384-8—*Fixed capacitors of ceramic dielectric, Class 1*
- IEC/EN 60384-9—*Fixed capacitors of ceramic dielectric, Class 2*
- IEC/EN 60384-21—*Fixed surface mount multilayer capacitors of ceramic dielectric, Class 1*
- IEC/EN 60384-22—*Fixed surface mount multilayer capacitors of ceramic dielectric, Class 2*

Film capacitors

- IEC/EN 60384-2—*Fixed metallized polyethylene-terephthalate film dielectric d.c. capacitors*
- IEC/EN 60384-11—*Fixed polyethylene-terephthalate film dielectric metal foil d.c. capacitors*
- IEC/EN 60384-13—*Fixed polypropylene film dielectric metal foil d.c. capacitors*
- IEC/EN 60384-16—*Fixed metallized polypropylene film dielectric d.c. capacitors*
- IEC/EN 60384-17—*Fixed metallized polypropylene film dielectric a.c. and pulse*
- IEC/EN 60384-19—*Fixed metallized polyethylene-terephthalate film dielectric surface mount d.c. capacitors*
- IEC/EN 60384-20—*Fixed metalized polyphenylene sulfide film dielectric surface mount d.c. capacitors*
- IEC/EN 60384-23—*Fixed metallized polyethylene naphthalate film dielectric chip d.c. capacitors*

Electrolytic capacitors

- IEC/EN 60384-3—*Surface mount fixed tantalum electrolytic capacitors with manganese dioxide solid electro* lyte
- IEC/EN 60384-4—*Aluminium electrolytic capacitors with solid (MnO2) and non-solid electrolyte*
- IEC/EN 60384-15—*fixed tantalum capacitors with non-solid and solid electrol* yte
- IEC/EN 60384-18—*Fixed aluminium electrolytic surface mount capacitors with solid (MnO2) and non-solid electrolyte*
- IEC/EN 60384-24—*Surface mount fixed tantalum electrolytic capacitors with conductive polymer solid electrolyte*

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337 `http://en.wikibooks.org/wiki/International%20Electrotechnical%20Commission`

338 `http://en.wikibooks.org/wiki/European%20Committee%20for%20Standardization`
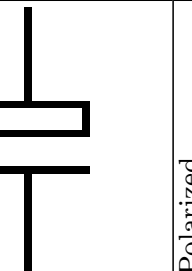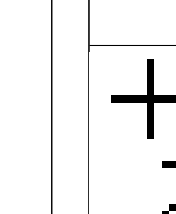
339 IEC/EN/DIN Standards, Beuth-Verlag ^{`http://www.beuth.de/de/`}

- IEC/EN 60384-25—*Surface mount fixed aluminium electrolytic capacitors with conductive polymer solid electrolyte*

Supercapacitors

- IEC/EN 62391-1—*Fixed electric double-layer capacitors for use in electric and electronic equipment - Part 1: Generic specification*
- IEC/EN 62391-2—*Fixed electric double-layer capacitors for use in electronic equipment - Part 2: Sectional specification - Electric double-layer capacitors for power application*

7.11.4 Capacitor symbols

Capacitor symbols

			Capacitor
			Polarized capacitor / Electrolytic capacitor
			Bipolar electrolytic capacitor
			Feed through capacitor
			Tuning variable capacitor
			Trimmer variable capacitor

7.11.5 Markings

Imprinted

Capacitors, like most other electronic components and if enough space is available, have imprinted markings to indicate manufacturer, type, electrical and thermal characteristics, and date of manufacture. If they are large enough the capacitor is marked with:

- manufacturer's name or trademark;
- manufacturer's type designation;
- polarity of the terminations (for polarized capacitors)
- rated capacitance;
- tolerance on rated capacitance
- rated voltage and nature of supply (AC or DC)
- climatic category or rated temperature;
- year and month (or week) of manufacture;
- certification marks of safety standards (for safety EMI/RFI suppression capacitors)

Polarized capacitors have polarity markings, usually "-" (minus) sign on the side of the negative electrode for electrolytic capacitors or a stripe or "+" (plus) sign, see #Polarity marking[340]. Also, the negative lead for leaded "wet" e-caps is usually shorter.

Smaller capacitors use a shorthand notation. The most commonly used format is: XYZ J/K/M VOLTS V, where XYZ represents the capacitance (calculated as $XY \times 10^Z$ pF), the letters J, K or M indicate the tolerance ($\pm 5\%$, $\pm 10\%$ and $\pm 20\%$ respectively) and VOLTS V represents the working voltage.

Examples:

- 105K 330V implies a capacitance of 10×10^5 pF $= 1$ µF (K $= \pm 10\%$) with a working voltage of 330 V.
- 473M 100V implies a capacitance of 47×10^3 pF $= 47$ nF (M $= \pm 20\%$) with a working voltage of 100 V.

Capacitance, tolerance and date of manufacture can be indicated with a short code specified in IEC/EN 60062. Examples of short-marking of the rated capacitance (microfarads): µ47 $= 0{,}47$ µF, 4µ7 $= 4{,}7$ µF, 47µ $= 47$ µF

The date of manufacture is often printed in accordance with international standards.

- Version 1: coding with year/week numeral code, "1208" is "2012, week number 8".
- Version 2: coding with year code/month code. The year codes are: "R" = 2003, "S"= 2004, "T" = 2005, "U" = 2006, "V" = 2007, "W" = 2008, "X" = 2009, "A" = 2010, "B" = 2011, "C" = 2012, "D" = 2013, etc. Month codes are: "1" to "9" = Jan. to Sept., "O" = October, "N" = November, "D" = December. "X5" is then "2009, May"

For very small capacitors like MLCC chips no marking is possible. Here only the traceability of the manufacturers can ensure the identification of a type.

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340 Chapter 7.11.6 on page 136

Colour coding

Main Page: Electronic color code as of 2013 Capacitors do not use color coding.

7.11.6 Polarity marking
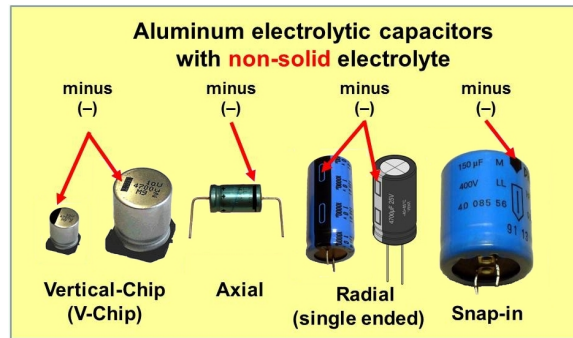
Figure 99
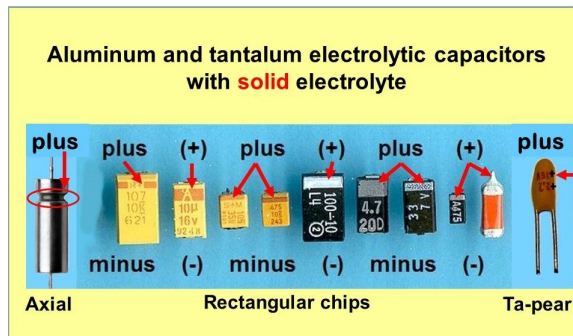
Figure 100
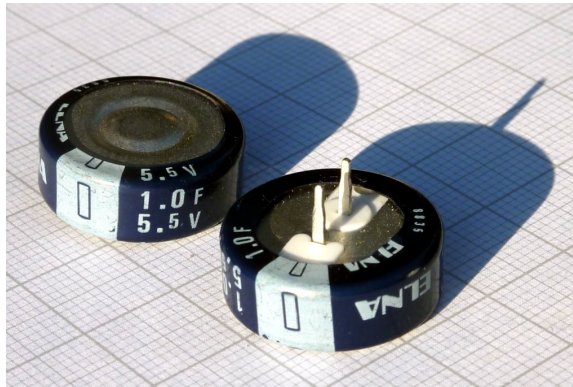
Figure 101

Aluminum e-caps with non-solid electrolyte have a polarity marking at the cathode (minus) side. Aluminum, tantalum, and niobium e-caps with solid electrolyte have a polarity marking at the anode (plus) side. Supercapacitor are marked at the minus side.

7.12 Footnotes

w:Electrolytic capacitor[341]

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341 http://en.wikipedia.org/wiki/Electrolytic%20capacitor

8 Inductors

8.1 Inductor

An inductor is a passive electronic component dependent on frequency used to store electric energy in the form of a magnetic field. An inductor has the symbol
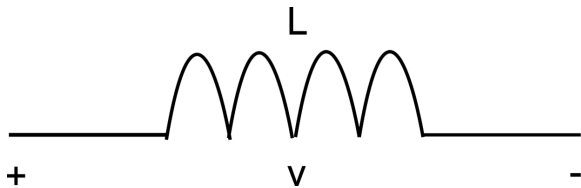
Figure 102

8.2 Inductance

Inductance is the characteristic of the Inductor to generates a magnetic field for a given current. Inductance has a letter symbol L and measured in units of Henry (H).

$$L = \frac{B}{I}$$

This section list formulas for inductances in specific situations. Beware that some of the equations are in Imperial units.

The permeability of free space, μ_0 , is constant and is defined to be exactly equal to $4\pi \times 10^{-7}$ H m^{-1}.

8.2.1 Basic inductance formula for a cylindrical coil

$L = \frac{\mu_0 \mu_r N^2 A}{l}$

$L =$ inductance / H

$\mu_r =$ relative permeability of core material

$N =$ number of turns

$A =$ area of cross-section of the coil / m^2

$l =$ length of coil / m

8.2.2 The self-inductance of a straight, round wire in free space

$$L_{self} = \frac{\mu_0 b}{2\pi} \left[\ln\left(\frac{b}{a} + \sqrt{1 + \frac{b^2}{a^2}} \right) - \sqrt{1 + \frac{a^2}{b^2}} + \frac{a}{b} + \frac{\mu_r}{4} \right]$$

L_{self} = self inductance / H(?)

b = wire length /m

a = wire radius /m

μ_r = relative permeability of wire

If you make the assumption that $b >> a$ and that the wire is nonmagnetic ($\mu_r = 1$), then this equation can be approximated to

$L_{self} = \frac{\mu_0 b}{2\pi} \left[\ln\left(\frac{2b}{a} \right) - 3/4 \right]$ (for low frequencies)

$L_{self} = \frac{\mu_0 b}{2\pi} \left[\ln\left(\frac{2b}{a} \right) - 1 \right]$ (for high frequencies due to the skin effect[1])

L = inductance / H

b = wire length / m

a = wire radius / m

The inductance of a straight wire is usually so small that it is neglected in most practical problems. If the problem deals with very high frequencies ($f > 20$ GHz), the calculation may become necessary. For the rest of this book, we will assume that this self-inductance is negligible.

8.2.3 Inductance of a short air core cylindrical coil in terms of geometric parameters:

$L = \frac{r^2 N^2}{9r + 10l}$

L = inductance in μH

r = outer radius of coil in inches

l = length of coil in inches

N = number of turns

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1   http://en.wikipedia.org/wiki/Skin_effect

8.2.4 Multilayer air core coil

$L = \frac{0.8r^2N^2}{6r+9l+10d}$

$L = $ inductance in μH

$r = $ mean radius of coil in inches

$l = $ physical length of coil winding in inches

$N = $ number of turns

$d = $ depth of coil in inches (i.e., outer radius minus inner radius)

8.2.5 Flat spiral air core coil

$L = \frac{r^2N^2}{(2r+2.8d)\times 10^5}$

$L = $ inductance / H

$r = $ mean radius of coil / m

$N = $ number of turns

$d = $ depth of coil / m (i.e. outer radius minus inner radius)

Hence a spiral coil with 8 turns at a mean radius of 25 mm and a depth of 10 mm would have an inductance of 5.13µH.

8.2.6 Winding around a toroidal core (circular cross-section)

$$L = \mu_0\mu_r \frac{N^2r^2}{D}$$

$L = $ inductance / H

$\mu_r = $ relative permeability of core material

$N = $ number of turns

r = radius of coil winding / m

D = overall diameter of toroid / m

8.2.7 Quality of good inductor

There are several important properties for an inductor that may need to be considered when choosing one for use in an electronic circuit. The following are the basic properties of a coil inductor. Other factors may be important for other kinds of inductor, but these are outside the scope of this article.

Current carrying capacity is determined by wire thickness and resistivity.

The quality factor, or Q-factor, describes the energy loss in an inductor due to imperfection in the manufacturing.

The **inductance** of the coil is probably most important, as it is what makes the inductor useful. The inductance is the response of the inductor to a changing current.

The inductance is determined by several factors.

Coil shape: short and squat is best

Core material

The number of turns in the coil. These must be in the same direction, or they will cancel out, and you will have a resistor.

Coil diameter. The larger the diameter (core area) the larger the induction.

8.2.8 Coil's Characteristics

For a Coil that has the following dimension
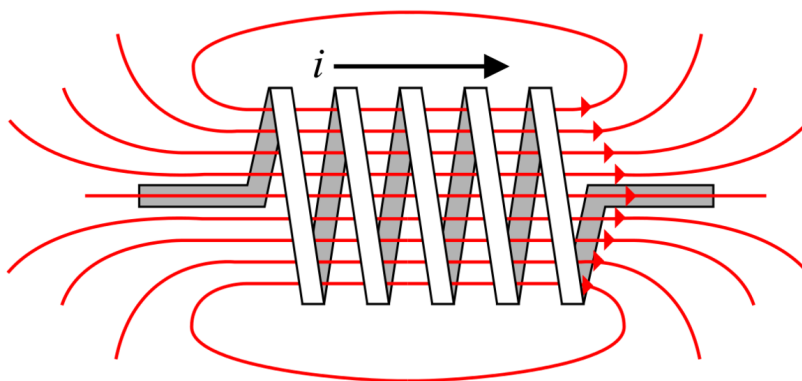
Figure 103

Area enclosed by each turn of the coil is A

Length of the coil is 'l'

Number of turns in the coil is N

Permeability of the core is μ . μ is given by the permeability of free space, μ_0 multiplied by a factor, the relative permeability, μ_r

The current in the coil is 'i'

The magnetic flux density, B , inside the coil is given by:

$$B = \frac{N \mu i}{l}$$

We know that the flux linkage in the coil, λ, is given by;

$$\lambda = NBA$$

Thus,

$$\lambda = \frac{N^2 A \mu}{l} i$$

The flux linkage in an inductor is therefore proportional to the current, assuming that A, N, l and μ all stay constant. The constant of proportionality is given the name **inductance** (measured in Henries) and the symbol L :

$$\lambda = Li$$

Taking the derivative with respect to time, we get:

$$\frac{d\lambda}{dt} = L\frac{di}{dt} + i\frac{dL}{dt}$$

Since L is time-invariant in nearly all cases, we can write:

$$\frac{d\lambda}{dt} = L\frac{di}{dt}$$

Now, Faraday's Law of Induction states that:

$$-\mathcal{E} = N\frac{d\Phi}{dt} = \frac{d\lambda}{dt}$$

We call $-\mathcal{E}$ the electromotive force (emf) of the coil, and this is opposite to the voltage v across the inductor, giving:

$$v = L\frac{di}{dt}$$

This means that the voltage across an inductor is equal to the rate of change of the current in the inductor multiplied by a factor, the inductance. note that for a constant current, the voltage is zero, and for an instantaneous change in current, the voltage is infinite (or rather, undefined). This applies only to ideal inductors which do not exist in the real world.

This equation implies that

- The voltage across an inductor is proportional to the derivative of the current through the inductor.
- In inductors, voltage leads current.
- Inductors have a high resistance to high frequencies, and a low resistance to low frequencies. This property allows their use in filtering signals.

An inductor works by opposing current change. Whenever an electron is accelerated, some of the energy that goes into "pushing" that electron goes into the electron's kinetic energy, but much of that energy is stored in the magnetic field. Later when that or some other electron is decelerated (or accelerated the opposite direction), energy is pulled back out of the magnetic field.

8.3 Inductor and Direct Current Voltage (DC)

When connect a Coil of several turns to an Electricity source in a closed loop . The current in the circuit set up a Magnetic Field that has the same properties like a Magnetic Field of a Magnet

B = L I

When the current is turned off , the Magnetic Field does not exist .

B = 0

Conducting Coil is called ElectroMagnet

8.4 Inductor and Alternating Current Voltage (AC)

8.4.1 Inductor's Voltage

$$v = L\frac{di}{dt}$$

8.4.2 Inductor's Current

$$i = \frac{1}{L}\int V dt$$

8.4.3 Reactance

$$X_L = \omega L \angle 90 = j\omega L = sL$$

8.4.4 Impedance

$$R_L + X_L = R_L \angle 0 + \omega L \angle 90 = R_L + j\omega L = R_L + sL$$

8.4.5 Angle Difference Between Voltage and Current

For Lossless Inductor

The angle difference between Voltage and Current is 90

For Lossy Inductor

$$Tan\theta = \omega \frac{L}{R_L} = 2\pi f \frac{L}{R_L} = \frac{2\pi}{t} \frac{L}{R_L}$$

Change the value of L and R_L will change the value of Angle of Difference , Angular Frequency, requenct and Time

$$\omega = \frac{1}{Tan\Theta} \frac{L}{R_L}$$

$$f = \frac{1}{2\pi Tan\Theta} \frac{L}{R_L}$$

$$t = \frac{t}{2\pi Tan\Theta} \frac{L}{R_L}$$

8.4.6 Time Constant

$$T = \frac{L}{R_L}$$

8.4.7 Quality factor

Quality factor denoted as Q is defined as the ability to store energy to the sum total of all energy losses within the component

$$Q = \frac{X}{R}$$

8.5 Inductor's Connection

8.5.1 Series Connection

Figure 104

$$L_{eq} = L_1 + L_2 + \cdots + L_n$$

8.5.2 Parallel Connection
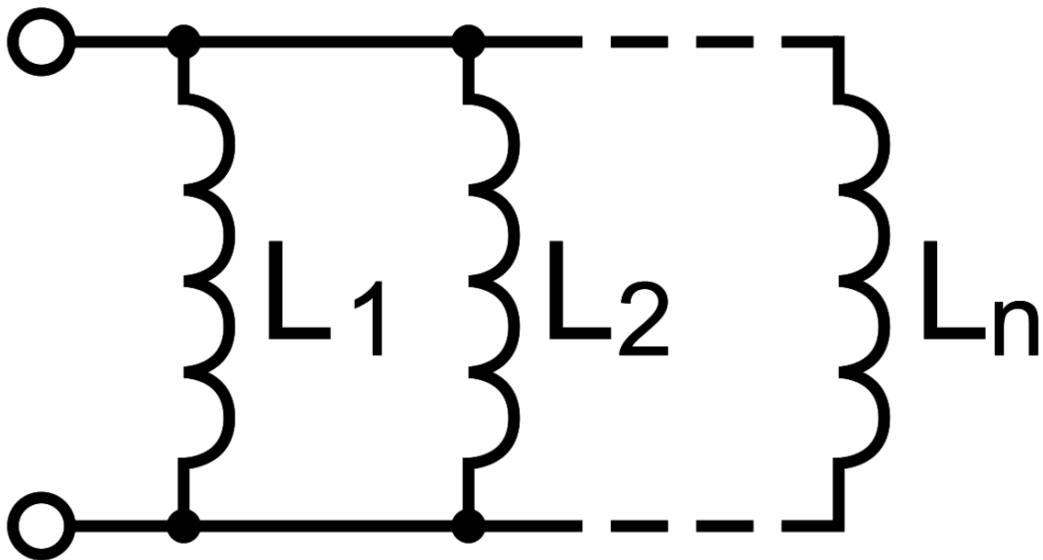
Figure 105

$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}$$

8.6 See Also

- /Networks/[2]
- /Real Inductors/[3]
- /Special Cases/[4]
- /Transient Analysis/[5]

2   http://en.wikibooks.org/wiki/%2FNetworks%2F
3   http://en.wikibooks.org/wiki/%2FReal%20Inductors%2F
4   http://en.wikibooks.org/wiki/%2FSpecial%20Cases%2F
5   http://en.wikibooks.org/wiki/%2FTransient%20Analysis%2F

9 Other Components

9.0.1 Ideal voltage sources
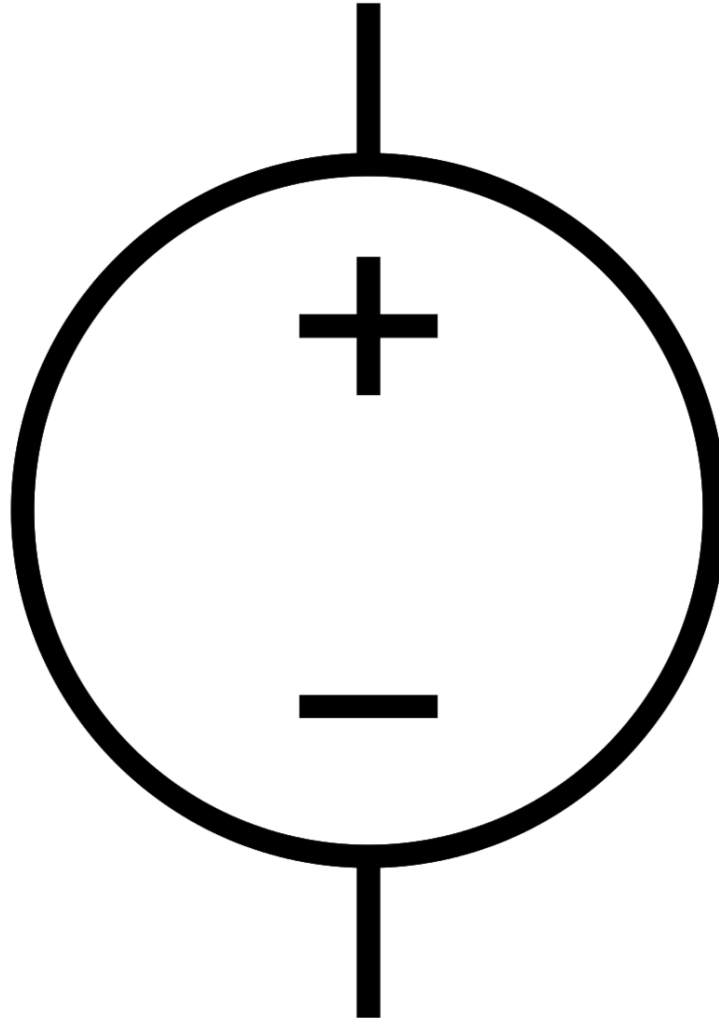
Figure 106

An ideal voltage source is a fundamental electronics component that creates a constant voltage between two points regardless of whatever else is connected to it. Since it is ideal,

some circuit configurations are not allowed, such as short circuits, which would create infinite current. (I = V / 0)

A water analogy would be a pump with pressure sensors on both sides. The *difference* in pressure between the in port and out port is constantly measured, regardless of the absolute pressure of each side, and the pump speed is adjusted so that the pressure difference stays constant.

Real voltage sources, such as batteries, power supplies, piezoelectric disks, generators, steam turbines, wall outlets, etc. have an internal source impedance (in series with the ideal voltage source), which is very important to understand.

9.0.2 Ideal current sources

Figure 107

An ideal current source is atronics component that creates a constant current through a section of circuit, regardless of whatever else is connected to it. Since it is ideal, some circuit configurations are not allowed, such as open circuits, which would create an infinite voltage.

A water analogy would be a pump with a flow meter. It measures the amount of water flowing by per unit time and changes the speed of the pump so that the current flow is constant.
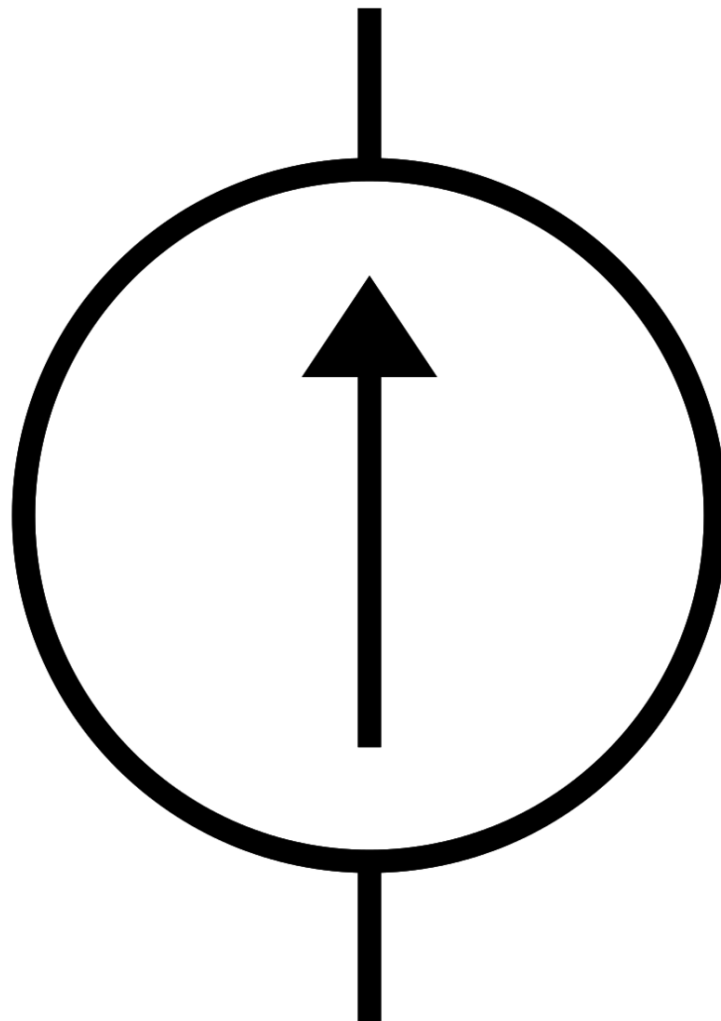
Real current sources, such as batteries, power supplies, piezoelectric disks, generators, etc. have an internal source impedance (in parallel with the source), which is very important to understand.

Real sources generally behave more like voltage sources than current sources, because the internal impedance in series is very low. A current source can be created from a voltage source with a circuit such as a *current mirror* .

9.0.3 Dependent Sources

A dependent source is either a voltage or a current source which is dependent upon another value within the circuit, usually another voltage or current. Typically, these are used in circuit modeling and analysis.

There are four main types of such sources.

Voltage-controlled voltage source (VCVS)

This is a voltage source whose value is controlled by another voltage elsewhere in the circuit. Its output will typically be given as $V_o = AV_c$, where A is a gain term and V_c is a control voltage.

An example of a VCVS may be an idealized amplifier[1], where A is the gain of the amplifier.

Current-controlled voltage source (CCVS)

This is a voltage source whose value is controlled by a current elsewhere in the circuit. Its output is typically given as $V_o = AI_c$, where A is a gain term and I_c is a control current.

Voltage-controlled current source (VCCS)

This is a current source whose value is controlled by a voltage elsewhere in the circuit. Its output is typically given as $I_o = AV_c$, where A is a gain term and V_c is a control voltage.

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1   http://en.wikipedia.org/wiki/Electronic_amplifier

Current-controlled current source (CCCS)

This is a current source whose value is controlled by a current elsewhere in the circuit. Its output is typically given as $I_o = AI_c$, where A is a gain term and I_c is a control current.

An example of a CCCS is an idealized bipolar junction transistor[2], which may be thought of as a small current controlling a larger one. Specifically the base current, I_b is the control and the collector current I_c is the output.

9.0.4 Switch

A switch is a mechanical device that connects or disconnects two parts of a circuit.
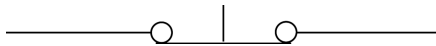
Figure 108

A switch is a short circuit when it is on.
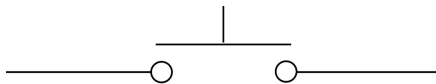
Figure 109

And it is a open circuit when it is off.

When you turn a switch on it completes a circuit that allows current to flow. When you turn the switch off it creates an air gap (depending on the type of switch), and since air is an insulator no current flows.

A switch is a device for making or breaking an electric circuit.

Usually the switch has two pieces of metal called contacts that touch to make a circuit, and separate to break the circuit. The contact material is chosen for its resistance to corrosion, because most metals form insulating oxides that would prevent the switch from working. Sometimes the contacts are plated with noble metals. They may be designed to wipe against each other to clean off any contamination. Nonmetallic conductors, such as conductive plastic, are sometimes used. The moving part that applies the operating force to the contacts is called the actuator, and may be a rocker, a toggle or dolly, a push-button or any type of mechanical linkage.

Contact Arrangements

Switches can be classified according to the arrangement of their contacts. Some contacts are normally open until closed by operation of the switch, while normally closed contacts are opened by the switch action. A switch with both types of contact is called a changeover switch.

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2   http://en.wikipedia.org/wiki/Bipolar_junction_transistor

The terms pole and throw are used to describe switch contacts. A pole is a set of contacts that belong to a single circuit. A throw is one of two or more positions that the switch can adopt. These terms give rise to the following abbreviations.
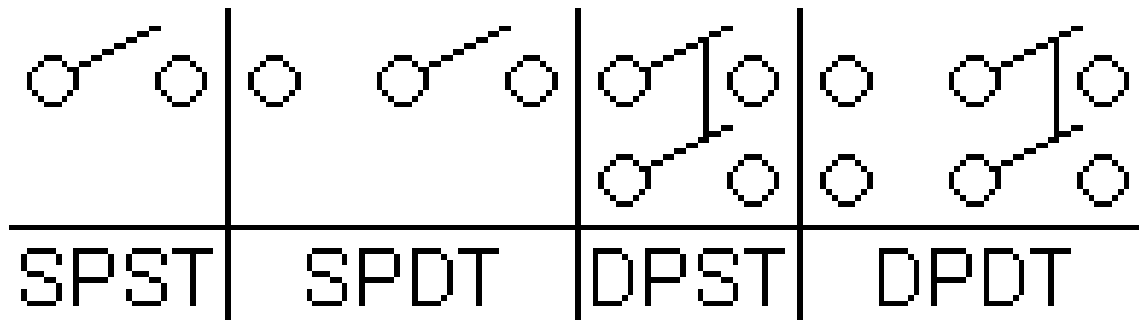
Figure 110

- S (single), D (double).
- T (throw), CO (changeover).
- CO = DT.

(single|double) pole ((single|double) throw|changeover)

- **SPST** = single pole single throw, a simple on-off switch.
- **SPDT** = single pole double throw, a simple changeover or on-off-on switch.
- **SPCO** = single pole changeover, equivalent to SPDT.
- **DPST** = double pole single throw, equivalent to two SPST switches controlled by a single mechanism.
- **DPDT** = double pole double throw, equivalent to two SPDT switches controlled by a single mechanism.
- **DPCO** = double pole changeover, equivalent to DPDT.

Switches with larger numbers of poles or throws can be described by replacing the "S" or "D" with a number.

Biased Switches

A biased switch is one containing a spring that returns the actuator to a certain position. The "on-off" notation can be modified by placing parentheses around all positions other than the resting position. For example, an (on)-off-(on) switch can be switched on by moving the actuator in either direction away from the centre, but returns to the central off position when the actuator is released.

The momentary push-button switch is a type of biased switch. This device makes contact when the button is pressed and breaks when the button is released.

Special Types

Switches can be designed to respond to any type of mechanical stimulus: for example, vibration (the trembler switch), tilt, air pressure, fluid level (the float switch), the turning of a key (key switch), linear or rotary movement (the limit switch or microswitch).

The mercury tilt switch consists of a blob of mercury inside a glass bulb. The two contacts pass through the glass, and are shorted together when the bulb is tilted to make the mercury roll on to them. The advantage of this type of switch is that the liquid metal flows around particles of dirt and debris that might otherwise prevent the contacts of a conventional switch from closing.

10 See also

- Other components[1]
- Wikipedia: Category: Components[2]
- Wikipedia: Category: Solid state switches[3]
- Audio for robotics[4]
- Wikipedia: Electronic components[5]
- Wikipedia: Resistors and Capacitors[6]
- Wikipedia: Batteries[7]
- Wikipedia: * Batteries, Rechargeable[8]
- Wikipedia: Capacitors[9]
- Wikipedia: Cathode ray tubes[10]
- Wikipedia: Circuit breakers[11]
- Wikipedia: Connectors[12]
- Wikipedia: Crystal filters[13]
- Diodes[14]
- Wikipedia: Diodes[15]
- Wikipedia: Filters[16]
- Wikipedia: Fuses[17]
- Identification[18]
- Wikipedia: Inductors[19]
- Integrated circuits[20]
- Wikipedia: Integrated circuits[21]

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1   http://en.wikibooks.org/wiki/Electronics%2FOther%20Components
2   http://en.wikipedia.org/wiki/Category%3AComponents
3   http://en.wikipedia.org/wiki/Category%3ASolid%20state%20switches
4   http://en.wikibooks.org/wiki/Robotics%3A%20Components%3A%20Audio
5   http://en.wikipedia.org/wiki/Electronic%20components
6   http://en.wikipedia.org/wiki/Circuit%20design
7   http://en.wikipedia.org/wiki/Battery%20%28electricity%29
8   http://en.wikipedia.org/wiki/Rechargeable%20battery
9   http://en.wikipedia.org/wiki/Capacitor
10   http://en.wikipedia.org/wiki/Cathode%20ray%20tube
11   http://en.wikipedia.org/wiki/Circuit%20breaker
12   http://en.wikipedia.org/wiki/Electrical%20connector
13   http://en.wikipedia.org/wiki/Crystal%20filter
14   http://en.wikibooks.org/wiki/GCSE%20Science%2FThree%20useful%20components
15   http://en.wikipedia.org/wiki/Diode
16   http://en.wikipedia.org/wiki/Electronic%20filter
17   http://en.wikipedia.org/wiki/Fuse
18   http://en.wikibooks.org/wiki/Electronics%2FComponent%20Identification
19   http://en.wikipedia.org/wiki/inductors
20   http://en.wikibooks.org/wiki/Electronics%2FIntegrated%20Circuit
21   http://en.wikipedia.org/wiki/Integrated%20circuit

- Wikipedia: Lasers[22]
- Loudspeakers[23]
- * Loudspeakers, Enclosures[24]
- Wikipedia: Loudspeakers[25]
- Measuring instruments[26]
- Mechanical components[27]
- Motors[28]
- Wikipedia: Piezoelectricity[29]
- Power sources[30]
- Wikipedia: Printed circuit boards[31]
- Wikipedia: Rectifiers[32]
- Wikipedia: * Rectifiers, Silicon-controlled (SCRs)[33]
- Software development[34]
- Wikipedia: * Rectifiers, Triacs[35]
- Resistors[36]
- * Resistors, Light dependent[37]
- * Resistors, Physics[38]
- Wikipedia: Resistors[39]
- Software components[40]
- Wikipedia: Switches[41]
- Thermistors[42]
- Wikipedia: Thyristors[43]
- Wikipedia: Transformers[44]
- Wikipedia: Transistors[45]

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22 http://en.wikipedia.org/wiki/Laser
23 http://en.wikibooks.org/wiki/Engineering%20Acoustics%2FTransducers%20-%20Loudspeaker
24 http://en.wikibooks.org/wiki/Engineering%20Acoustics%2FBass%20Reflex%20Enclosure%20Design
25 http://en.wikipedia.org/wiki/Loudspeaker
26 Chapter 19 on page 209
27 http://en.wikibooks.org/wiki/Robotics%3A%20Design%20Basics%3A%20Mechanical%20Components
28 http://en.wikibooks.org/wiki/Robotics%3A%20Components%3A%20Actuation%20Devices%3A%20Motors
29 http://en.wikipedia.org/wiki/Piezoelectricity
30 http://en.wikibooks.org/wiki/Robotics%3A%20Components%3A%20Power%20Sources
31 http://en.wikipedia.org/wiki/Printed%20circuit%20board
32 http://en.wikipedia.org/wiki/Rectifier
33 http://en.wikipedia.org/wiki/Silicon%20controlled%20rectifier
34 http://en.wikibooks.org/wiki/Computer%20programming%2FComponent%20based%20software%20development
35 http://en.wikipedia.org/wiki/Triac
36 Chapter 6 on page 23
37 http://en.wikibooks.org/wiki/GCSE%20Science%2FThree%20useful%20components
38 http://en.wikibooks.org/wiki/FHSST%20Physics%20Electricity%3AResistors
39 http://en.wikipedia.org/wiki/Resistor
40 http://en.wikibooks.org/wiki/Computer%20programming%2FComponent%20based%20software%20development
41 http://en.wikipedia.org/wiki/Switch
42 http://en.wikibooks.org/wiki/GCSE%20Science%2FThree%20useful%20components
43 http://en.wikipedia.org/wiki/Thyristor
44 http://en.wikipedia.org/wiki/Transformer
45 http://en.wikipedia.org/wiki/Transistor

- Wikipedia: Triacs[46]
- Wikipedia: Trisils[47]
- Vacuum tubes[48]
- Wikipedia: Vacuum tubes[49]
- Wikipedia: Varistors[50]

46   http://en.wikipedia.org/wiki/Triac
47   http://en.wikipedia.org/wiki/Trisil
48   Chapter 32 on page 243
49   http://en.wikipedia.org/wiki/Vacuum%20tube
50   http://en.wikipedia.org/wiki/Varistor

11 DC Voltage and Current Laws

11.1 Ohm's Law

Ohm's law describes the relationship between voltage, current, and resistance. Voltage and current are proportional to the potential difference and inversely proportional to the resistance of the circuit

$$V = I \cdot R$$

Voltage (V) is measured in volts (V); Current (I) in amperes (A); and resistance (R) in ohms (Ω).
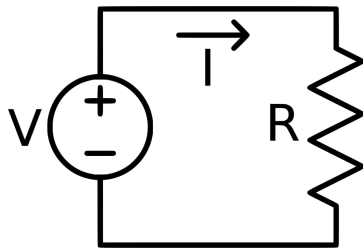
Figure 111

In this example, the current going through any point in the circuit, I, will be equal to the voltage V divided by the resistance R.
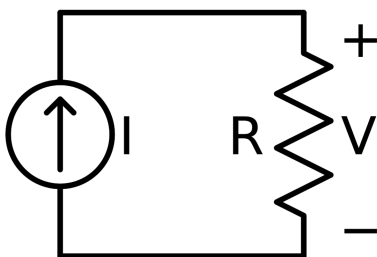
Figure 112

In this example, the voltage across the resistor, V, will be equal to the supplied current, I, times the resistance R.

If two of the values (V, I, or R) are known, the other can be calculated using this formula.

Any more complicated circuit has an equivalent resistance that will allow us to calculate the current draw from the voltage source. Equivalent resistance is worked out using the fact that all resistors are either in parallel or series. Similarly, if the circuit only has a current source, the equivalent resistance can be used to calculate the voltage dropped across the current source.

11.2 Kirchoff's Voltage Law

Kirchoff's Voltage Law (KVL):

The sum of voltage drops around any loop in the circuit that starts and ends at the same place must be zero.

11.3 Voltage as a Physical Quantity

1. Voltage is the potential difference between two charged objects.
2. Potentials can be added or subtracted in series to make larger or smaller potentials as is commonly done in batteries.
3. Positive charge flow from areas of high potential to lower potential.
4. All the components of a circuit have resistance that acts as a potential drop.

11.4 Kirchoff's Current Law

Kirchoff's Current Law (KCL):

The sum of all current entering a node must equal the sum of all currents leaving the node.

11.4.1 KCL Example
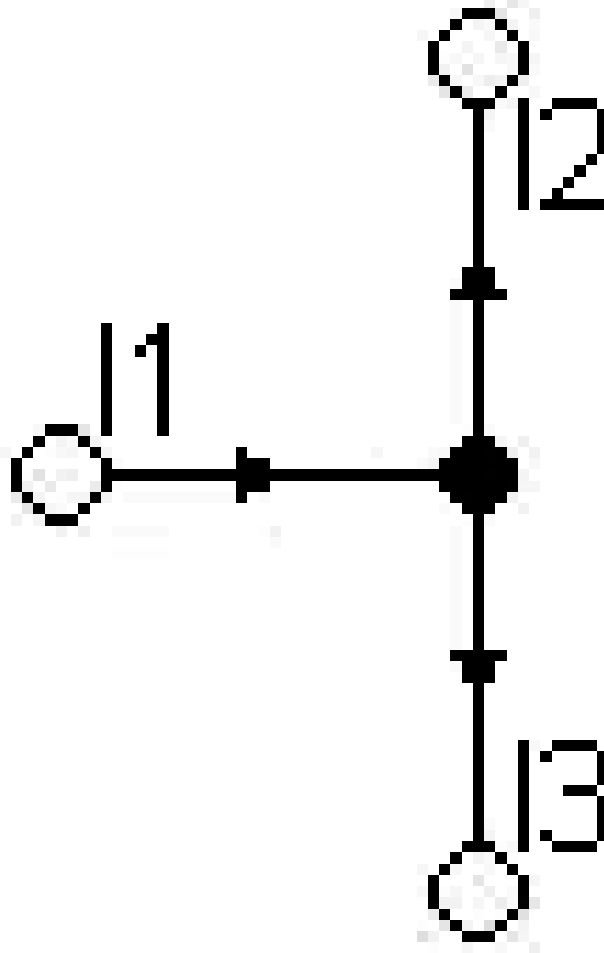
Figure 113

$-I_1 + I_2 + I_3 = 0 \leftrightarrow I_1 = I_2 + I_3$
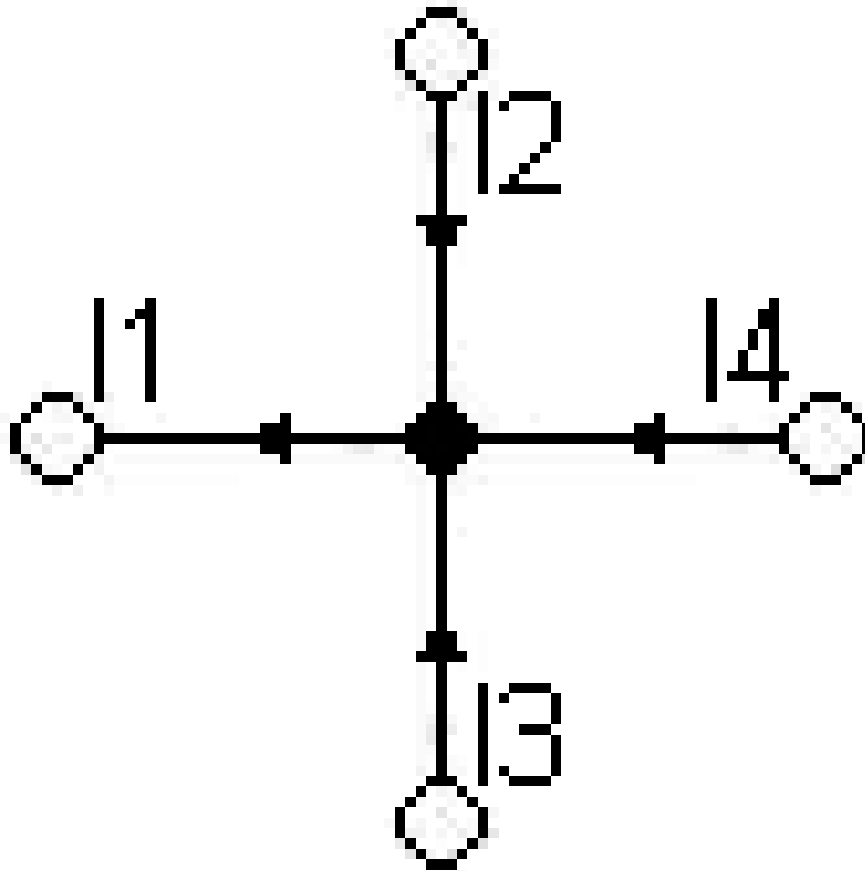
Figure 114

I_1 - I_2 - I_3 - $I_4 = 0 \leftrightarrow I_2 + I_3 + I_4 = I_1$

$$I_1 = I_2 + I_3 + \cdots + I_n$$

Here is more about Kirchhoff's laws[1], which can be integrated here

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1   http://en.wikipedia.org/wiki/Kirchhoff%27s%20laws

11.5 Consequences of KVL and KCL

Voltage Dividers

If two circuit elements are in series, there is a voltage drop across each element, but the current through both must be the same. The voltage at any point in the chain divides according to the resistances. A simple circuit with two (or more) resistors in series with a source is called a voltage divider[2].
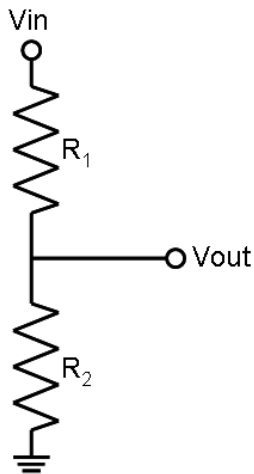
Figure 115

Figure A: Voltage Divider circuit.

Consider the circuit in Figure A. According to KVL the voltage V_{in} is dropped across resistors R_1 and R_2. If a current i flows through the two series resistors then by Ohm's Law.

$$i = \frac{V_{in}}{R_1 + R_2}$$

So

$$V_{out} = iR_2$$

Therefore

$$V_{out} = \frac{V_{in}R_2}{R_1 + R_2}$$

Similary if V_{R1} is the voltage across R_1 then

---

2   http://en.wikibooks.org/wiki/Electronics%2FVoltage%20Dividers

$$V_{R1} = \frac{V_{in} R_1}{R_1 + R_2}$$

In general for n series resistors the voltage dropped across one of them say R_i is

$$V_{Ri} = \frac{V_{in} R_i}{R_{eq}}$$

Where

$$R_{eq} = R_1 + \cdots + R_n$$

Voltage Dividers as References

Clearly voltage dividers can be used as references. If you have a 9 volt battery and you want 4.5 volts, then connect two equal valued resistors in series and take the reference across the second and ground. There are clearly other concerns though, the first concern is current draw and the effect of the source impedance. Clearly connecting two 100 ohm resistors is a bad idea if the source impedance is, say, 50 ohms. Then the current draw would be 0.036 mA which is quite large if the battery is rated, say, 200 milliampere hours. The loading is more annoying with that source impedance too, the reference voltage with that source impedance is $\frac{9(100)}{250} = 3.6$ V. So clearly, increasing the order of the resistor to at least 1 kΩ is the way to go to reduce the current draw and the effect of loading. The other problem with these voltage divider references is that the reference cannot be loaded if we put a 100 Ω resistor in parallel with a 10 kΩ resistor. When the voltage divider is made of two 10 kΩ resistors, then the resistance of the reference resistor becomes somewhere near 100 Ω. This clearly means a terrible reference. If a 10 MΩ resistor is used for the reference resistor will still be some where around 10 kΩ but still probably less. The effect of tolerances is also a problem; if the resistors are rated 5% then the resistance of 10 kΩ resistors can vary by ±500 Ω. This means more inaccuracy with this sort of reference.

Current Dividers

If two elements are in parallel, the voltage across them must be the same, but the current divides according to the resistances. A simple circuit with two (or more) resistors in parallel with a source is called a current divider[3].

---

3   http://en.wikibooks.org/wiki/Electronics%2FCurrent%20Dividers
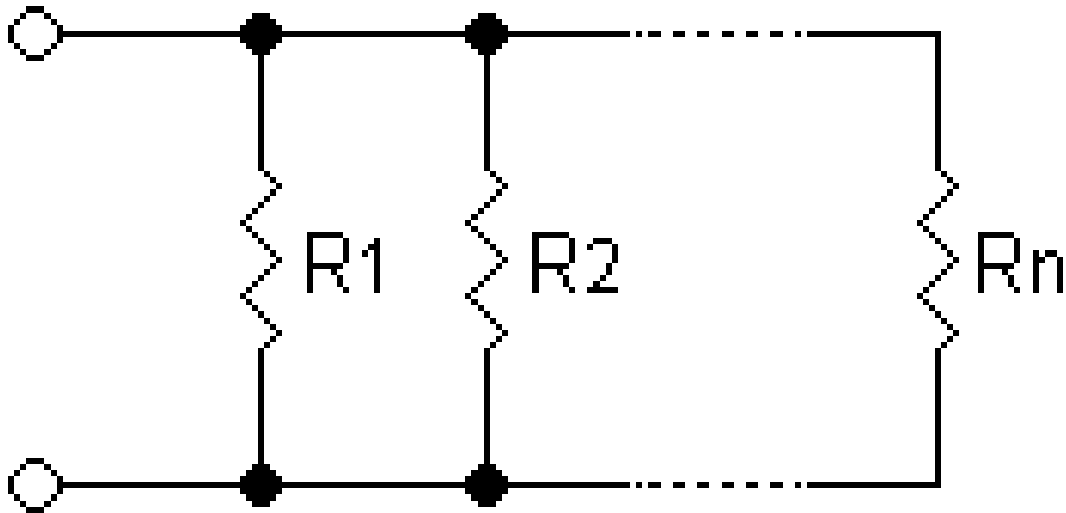
Figure 116

Figure B: Parallel Resistors.

If a voltage V appears across the resistors in Figure B with only R_1 and R_2 for the moment then the current flowing in the circuit, before the division, i is according to Ohms Law.

$$i = \frac{V}{R_{eq}}$$

Using the equivalent resistance for a parallel combination of resistors is

$i = \frac{V(R_1+R_2)}{R_1 R_2}$ (1)

The current through R_1 according to Ohms Law is

$i_1 = \frac{V}{R_1}$ (2)

Dividing equation (2) by (1)

$$i_1 = \frac{iR_2}{R_2 + R_1}$$

Similarly

$$i_2 = \frac{iR_1}{R_2 + R_1}$$

In general with n Resistors the current i_x is

$$i_x = \frac{iR_1 R_2 \cdots R_n}{(R_2 \cdots R_n + \cdots + R_1 \cdots R_{n-1})R_x}$$

Or possibly more simply

$$\frac{i_x}{i} = \frac{R_{eq}}{R_x}$$

Where

$$R_{eq} = \frac{R_1 \cdots R_n}{R_2 \cdots R_n + \cdots + R_1 \cdots R_{n-1}}$$

12 Nodal Analysis

12.1 Nodes

A node is a section of a circuit which connects components to each other. All of the current entering a node must leave a node, according to Kirchoff's Current Law. Every point on the node is at the same voltage, no matter how close it is to each component, because the connections between components are perfect conductors. This voltage is called the node voltage, and is the voltage difference between the node and an arbitrary reference, the ground point. The ground point is a node which is defined as having zero voltage. The ground node should be chosen carefully for convenience. Note that the ground node does not necessarily represent an actual connection to ground, it is just a device to make the analysis simpler. For example, if a node has a voltage of 5 Volts, then the voltage drop between that node and the ground node will be 5 Volts.

Note that in real circuits, nodes are made up of wires, which are not perfect conductors, and so the voltage is not perfectly the same everywhere on the node. This distinction is only important in demanding applications, such as low noise audio, high speed digital circuits (like modern computers), etc. If we look at how a particular circuit functions an engineer might be able to select check points that are diametrically apposite of each other, this signafies two points of current crossing over to another point this can be another method in testing a circuit to determine how nodes work.

12.2 Nodal Analysis

Nodal analysis is a formalized procedure based on KCL equations.

Steps:

1. Identify all nodes.
2. Choose a reference node. Identify it with reference (ground) symbol. A good choice is the node with the most branches, or a node which can immediately give you another node voltage (e.g., below a voltage source).
3. Assign voltage variables to the other nodes (these are node voltages.)
4. Write a KCL equation for each node (sum the currents leaving the node and set equal to zero). Rearrange these equations into the form A*V1+B*V2=C (or similar for equations with more voltage variables.)
5. Solve the system of equations from step 4. There are a number of techniques that can be used: simple substitution, Cramer's rule, the adjoint matrix method, etc.

12.3 Complications in Nodal Analysis

1. Dependent Current Source
   Solution: Write KVL equations for each node. Then express the extra variable (whatever the current source depends on) in terms of node voltages. Rearrange into the form from step 4 above. Solve as in step 5.
2. Independent Voltage Source
   Problem: We know nothing about the current through the voltage source. We cannot write KCL equations for the nodes the voltage source is connected to.
   Solution: If the voltage source is between the reference node and any other node, we have been given a 'free' node voltage: the node voltage must be equal to the voltage source value! Otherwise, use a 'super-node', consisting of the source and the nodes it is connected to. Write a KCL equation for all current entering and leaving the super-node. Now we have one equation and two unknowns (the node voltages). Another equation that relates these voltages is the equation provided by the voltage source (V2-V1=source value). This new system of equations can be solved as in Step 5 above.
3. Dependent Voltage Source
   Solution: Same as an independent voltage source, with an extra step. First write a super-node KCL equation. Then write the source controlling quantity (dependence quantity?) in terms of the node voltages. Rearrange the equation to be in the A*V1+B*V2=C form. Solve the system as above.

12.4 Example

Given the Circuit below, find the voltages at all nodes.
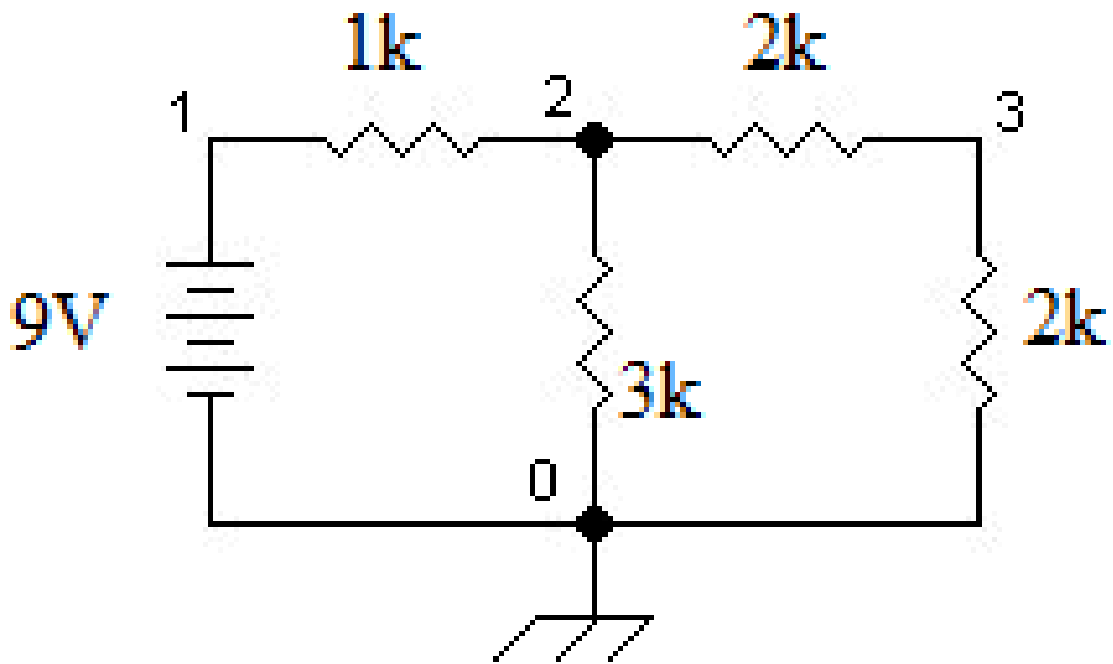
Figure 117

node 0: $V_0 = 0V$ (defined as ground node)

node 1: $V_1 = 9V$ (free node voltage)

node 2: $\frac{V_1 - V_2}{1k} = \frac{V_2 - V_0}{3k} + \frac{V_2 - V_3}{2k}$

node 3: $\frac{V_2 - V_3}{2k} = \frac{V_3 - V_0}{2k}$

which results in the following system of linear equations: $\begin{cases} +11V_2 & -3V_3 & = & 54 \\ +1V_2 & -2V_3 & = & 0 \end{cases}$

therefore, the solution is: $\begin{cases} V_0 = 0.00V \\ V_1 = 9.00V \\ V_2 = 5.68V \\ V_3 = 2.84V \end{cases}$

Another solution with KCL would be to solve node in terms of node 2;

$\frac{V_2 - 9V}{1k} + \frac{V_2}{3k} + \frac{V_2}{4k} = 0$

12.5 External Links

- Free Nodal Analysis EBook by Dr. Yaz Li[1]

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1   http://circuits.solved-problems.com/nodal-analysis/

13 Mesh Analysis

13.1 Meshes

A 'mesh' (also called a loop) is simply a path through a circuit that starts and ends at the same place. For the purpose of mesh analysis, a mesh is a loop that does not enclose other loops.

13.2 Mesh Analysis

Similar to nodal analysis, mesh analysis is a formalized procedure based on KVL equations. A caveat: mesh analysis can only be used on 'planar' circuits (i.e. there are no crossed, but unconnected, wires in the circuit diagram.)

Steps:

1. Draw circuit in planar form (if possible.)
2. Identify meshes and name mesh currents. Mesh currents should be in the clockwise direction. The current in a branch shared by two meshes is the difference of the two mesh currents.
3. Write a KVL equation in terms of mesh currents for each mesh.
4. Solve the resulting system of equations.

13.3 Complication in Mesh Analysis

1. Dependent Voltage Sources

Solution: Same procedure, but write the dependency variable in terms of mesh currents.

2. Independent Current Sources

Solution: If current source is not on a shared branch, then we have been given one of the mesh currents! If it is on a shared branch, then use a 'super-mesh' that encircles the problem branch. To make up for the mesh equation you lose by doing this, use the mesh current relationship implied by the current source (i.e. $I_2 - I_1 = 4mA$).

3. Dependent Current Sources

Solution: Same procedure as for an independent current source, but with an extra step to eliminate the dependency variable. Write the dependency variable in terms of mesh currents.

13.4 Example

Given the Circuit below, find the currents I_1, I_2.
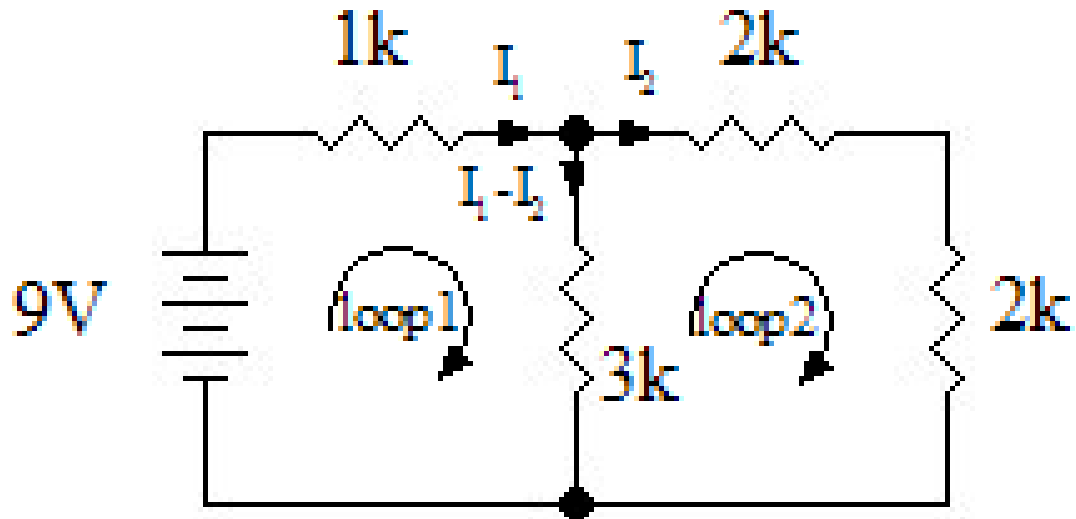
Figure 118

The circuit has 2 loops indicated on the diagram. Using KVL we get:

Loop1: $0 = 9 - 1000I_1 - 3000(I_1 - I_2)$

Loop2: $0 = 3000(I_1 - I_2) - 2000I_2 - 2000I_2$

Simplifying we get the simultaneous equations:

$0 = 9 - 4000I_1 + 3000I_2$

$0 = 0 + 3000I_1 - 7000I_2$

solving to get:

$I_1 = 3.32mA$

$I_2 = 1.42mA$

14 Thevenin and Norton Equivalent Circuits

14.1 Source Transformation

Any linear time invariant network of impedances can be reduced to one equivalent impedance. In particular, any network of sources and resistors can be reduced to one ideal source and one resistor, in either the Thevenin or Norton configurations. In this way, a complicated network attached to a load resistor can be reduced to a single voltage divider (Thevenin) or current divider (Norton).
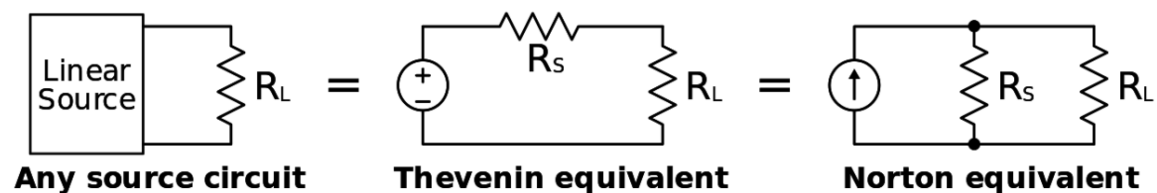
Figure 119

Thevenin and Norton equivalents let you replace a Voltage source in series with a resistor by a current source in parallel with a resistor, or vice versa. This is called a source transformation.

The point to be noted is that the block that is replaced with such an equivalent should be linear and time invariant, i.e. a linear change in the electrical source in that block produces a linear change in the equivalent source, and the behavior can be replicated if the initial conditions are replicated. **The above shown transformation figures are true only if the circuit contains at least one independent voltage or current source. If the circuit comprises only dependent sources then Thevenin equivalent consists of $\mathbf{R}_{\text{Th}}$ alone**

14.2 Thevenin Equivalents

The Thevenin equivalent circuit of a (two-terminal) network consists of a voltage source in series with a resistor. The Thevenin equivalent will have the same output voltage and current regardless of what is attached to the terminals.

14.3 Techniques For Finding Thevenin Equivalents

- Network contains no sources (only resistors): The Thevenin resistance is equal to the equivalent resistance of the network. The Thevenin voltage is zero.

- Basic: Works for any network except one with no independent sources. Find the voltage across the terminals (with positive reference at terminal A) when they are open-circuited. Find the current from terminal A to terminal B when they are short-circuited. Then

$$R_{th} = \frac{V_{oc}}{I_{sc}}$$

The Thevenin voltage source value is equivalent to the open-circuit voltage.

If the network has no dependent sources, the independent sources can be zeroed, and the Thevenin resistance is equal to the equivalent resistance of the network with zeroed sources. Then, find V_{oc}.

- Only Dependent Sources:

If the network has only dependent sources, either attach a test voltage source to the terminal points and measure the current that passes from the positive terminal, or attach a test current source to the terminal points and measure the voltage difference across the terminals. In both cases you will have values for V_{oc} and I_{sc}, allowing you to use the $R_{th} = \frac{V_{oc}}{I_{sc}}$ relation to find the Thevenin resistance.

14.4 Norton Equivalents

Norton equivalents can be found by performing a source transformation on the Thevenin equivalent. The Norton Equivalent of a Thevenin Equivalent consists of a current source, $I_N = \frac{V_{th}}{R_{th}}$ in parallel with R_{th}.

14.5 Thevenin and Norton Equivalent
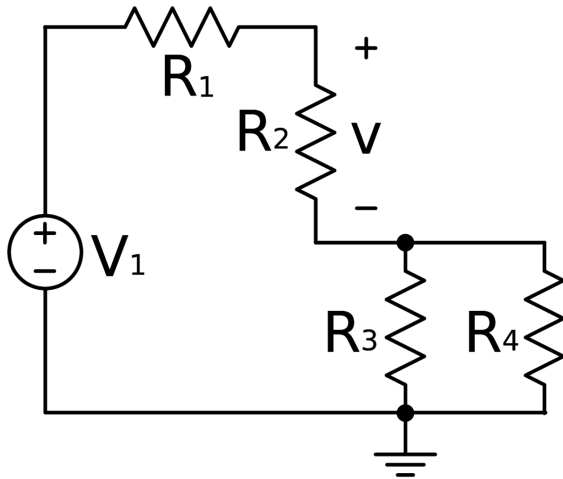
Figure 120 Figure 1: Circuit for the determination of Equivalents

The steps for creating the Equivalent are:

1. Remove the load circuit.

2. Calculate the voltage, V, at the output from the original sources.

3. Now replace voltage sources with shorts and current sources with open circuits.

4. Replace the load circuit with an imaginary ohm meter and measure the total resistance, R, looking back into the circuit, with the sources removed.

5. The equivalent circuit is a voltage source with voltage V in series with a resistance R in series with the load.

The Thevenin Equivalent is determined with R_2 as the load as shown in Figure 1. The first step is to open circuit R_2. Then the voltage v is calculated with R_2 open circuited must be calculated. The voltage across R_2 is V_1 this is because no current flows in the circuit so the voltage across R_2 must be V_1 by KVL.

Since this circuit does not contain any dependent sources, all that needs to be done is for all the Independent Voltage sources to be shorted and for all Independent Current Sources to be open circuited. This results in the circuit shown in Figure 2.
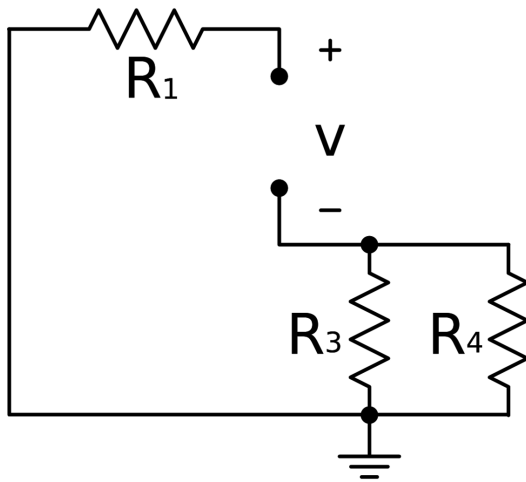
Figure 121 Figure 2: Circuit for the Equivalent Resistance

Now the Thevenin Resistance is calculated looking into the two nodes. The Thevenin resistance is clearly $R_1 + R_3 || R_4$. The Thevenin Equivalent is shown in Figure 3 and R_{th} and V_{th} have the values shown below.

$R_{th} = R_1 + R_3 || R_4$ (1)

$V_{th} = V_1$
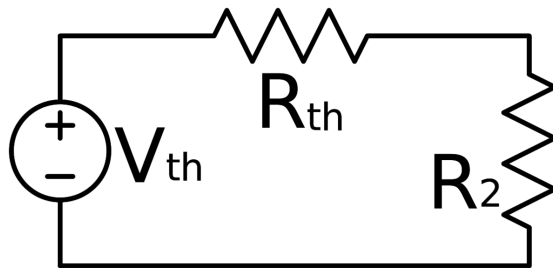
Figure 122 Figure 3: Equivalent Thevenin Circuit

The Norton Equivalent is created by doing a source transformation using $I_N = \frac{V_{th}}{R_{th}}$.(2)
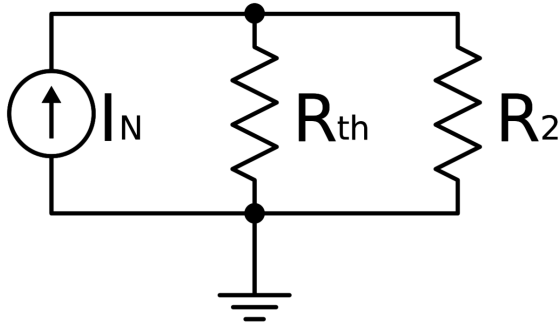
Figure 123   Figure 4: Equivalent Norton
Circuit

If $R_2 = R_1 = 6k\Omega$ and $R_3 = R_4 = 2k\Omega$ and $V_1 = 15V$ then

$$R_{th} = 1k + 4k||4k$$

$$R_{th} = 6k\Omega$$

As a final note if the voltage across R_2 is calculate by Voltage Divider Rule using the Thevenin Equivalent circuit in Figure 3.

$V_{R2} = \frac{V_{th}R_2}{R_{th}+R_2}$ (3)

If the value of R_{th} form equation 1 is substituted into equation 3.

$V_{R2} = \frac{V_{th}R_2}{R_1+R_3||R_4+R_2}$ (4)

Now look at Figure 1 and calcute V_{R2} by voltage divider rule it has the same value as equation 4. If the current through R_2 is calculated in Figure 4 by current divider rule.

$$I_{R2} = \frac{I_N R_{th}}{R_{th} + R_2}(5)$$

Substituting equation 2 into 5.

$$I_{R2} = \frac{V_{th}}{R_{th} + R_2}(4)$$

If equation 4 and Ohm's Law are used to get the voltage across R_2 equation 3 is reached.

Please note: The "||", a symbol that is used as an operator here, holds higher precedence than the "+" operator. As such, it is evaluated before a sum.

See Norton's theorem[1] and Thevenin's theorem[2] for more examples.

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1   http://en.wikipedia.org/wiki/Norton%27s%20theorem
2   http://en.wikipedia.org/wiki/Thevenin%27s%20theorem

15 Superposition

15.1 Superposition Principle
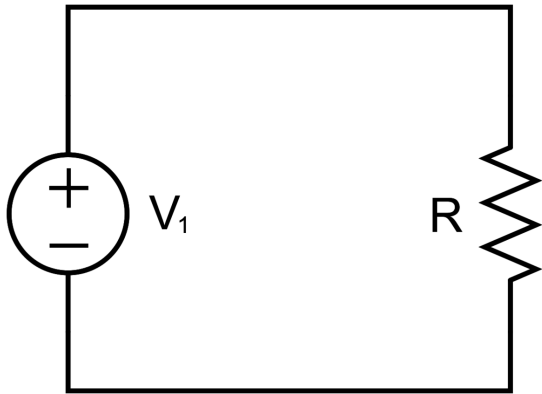
Figure 124

(a)
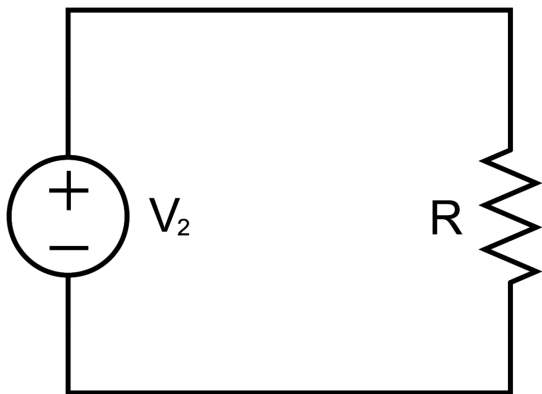
Figure 125

(b)
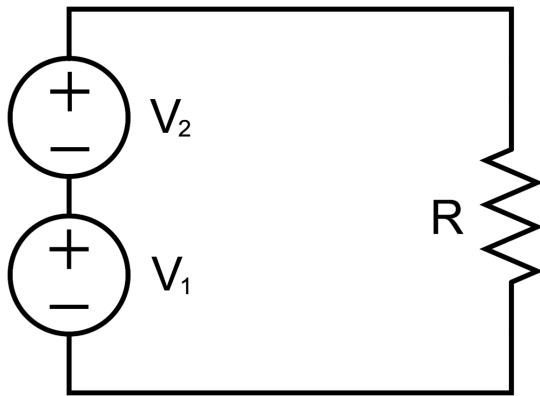
Figure 126

(c)

Figure 1: The circuits showing the linearity of resistors.

Most basic electronic circuits are composed of linear elements. Linear elements are circuit elements which follow Ohm's Law. In Figure 1 (a) with independent voltage source, V_1, and resistor, R, a current i_1 flows. The current i_1 has a value according to Ohm's Law. Similarly in Figure 1 (b) with independent voltage source, V2, and resistor, R, a current i_2 flows. In Figure 1 (c) with independent voltage sources, V1 and V2, and resistor, R, a current i flows. Using Ohm's Law equation 1 is reached. If some simple algebra is used then equation 2 is reached. But V_1/R has a value i_1 and the other term is i_2 this gives equation 3. This is basically what the Superposition Theorem states.

$i = \frac{V_1 + V_2}{R} (1)$

$i = \frac{V_1}{R} + \frac{V_2}{R} (2)$

$i = i_1 + i_2 (3)$

The **Superposition Theorem** states that the effect of all the sources with corresponding stimuli on a circuit of linear elements is equal to the algebraic sum of each individual effect. Each individual effect is calculated by removing all other stimuli by replacing voltage sources with short circuits and current sources with open circuits. Dependent sources can be removed as long as the controlling stimuli is not set to zero. The process of calculating each effect with one stimulus connected at a time is continued until all the effects are calculated. If kth stimulus is denoted sk and the effect created by sk denoted ek.

$\sum_{k=1}^{N} e_k (4)$

The steps for using superposition are as follows:

1. Calculate the effect of each source in turn with all other independent voltage sources short circuited and independent current sources open circuited.

2. Sum these effects to get the complete effect.

Note: the removal of each source is often stated differently as: replace each voltage source with its internal resistance and each current with its internal resistance. This is identical to

what has been stated above. This is because a real voltage source consists of an independent voltage source in series with its internal resistance and a real current source consists of an independent current source in parallel with its internal resistance.

15.1.1 Superposition Example
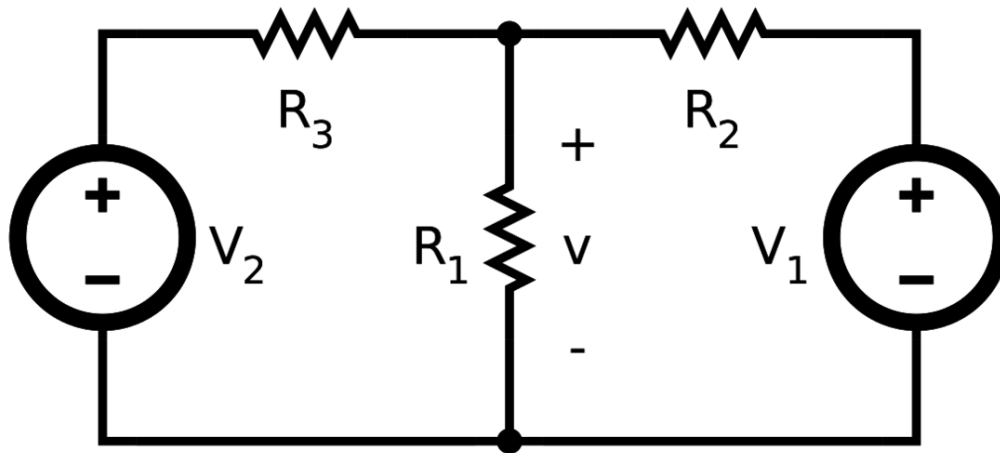
Figure 127

Figure 2: The circuit for the example.

Problem: Calculate the voltage, v, across resistor R_1.

Step 1: Short circuit V_2 and solve for v_1. By voltage divider rule.

$v_1 = \frac{V_1(R_1||R_3)}{R_2+(R_1||R_3)}(5)$

Short circuit V_1 and solve for v_2. By voltage divider rule.

$v_2 = \frac{V_2(R_1||R_2)}{R_3+(R_1||R_2)}(6)$

Step 2: Sum the effects.

$$v = v_1 + v_2$$

Using equations 5 and 6.

$$v = \frac{V_1(R_1||R_3)}{R_2+(R_1||R_3)} + \frac{V_2(R_1||R_2)}{R_3+(R_1||R_2)}$$

If $R_1 = R_2 = R_3 = 2k\Omega$ and $V_1 = V_2 = 15V$ then

$$v = \frac{15(2k||2k)}{2k + (2k||2k)} + \frac{15(2k||2k)}{2k + (2k||2k)}$$

$$v = \frac{15(1k)}{3k} + \frac{15(1k)}{3k}$$

$$v = 10V$$

16 Diagnostic Equipment

17 Diagnostic and Testing Equipment

There is a wide array of devices used to test and diagnose electronic equipment. This chapter will attempt to explain the differences and different types of equipment used by electronics technicians and engineers.

17.1 Ammeter

An ammeter measures current.Current in electronics is usually measured in mA which are called milliamperes, which are 1/1000s of an ampere.
. The ammeter's terminals must be *in series* with the current being measured. Ammeters have a small resistance (typically 50 ohms) so that they only have a small effect on the current.
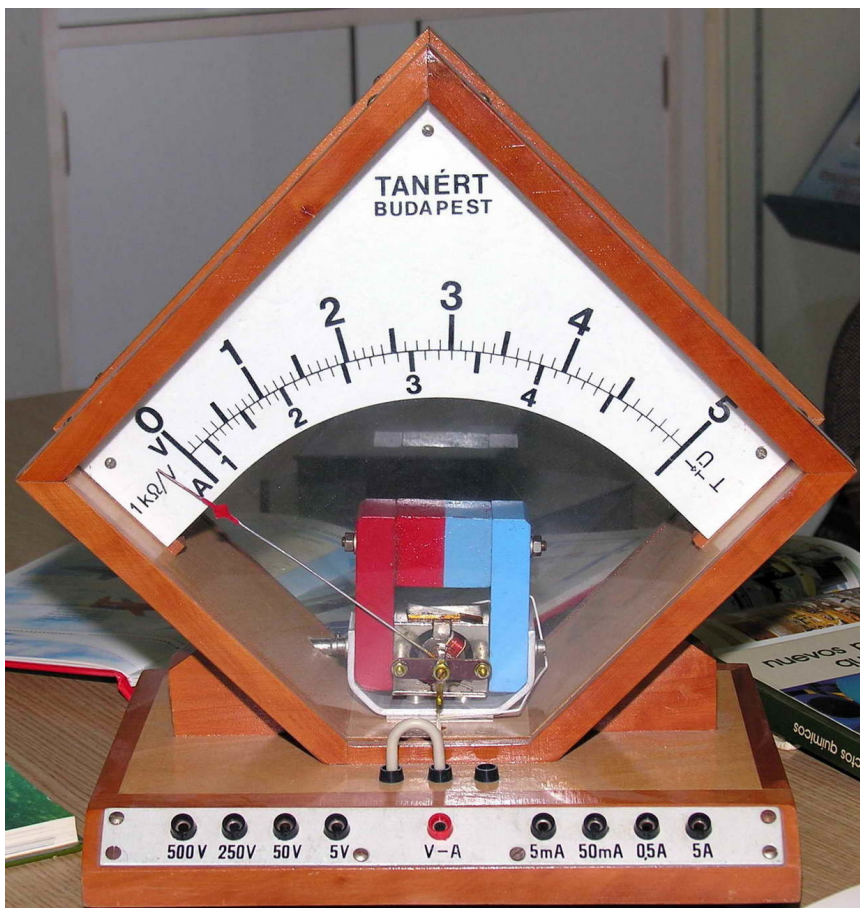
Figure 128

Basically an ammeter consists of a coil that can rotate inside a magnet, but a spring is trying to push the coil back to zero. The larger the current that flows through the coil, the larger the angle of rotation, the torque (= a rotary force) created by the current being counteracted by the return torque of the spring.

. Usually ammeters are connected in parallel with various switched resistors that can extend the range of currents that can be measured. Assume, for example, that the basic ammeter is "1000 ohms per volt", which means that to get the full-scale deflection of the pointer a current of 1 mA is needed (1 volt divided by 1000 ohms is 1 mA - see "Ohm's Law").

. To use that ammeter to read 10 mA full-scale it is *shunted* with another resistance, so that when 10 mA flows, 9 mA will flow through the shunt, and only 1 mA will flow through the meter. Similarly, to extend the range of the ammeter to 100 mA the shunt will carry 99 mA, and the meter only 1 mA.

17.2 Ohmmeter

An ohmmeter measures resistance.The two terminals of ohmmeter are each placed on a terminal of the resistance being measured. This resistance should be isolated from other effects. (It should be taken out of a circuit, if it is in one.)

Ohmmeters are basically ammeters that are *connected to an internal battery, with a suitable resistance in series* . Assume that the basic ammeter is "1000 ohms per volt", meaning that 1 mA is needed for full-scale deflection. When the external resistance that is connected to its terminals is zero (the leads are connected together at first for calibration), then the internal, variable, resistor in series with the ammeter is adjusted so that 1 mA will flow; that will depend on the voltage of the battery, and as the battery runs down that setting will change. The full scale point is marked as zero resistance. If an external resistance is then connected to the terminals that causes only half of the current to flow (0.5 mA in this example), then the external resistance will equal the internal resistance, and the scale is marked accordingly. When no current flows, the scale will read infinity resistance. The scale of an ohmmeter is NOT linear.Ohmmeters are usually usuful in cheking the short circuit and open circuit in boards.

17.3 Voltmeter

A voltmeter measures voltage.The voltmeter's terminals must be *in parallel* with the voltage being measured. Voltmeters have a large resistance (typically 1 megaohm), so that they only have a small effect on the voltage.

Figure 129

17.4 Multimeter
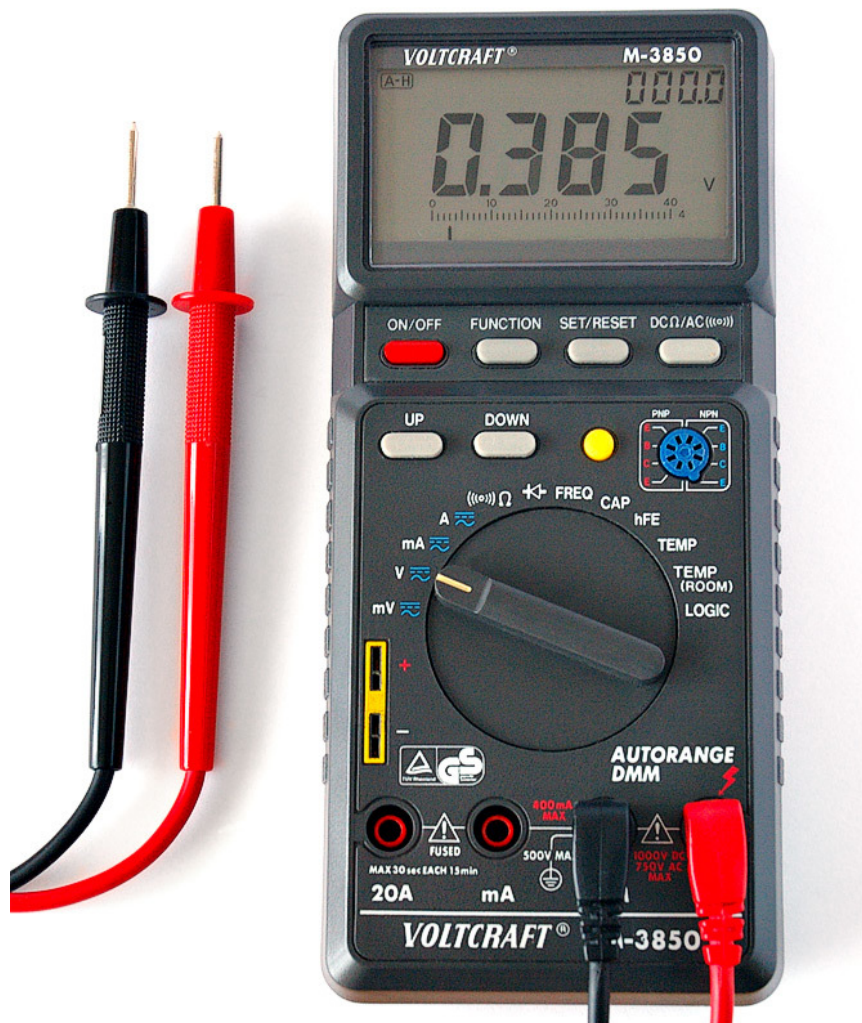
Figure 130

A multimeter is a combination device, (usually) capable of measuring current, resistance, or voltage. Most modern models measure all three, and include other features such as a diode tester, which can be used to measure continuity in circuits (emitting a loud 'beep' if there is a short).

17.5 Oscilloscope

An oscilloscope, commonly called a 'scope' by technicians, is used to display a voltage waveform on a screen, usually graphing voltage as a function of time.

Figure 131

17.6 Spectrum Analyzer

Spectrum analyzer shows voltage (or power) densities as function of frequency on radio frequency spectrum. Spectrum analyzer can use analog frequency scanning principle (like radio receiver always changing frequency and measuring receiving amplitude) or digital sampling and FFT (Fast Fourier Transformation).

Figure 132

17.7 Logic analyzer

A logic analyzer is, in effect, a specialised oscilloscope. The key difference between an analyzer and an oscilloscope is that the analyzer can only display a digital (on/off) waveform, whereas an oscilloscope can display any voltage (depending on the type of probe connected). The other difference is that logic analyzers tend to have many more signal inputs than oscilloscopes - usually 32 or 64, versus the two channels most oscilloscopes provide. Logic analyzers can be very useful for debugging complex logic circuits, where one signal's state may be affected by many other signals.

Figure 133

17.8 Frequency counter

A frequency counter is a relatively simple instrument used to measure the frequency of a signal in Hertz (cycles per second). Most counters work by counting the number of signal cycles that occur in a given time period (usually one second). This count is the frequency of the signal in Hertz, which is displayed on the counter's display.

Figure 134

17.9 Electrometer

A voltmeter with extremely high input resistance capable of measuring electrical charge with minimal influence to that charge. Ubiquitous in nucleonics, physics and bio-medical disciplines. Enables the direct verification of charge measured in coulombs according to Q=CV. Additionally, electrometers can generally measure current flows in the femtoampere range, i.e. .000000000000001 ampere.

17.10 Signal Generator

Figure 135

18 DC Circuit Analysis

18.1 DC Circuit Analysis

In this chapter, capacitors and inductors will be introduced (without considering the effects of AC current.) The big thing to understand about Capacitors and Inductors in DC Circuits is that they have a transient (temporary) response. During the transient period, capacitors build up charge and stop the flow of current (eventually acting like infinite resistors.) Inductors build up energy in the form of magnetic fields, and become more conductive. In other words, in the steady-state (long term behavior), capacitors become open circuits and inductors become short circuits. Thus, for DC analysis, you can replace a capacitor with an empty space and an inductor with a wire. The only circuit components that remain are voltage sources, current sources, and resistors.

18.2 Capacitors and Inductors at DC
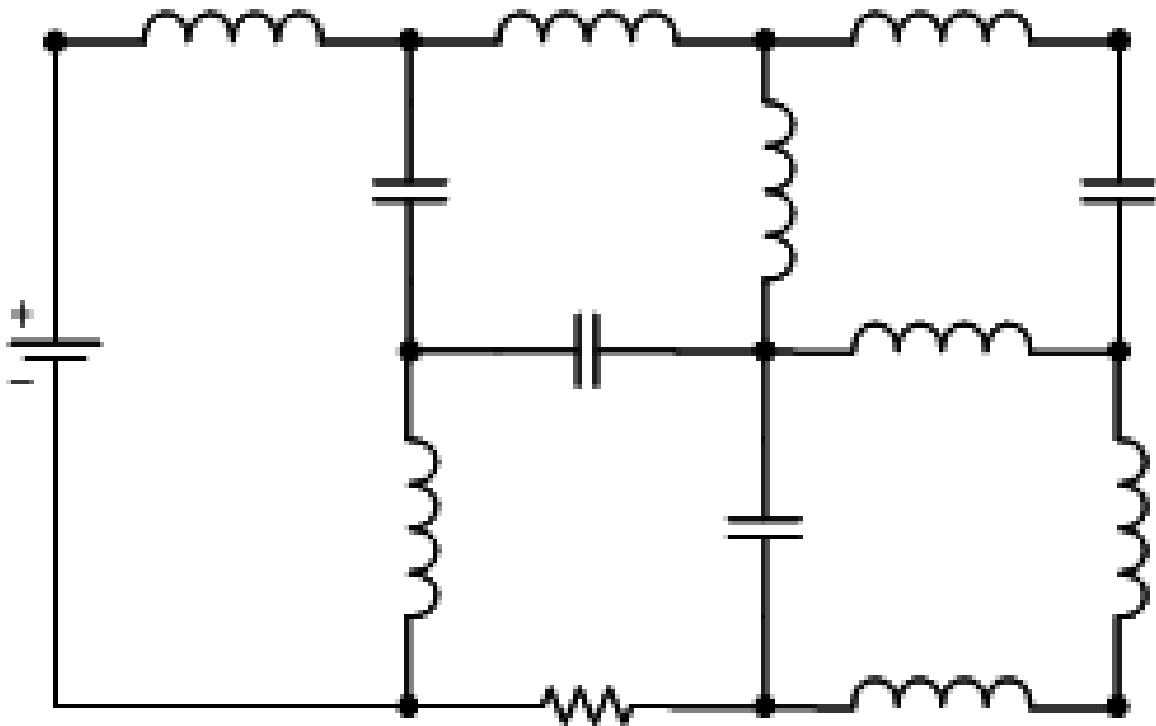
Figure 136
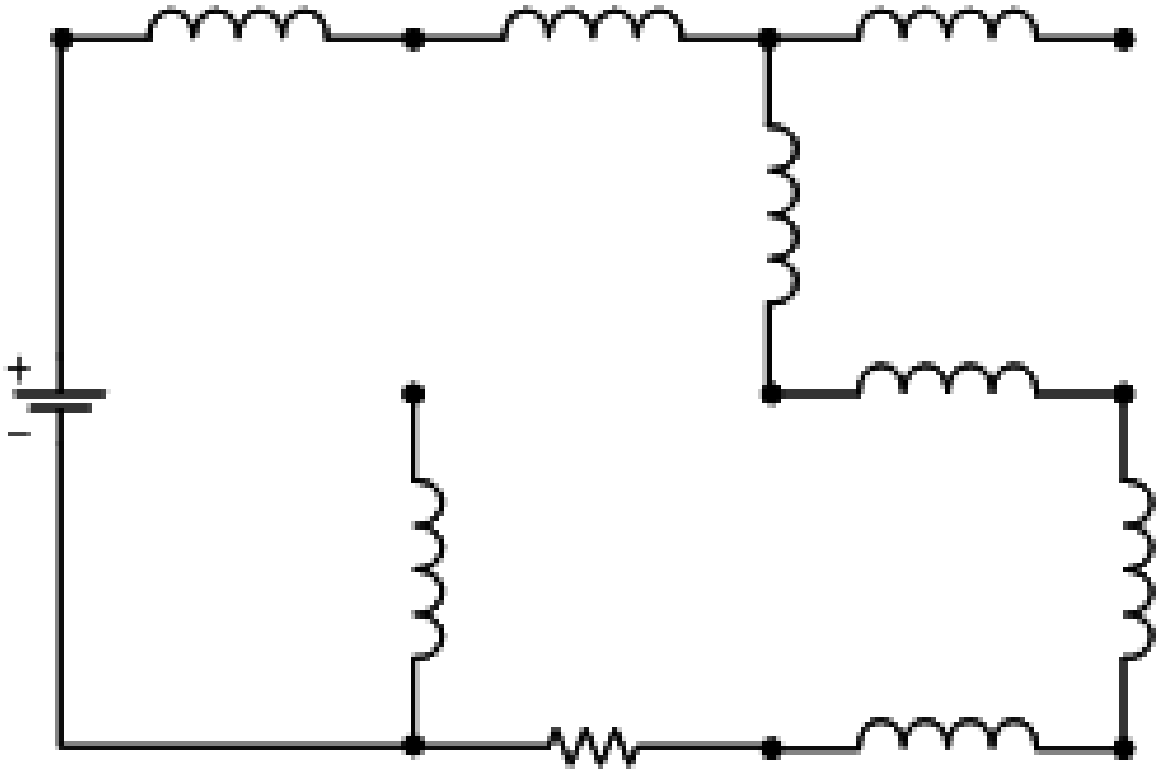
Figure 137
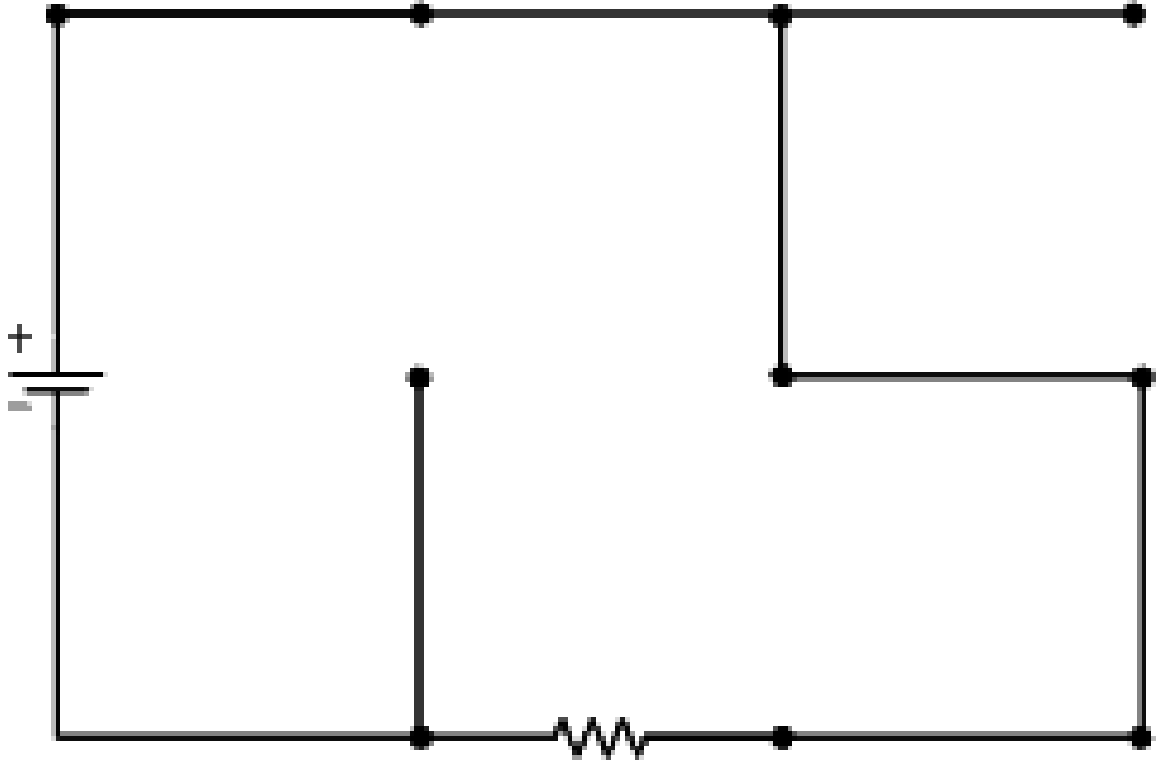
Figure 138
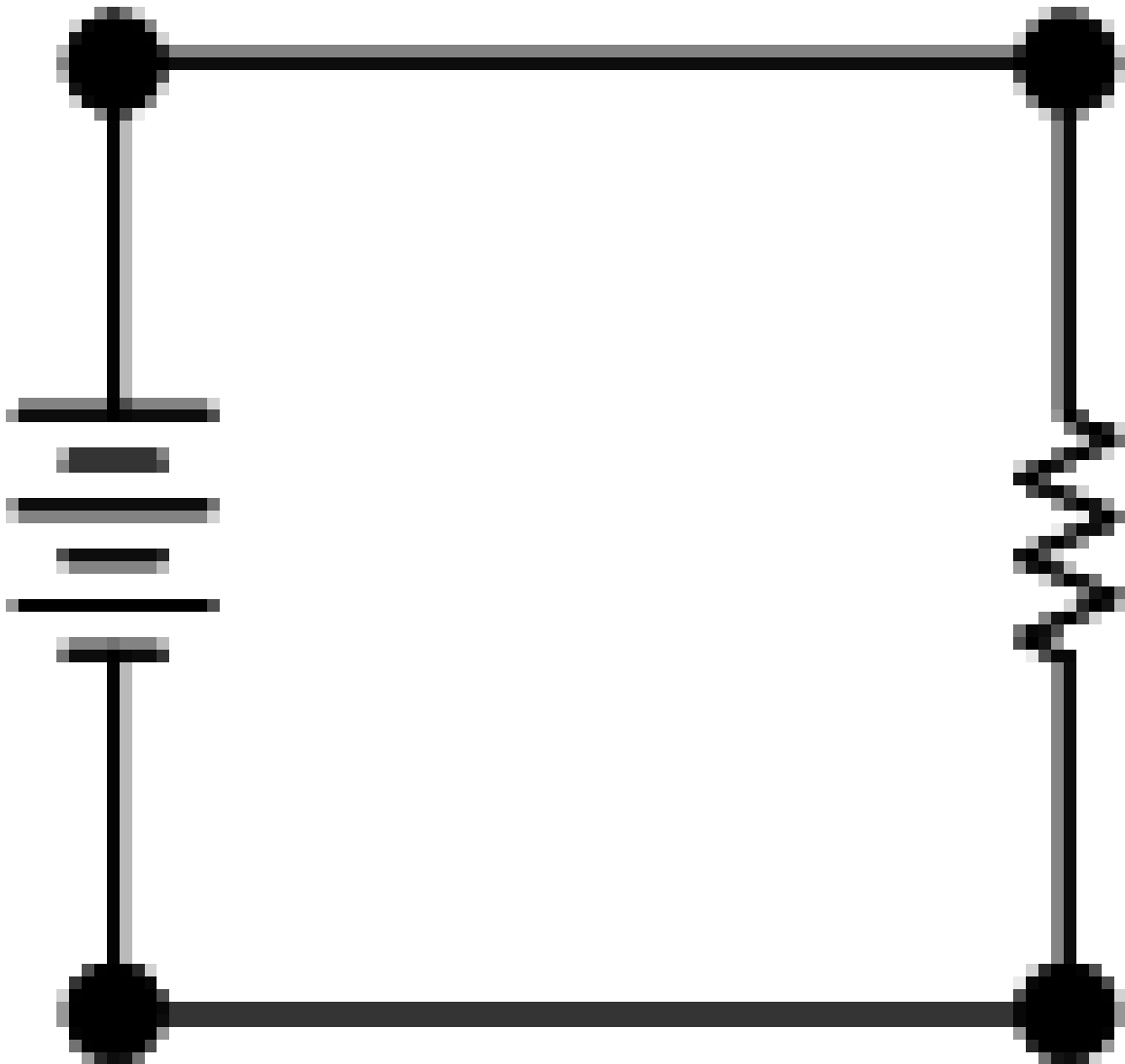
Figure 139

DC steady-state (meaning the circuit has been in the same state for a long time), we've seen that capacitors act like open circuits and inductors act like shorts. The above figures show the process of replacing these circuit devices with their DC equivalents. In this case, all that remains is a voltage source and a lone resistor. (An AC analysis of this circuit can be found in the AC section.)

18.3 Resistors

If a circuits contains only resistors possibly in a combination of parallel and series connections then an equivalent resistance is determined. Then Ohm's Law is used to determine the current flowing in the main circuit. A combination of voltage and current divider rules are then used to solve for other required currents and voltages.

Simplify the following:
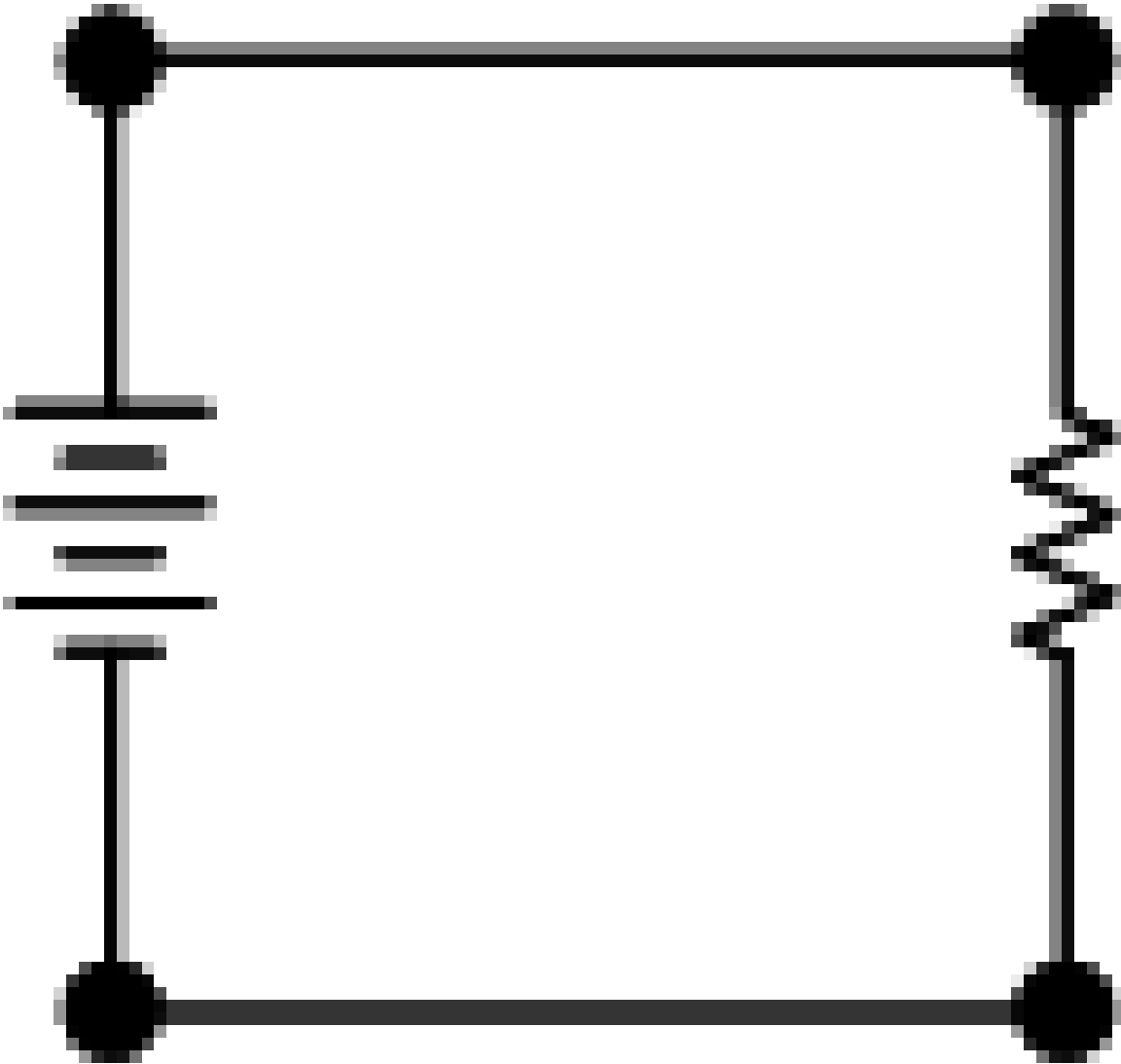
Figure 140

(a)
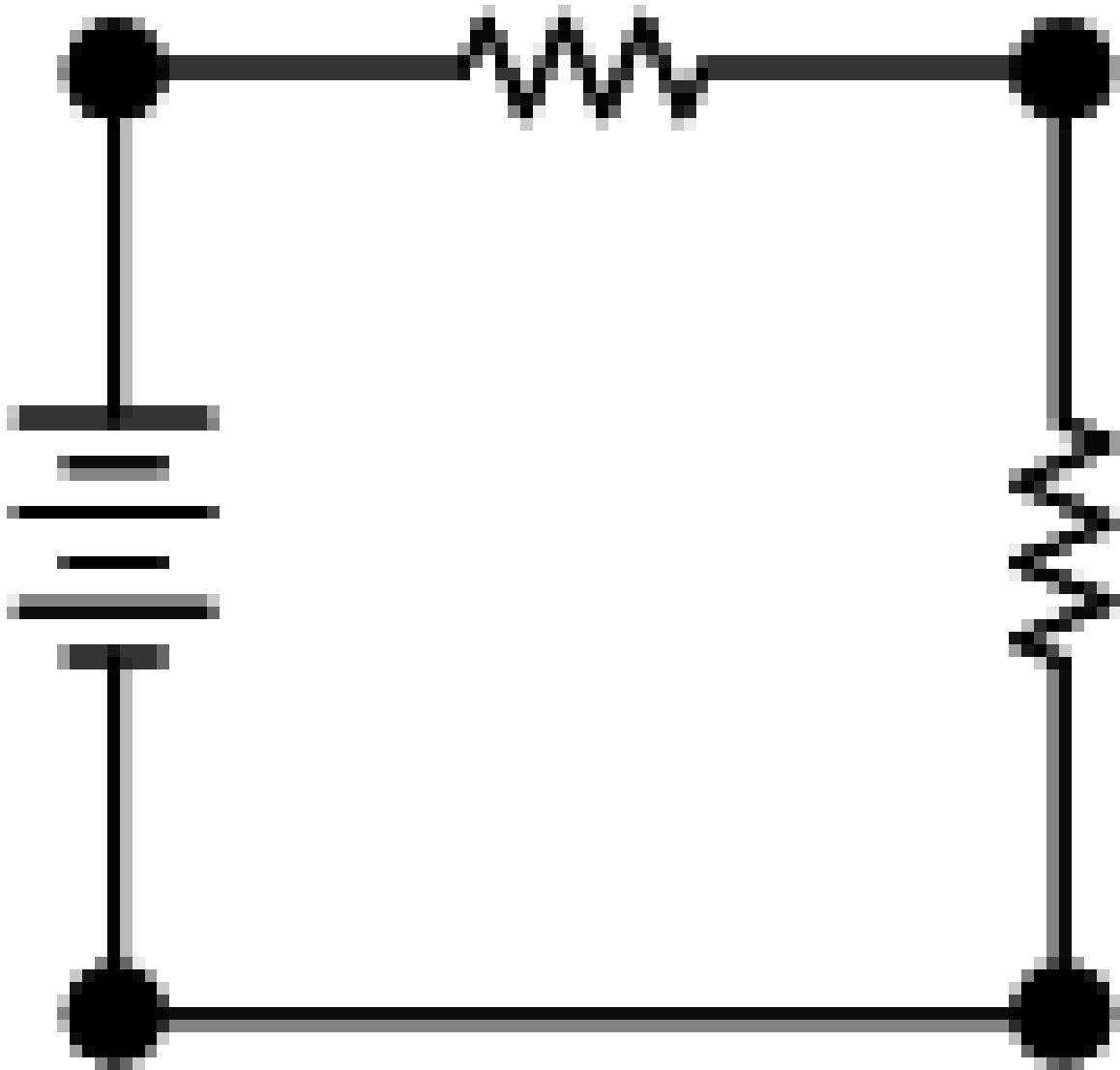
Figure 141

(b)
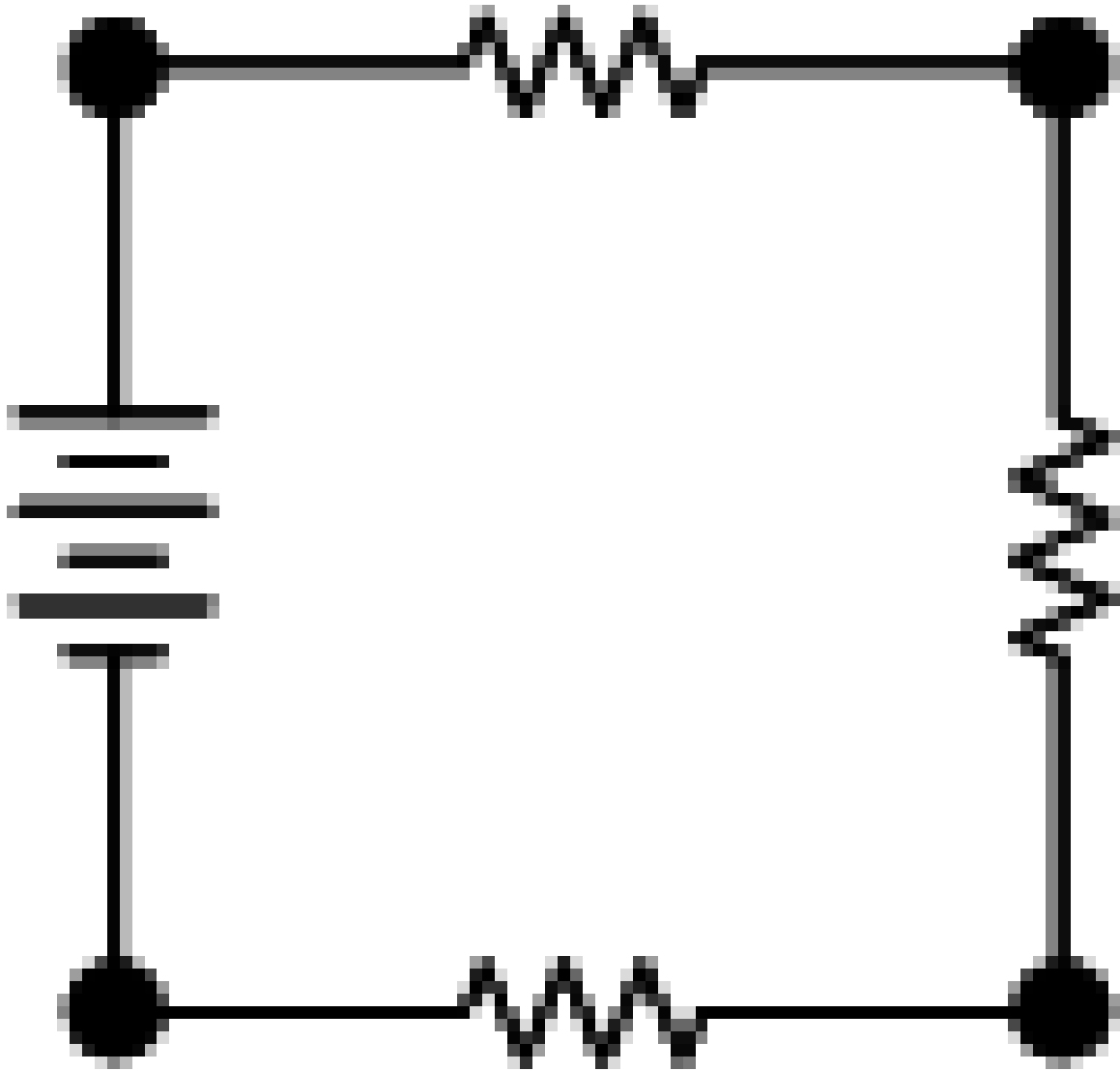
Figure 142

(c)

Figure 1: Simple circuits series circuits.

The circuit in Figure 1 (a) is very simple if we are given R and V, the voltage of the source, then we use Ohm's Law to solve for the current. In Figure 1 (b) if we are given R1, R2 and V then we combine the resistor into an equivalent resistors noting that are in series. Then we solve for the current as before using Ohm's Law. In Figure 1 (c) if the resistors are labeled clockwise from the top resistor R1, R2 and R3 and the voltage source has the value: V. The analysis proceeds as follows.

$$R_{eq} = R_1 + R_2 + R_3$$

This is the formula for calculating the equivalent resistance of series resistor. The current is now calculated using Ohm's Law.

$$i = \frac{V}{R_{eq}} = \frac{V}{R_1 + R_2 + R_3}$$

If the voltage is required across the third resistor then we can use voltage divider rule.

$$V_{R3} = \frac{V R_3}{R_1 + R_2 + R_3}$$

Or alternatively one could use Ohm's Law together with the current just calculated.

$$V_{R3} = i R_3 = \frac{V R_3}{R_1 + R_2 + R_3}$$
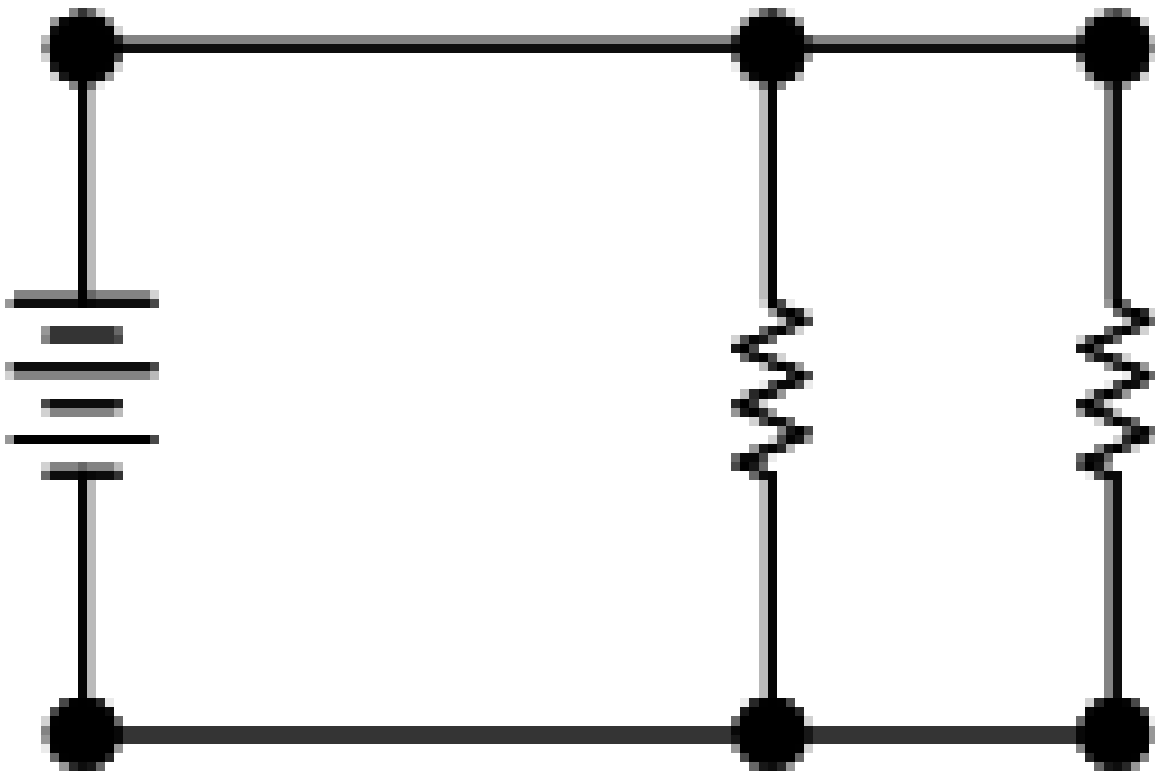
Figure 143

(a)
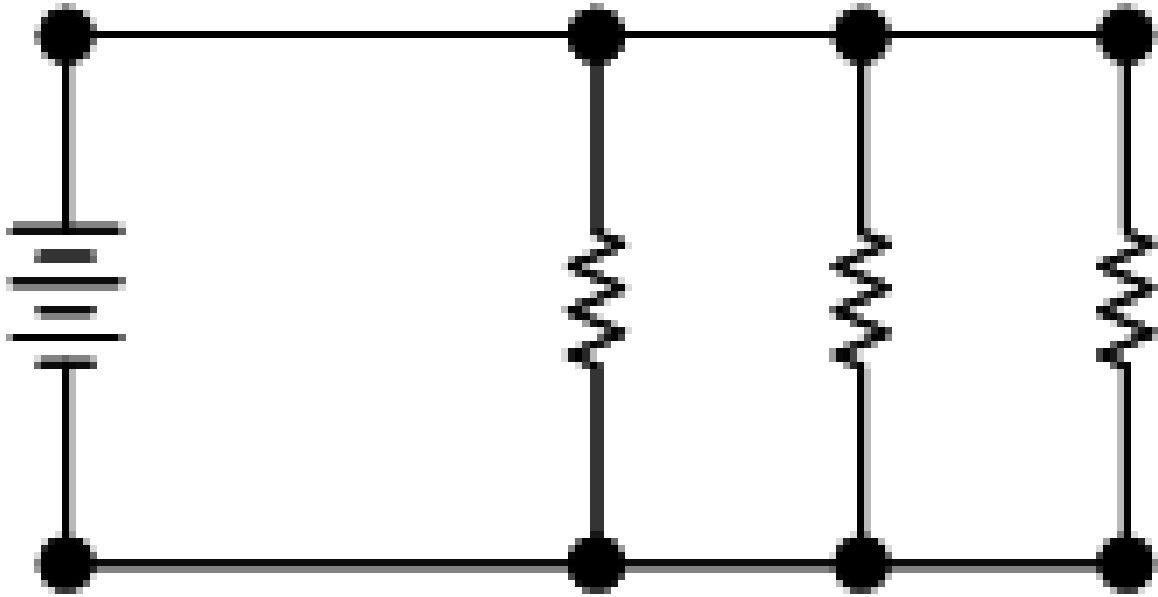
Figure 144

(b)

Figure 2: Simple parallel circuits.

In Figure 2 (a) if the Resistor nearest the voltage source is R1 and the other resistor R2. If we need to solve for the current i. then we proceed as before. First we calculate the equivalent resistance then use Ohm's Law to solve for the current. The resistance of a parallel combination is:

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

So the current, i , flowing in the circuit is, by Ohm's Law:

$$i = \frac{V(R_1 + R_2)}{R_1 R_2}$$

If we need to solve for current through R2 then we can use current divider rule.

$i_{R2} = \frac{V(R_1+R_2)(R_1)}{(R_1 R_2)(R_1+R_2)} = \frac{V}{R_2}(1)$

But it would probably have been simpler to have used the fact that V most be dropped across R2. This means that we can simply use Ohm's Law to calculate the current through R2. The equation is just equation 1. In Figure 2 (b) we do exactly the same thing except this time there are three resistors this means that the equivalent resistance will be:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$R_{eq} = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

Using this fact we do exactly the same thing.
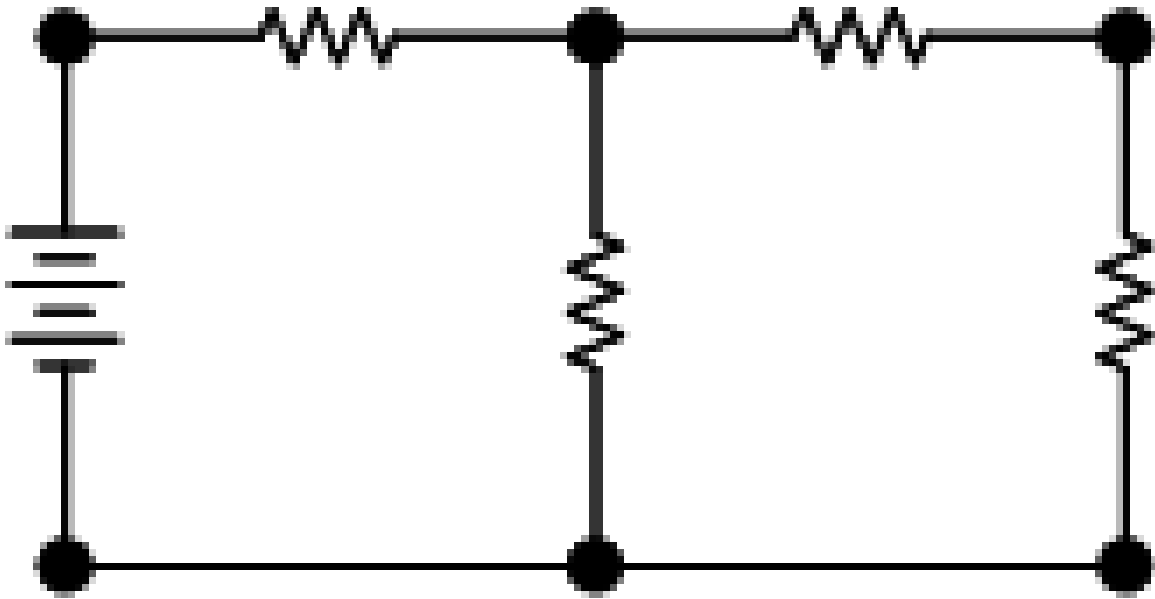
Figure 145

(a)
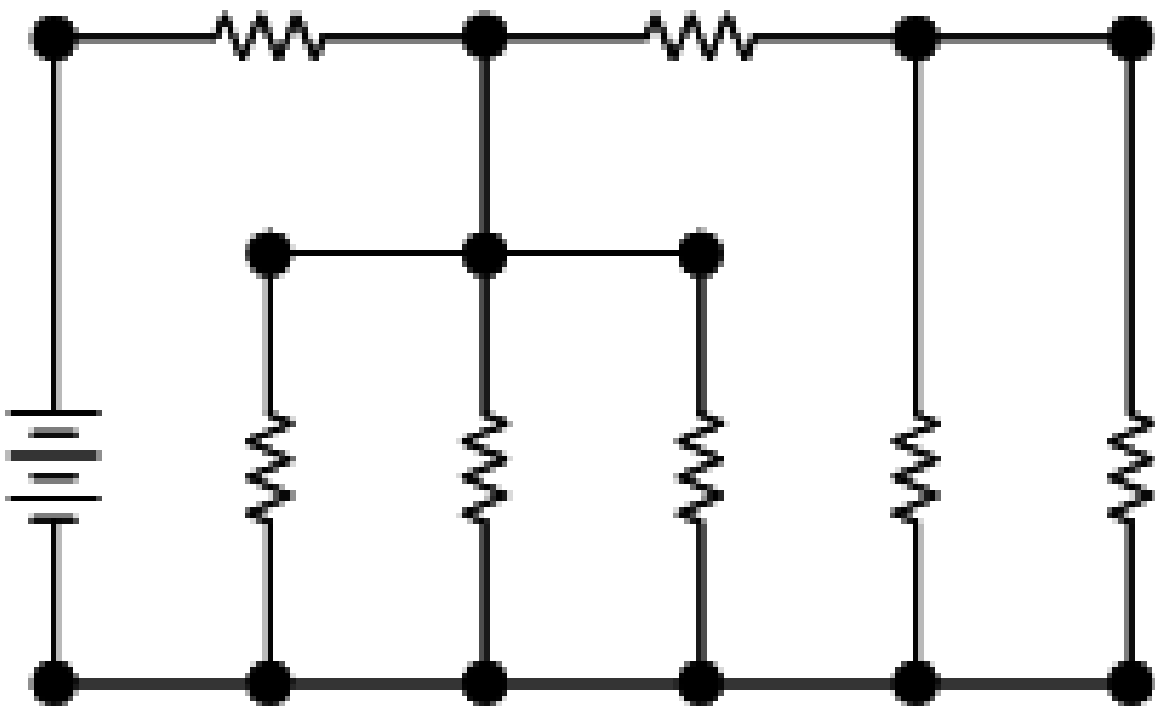
Figure 146

(b)
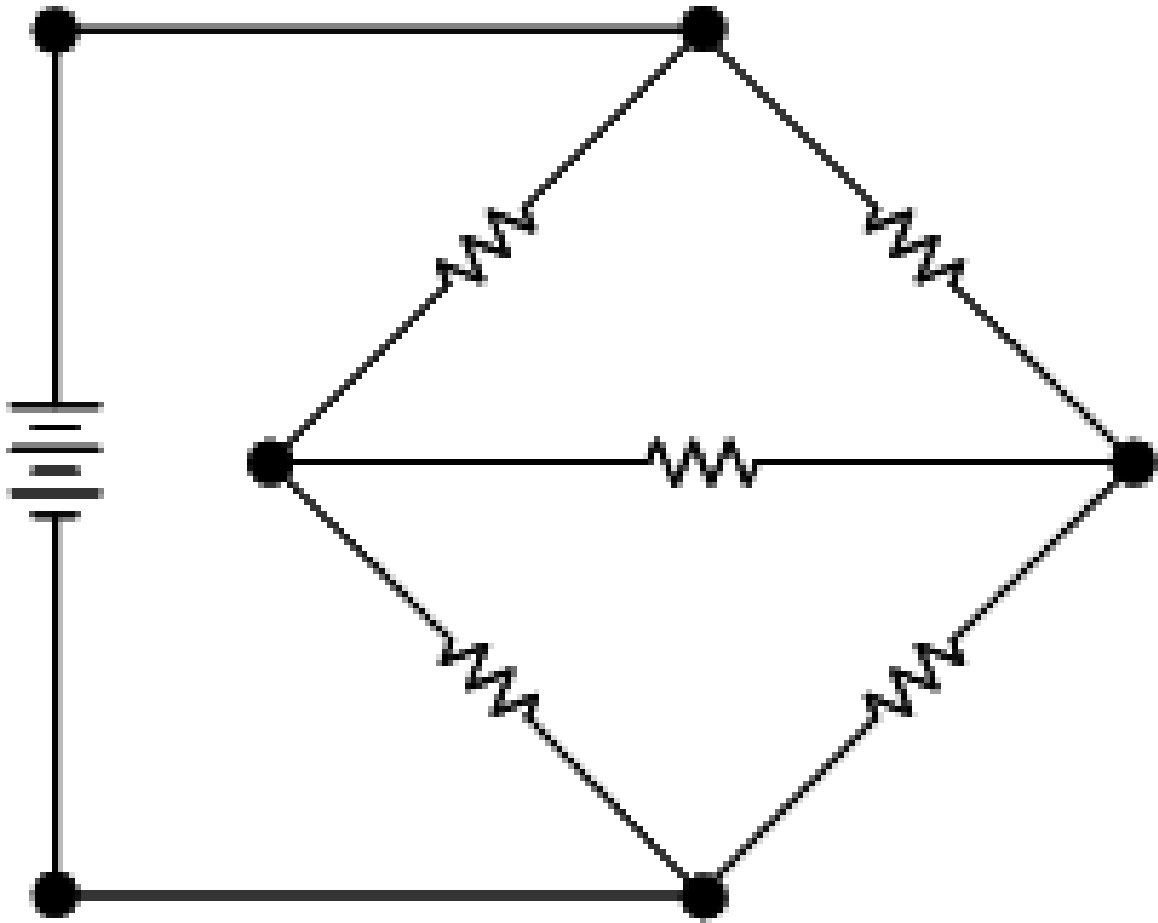
Figure 147

(c)

Figure 3: Combined parallel and series circuits

In Figure 3 (a), if the three resistors in the outer loop of the circuit are R1, R2 and R3 and the other resistor is R4. It is simpler to see what is going on if we combine R2 and R3 into their series equivalent resistance $R_2 3$. It is clear now that the equivalent resistance is R1 in series with the parallel combination of $R_2 3$ and R4. If we want to calculate the voltage across the parallel combination of R4 and R_{23} then we just use voltage divider.

$$V_{4||23} = \frac{R_4||(R_2+R_3)V}{R_4||(R_2+R_3)+R_1}$$

If we want to calculate the current through R2 and R3 then we can use the voltage across $R_4||(R_2+R_3)$ and Ohm's law.

$$i_{23} = \frac{R_4||(R_2+R_3)V}{(R_4||(R_2+R_3)+R_1)(R_2+R_3)}$$

Or we could calculate the current in the main circuit and then use current divider rule to get the current.

In Figure 3 (b) we take the same approach simplifying parallel combinations and series combinations of resistors until we get the equivalent resistance.

In Figure 3 (c) this process doesn't work then because there are resistors connected in a delta this means that there is no way to simplify this beyond transforming them to a star or wye connection.

Note: To calculate the current draw from the source the equivalent resistance always must be calculated. But if we just need the voltage across a series resistor this may be necessary. If we want to calculate the current in parallel combination then we must use either current divider rule or calculate the voltage across the resistor and then use Ohm's law to get the current. The second method will often require less work since the current flowing from the source is required for the use of current divider rule. The use of current divider rule is much simpler in the case when the source is a current source because the value of the current is set by the current source.

Figure 148   Star Network

The above image shows three points 1, 2, and 3 connected with resistors R_1 , R_2 , and R_3 with a common point. Such a configuration is called a *star network* or a *Y-connection* .
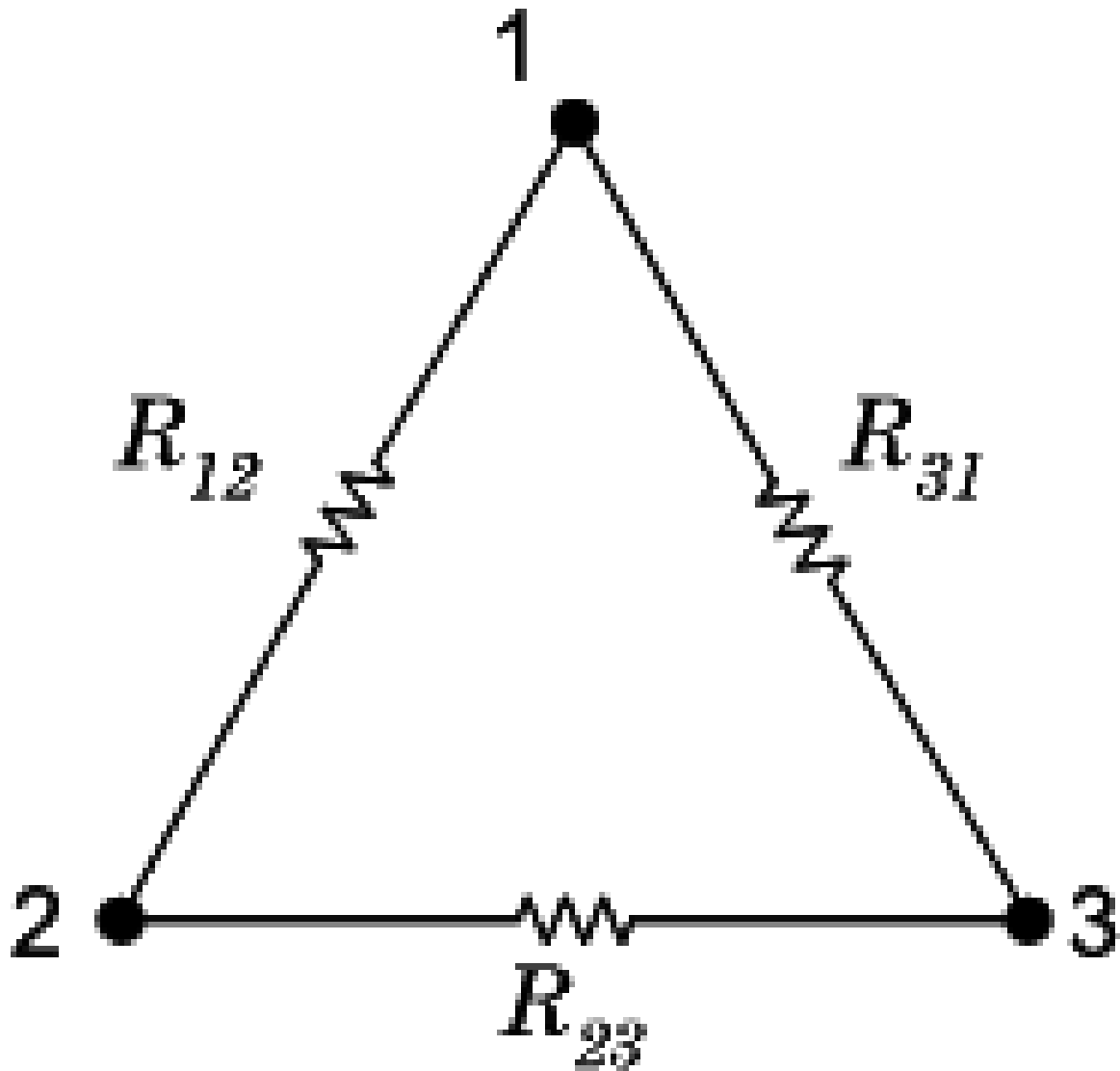
Figure 149 Delta Network

The above image shows three points 1, 2, and 3 connected with resistor R_{12} , R_{23} , and R_{31} . The configuration is called a *delta network* or *delta connection* .

We have seen that the series and parallel networks can be reduced by the use of simple equations. Now we will derive similar relations to convert a star network to delta and vice versa. Consider the points 1 and 2. The resistance between them in the star case is simply

$R_1 + R_2$

For the delta case, we have

$R_{12} \parallel (R_{31} + R_{23})$

We have similar relations for the points 2, 3 and 3, 1. Making the substitution $r_1 = R_{23}$ etc., we have, simplifying,

$R_1 = \frac{r_2 r_3}{r_1 + r_2 + r_3}$

$r_1 = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_1}$

in the most general case. If all the resistances are equal, then $R = r/3$.

19 Measuring Instruments

20 Measuring Instruments

20.1 Ammeters

Ammeters are devices that measure current. Current in electronics is usually measured in mA which are called milliamperes, which are 1/1000s of an ampere.

..... Basically an ammeter consists of a coil that can rotate inside a magnet, but a spring is trying to push the coil back to zero. The larger the current that flows through the coil, the larger the angle of rotation, the torque (= a rotary force) created by the current being counteracted by the return torque of the spring.

..... Usually ammeters are connected in parallel with various switched resistors that can extend the range of currents that can be measured. Assume, for example, that the basic ammeter is "1000 ohms per volt", which means that to get the full-scale deflection of the pointer a current of 1 mA is needed (1 volt divided by 1000 ohms is 1 mA - see "Ohm's Law").

..... To use that ammeter to read 10 mA full-scale it is *shunted* with another resistance, so that when 10 mA flows, 9 mA will flow through the shunt, and only 1 mA will flow through the meter. Similarly, to extend the range of the ammeter to 100 mA the shunt will carry 99 mA, and the meter only 1 mA.

20.2 Ohmmeters

Ohmmeters are basically ammeters that are *connected to an internal battery, with a suitable resistance in series* . Assume that the basic ammeter is "1000 ohms per volt", meaning that 1 mA is needed for full-scale deflection. When the external resistance that is connected to its terminals is zero (the leads are connected together at first for calibration), then the internal, variable, resistor in series with the ammeter is adjusted so that 1 mA will flow; that will depend on the voltage of the battery, and as the battery runs down that setting will change. The full scale point is marked as zero resistance. If an external resistance is then connected to the terminals that causes only half of the current to flow (0.5 mA in this example), then the external resistance will equal the internal resistance, and the scale is marked accordingly. When no current flows, the scale will read infinity resistance. The scale of an ohmmeter is NOT linear.Ohmmeters are usually useful in checking the short circuit and open circuit in boards.

20.3 Multimeters

Figure 150 A digital multimeter

Multimeters contain Ohmeters, Voltmeters, Ammeters and a variety of capabilities to measure other quantities. AC and DC voltages are most often measurable. Frequency of AC voltages. Multimeters also feature a continuity detector, basically an Ohmmeter with a beeper if the multimeter sees less than 100 Ω then it beeps otherwise it is silent. This is very useful for finding whether components are connected when debugging or testing circuits. Multimeters are also often able to measure capacitance and inductance. This may be achieved using a Wien bridge. A diode tester is also generally onboard, this allows one to determine the anode and cathode of an unknown diode. A LCD display is also provided for easily reading of results.

Wikipedia:Multimeter[1]

1   http://en.wikipedia.org/wiki/Multimeter

21 Electronics Laboratory Instruments

21.1 Oscilloscope

The instrument is used to view AC waveforms. For better explanation of the oscilloscope.

21.2 Spectrum Analyzer

Wikipedia:Spectrum_Analyzer[1]

21.3 Signal Generator

This instrument is used to generate low voltage AC signals. Most common signal generators can create sinusoidal(sine), triangular and square waves of various frequencies. They are used in conjunction with the oscilloscope to test analogue circuits.

Wikipedia:Signal_Generator[2]

21.4 Logic Probe

This instrument generates high and low logic states to test digital circuits. If a logic probe is not available a square wave through a signal generator can be used. Square waves can also be used to test the response time of a digital circuits.

Wikipedia:Logic Probe[3]

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1   http://en.wikipedia.org/wiki/Spectrum_analyzer
2   http://en.wikipedia.org/wiki/Signal_generator
3   http://en.wikipedia.org/wiki/Logic_probe

22 Noise in electronic circuits

Electrical Noise

any unwanted form of energy tending to interfere with the proper and easy reception and reproduction of wanted signals.

22.1 Classification

22.1.1 Based on Origin

1. External noise
    a) Atmospheric
    b) Extraterrestrial
        i. solar
        ii. Cosmic
    c) Industrial
2. Internal noise
    a) Thermal Agitation Noise
    b) Shot Noise
    c) Transit Time Noise
    d) Flicker Noise
    e) Miscellaneous Sources

Thermal noise

Thermal Agitation Noise

Also known as **Johnson noise or White noise** .

$$P_n \propto\ T = kT$$

where k = Boltzmann's[1] constant = 1.38×10^{-23} J/K

T = absolute temperature, K = 273 + °C

δf = bandwidth of interest

P_n = maximum noise power output of a resistor

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1   http://en.wikipedia.org/wiki/boltzmann

$$P_n = \frac{V^2}{R_L} = \frac{\left(\frac{V_n}{2}\right)^2}{R} = \frac{V_n^2}{4R}$$

$$V_n^2 = 4RP_n = 4RkT$$

$$V_n = \sqrt{4kT}$$

Shot Noise

w:shot noise#In electronic devices[2]

$$i_n = \sqrt{2ei_p}$$

where i_n = r.m.s. shot-noise current

e = charge of an electron = 1.6x10^{-19}C

i_p = direct diode[3] current

δf = bandwidth of system

22.2 Noise Calculations

Addition due to several sources

noise voltages:

$$V_n1 = \sqrt{4kT\ R_1}$$

,

$$V_n2 = \sqrt{4kT\ R_2}$$

...and so on, then

$$V_{n,tot} = \sqrt{V_n1^2 + V_n2^2 + ...} = \sqrt{4kT\ R_{tot}}$$

where R$_{tot}$ = R$_1$+R$_2$+...

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2   http://en.wikipedia.org/wiki/shot%20noise%23In%20electronic%20devices
3   Chapter 33 on page 247

Addition due to Cascaded Amplifier stages

$$R_{eq} = R_1 + R'_2$$

$$R_{eq} = R_1 + \frac{R_2}{A_1^2} + \frac{R_3}{A_1^2 A_2^2}$$

22.3 Analog Noise Models

22.3.1 CMOS

22.3.2 BJT

22.4 Noise in digital circuits:

22.5 Methods of reducing noise

22.5.1 Differential signaling

Differential signaling is a method of transmitting information electrically by means of two complementary signals sent on two separate wires. The technique can be used for both analogue signaling, as in some audio systems, and digital signaling, as in RS-422, RS-485, PCI Express and USB.

22.5.2 Good grounding

An ideal signal ground maintains zero voltage regardless of how much electrical current flows into ground or out of ground.

When low-level signals travel near high currents, their return currents shouldn't be allowed to flow in the same conductor. Otherwise, noise such as AC ripple on the high current will modulate the low-level signal.

22.6 References

Kennedy, George *'Electronic Communication Systems'* , 3rd Ed. ISBN 0-07-034054-4

22.7 Chapter 2: AC Circuits

23 AC Circuits

23.1 Relationship between Voltage and Current

23.1.1 Resistor

In a resistor, the current is in phase with the voltage always. This means that the peaks and valleys of the two waveforms occur at the same times. Resistors can simply be defined as devices that perform the sole function of inhibiting the flow of current through an electrical circuit. Resistors are commercially available having various standard values, nevertheless variable resistors are also made called potentiometers, or pots for short. In theory electricity is a method used to harness myriad numbers including symbols to give the notion on how circuits function on a schematic drawing

23.1.2 Capacitor

The capacitor is different from the resistor in several ways. First, it consumes no real power. It does however, supply reactive power to the circuit. In a capacitor, as voltage is increasing the capacitor is charging. Thus a large initial current. As the voltage peaks the capacitor is saturated and the current falls to zero. Following the peak the circuit reverses and the charge leaves the capacitor. The next half of the cycle the circuit runs mirroring the first half.

The relationship between voltage and current in a capacitor is: $i(t) = C\frac{d(v(t))}{dt}$. This is valid not only in AC but for any function v(t). As a direct consequence we can state that in the real world, the voltage across a capacitor is always a continuous function of the time.

If we apply the above formula to a AC voltage (i.e. $v(t) = V \cdot sin(\omega t + \Phi)$), we get for the current a 90° phase shift: $i(t) = V \cdot \omega \cdot cos(\omega t + \Phi)$.

In an AC circuit, current leads voltage by a quarter phase or 90 degrees. Note that while in DC circuits after the initial charge or discharge no current can flow, in AC circuits a current flows all the time into and out of the capacitor, depending on the impedance[1] in the circuit. This is similar to the resistance[2] in DC circuits, except that the impedance has 2 parts; the resistance included in the circuit, and also the reactance[3] of the capacitor, which depends not only on the size of the capacitor, but also on the frequency[4] of the applied voltage. In a

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1   http://en.wikipedia.org/wiki/impedance
2   http://en.wikipedia.org/wiki/resistance
3   http://en.wikibooks.org/wiki/reactance
4   http://en.wikipedia.org/wiki/frequency

circuit that has DC applied plus a signal[5], a capacitor can be used to block the DC, while letting the signal continue.

23.1.3 Inductor

In inductors, current is the negative derivative of voltage, meaning that however the voltage changes the current tries to oppose that change. When the voltage is not changing there is no current and no magnetic field.

In an AC Circuit, voltage leads current by a quarter phase or 90 degrees.

Voltage Defined as the derivative of the flux linkage:

$V(t) = \frac{d(Ni(t))}{dt}$

23.2 Resonance

A circuit containing resistors, capacitors, and inductors is said to be in resonance when the reactance of the inductor cancels that of the capacitor to leave the resulting total resistance of the circuit to be equal to the value of the component resistor. The resonance state is achieved by fine tuning the frequency of the circuit to a value where the resulting impedance of the capacitor cancels that of the inductor, resulting in a circuit that appears entirely resistive.

23.3 See also

AC Voltage:

When the Voltage between two points is changing continuously with time then the voltage is called AC Voltage. For AC Voltages there will be no constant value so we define it by the average value called RMS value RMS means Root Means Square. In retrospect on AC the power that is used to theoretically determine by an unkown which we assume to be a steady flow, this is also what technicians label the fluctuation of current that determines how electricity moves in a diagram.

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5   http://en.wikipedia.org/wiki/signal

24 Phasors

24.1 Phasors
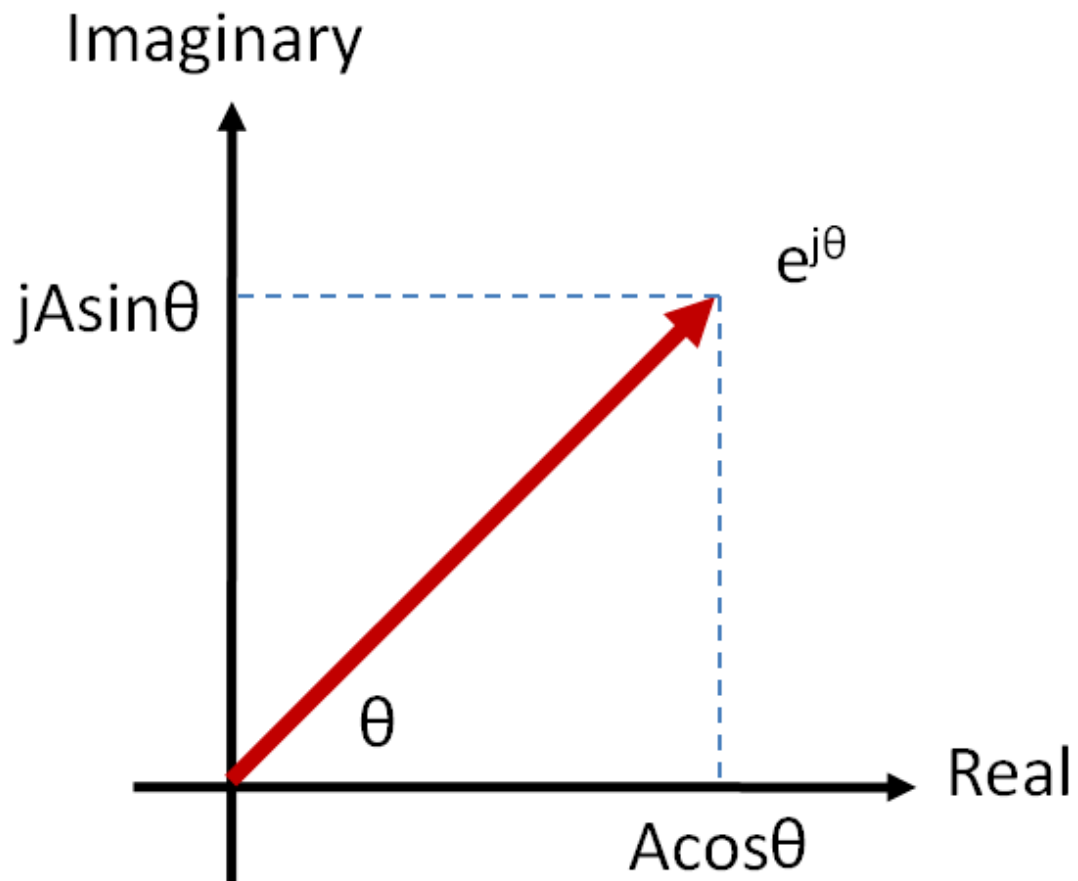
Figure 151   Figure One: Rectangular Notation
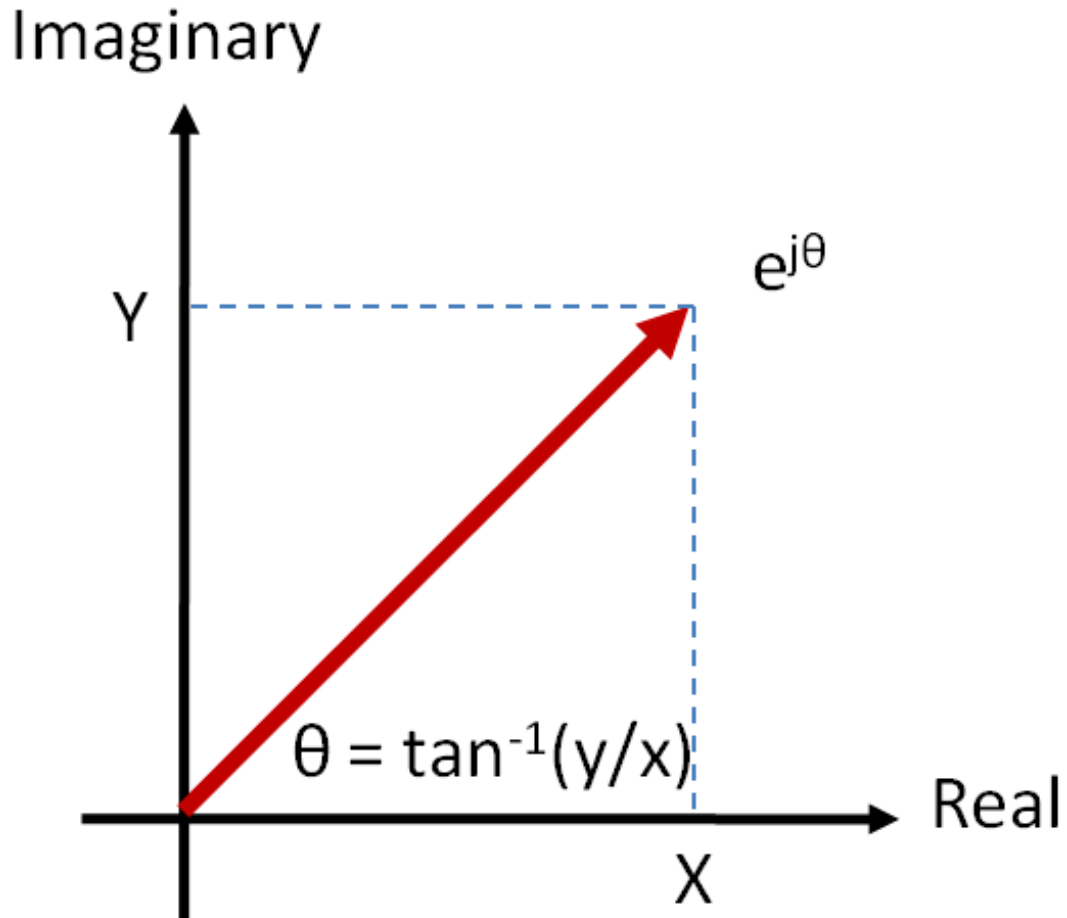
Figure 152   Figure Two: Polar Notation

Phasors provide a simple means of analyzing linear circuits. At the heart of phasor analysis lies Euler's formula[1]:

$$Ae^{j(\omega t+\theta)} = A\cos(\omega t+\theta) + jA\sin(\omega t+\theta)\,[2]$$

[3]

A complex exponential can also be expressed as

$$Ae^{j(\omega t+\theta)} = Ae^{j\theta} \cdot e^{j\omega t}$$

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1   http://en.wikibooks.org/wiki/Algebra%2FComplex%20Numbers%23Euler%27s%20formula

2

3
- **j** is the Imaginary unit ($j^2 = -1$).
- In electrical engineering, the imaginary unit is symbolized by j rather than the symbol i because i is used to denote current in electrical engineering.
- The frequency of the wave, in Hz ^{http://en.wikibooks.org/wiki/Hertz} , is given by $\omega/2\pi$.

$\tilde{A} = Ae^{j\theta}$ is called a phasor. It contains information about the magnitude and phase of a sinusoidal signal, but not the frequency or time. This simplifies use in circuit analysis, since most of the time, all quantities in the circuit will have the same frequency. (For circuits with sources at different frequencies, the principle of superposition must be used.)

A shorthand phasor notation is: $\tilde{A} = A\angle\theta$

Note that this is simply a polar form, and can be converted to rectangular notation by (see figure one):

$$\tilde{A} = Ae^{j\theta} = A\angle\theta = A\cos\theta + jA\sin\theta$$

and back again by (see figure two):

$\tilde{A} = X + jY = \sqrt{X^2 + Y^2}\angle\tan^{-1}\frac{Y}{X} = \sqrt{X^2 + Y^2}e^{j\tan^{-1}\frac{Y}{X}}$. Let us understand how this process works, even though a phasor causes circuits to heat up steady flow in current will explain on a basis that disallows overheating. Since according to the formula the outcome will be there is a time in duration which the current usage stays the same.

24.2 Sinusoidal Signals

To begin, we must first understand what sinusoidal signals are. Sinusoidal signals can be represented as

$$A\cos(\omega t + \theta)$$

where A is the amplitude, ω is the frequency in radians per second, and θ is the phase angle in degrees(phase shift). We can return to the sinusoidal signal by taking the real part of Euler's formula:

$$A\cos(\omega t + \theta) = \mathfrak{Re}(Ae^{j(\omega t + \theta)})$$

For the moment, consider single-frequency circuits. Every steady state current and voltage will have the same basic form:

$\tilde{A}_i e^{j\omega t}$ where $\tilde{A}_i$ is a phasor. So we can "divide through" by $e^{j\omega t}$ to get phasor circuit equations. We can solve these equations for some phasor circuit quantity $\tilde{Y}$, multiply by $e^{j\omega t}$, and convert back to the sinusoidal form to find the time-domain sinusoidal steady-state solution.

24.3 Example

We have three sinusoidal signals with the same frequency added together:

$$v(t) = 5\cos(200t + 30°) + 2\cos(200t + 45°) + \cos(200t - 60°)$$

In phasor notation, this is:

$$\tilde{V} = 5e^{j30°} + 2e^{j45°} + e^{-j60°} = 5\angle 30 + 2\angle 45 + \angle -60$$

We can combine these terms to get one phasor notation. This is done first by separating the real and imaginary components:

$$\text{X: } 5\cos(30°) + 2\cos(45°) + \cos(-60°) \approx 6.2443$$

$$\text{Y: } 5\sin(30°) + 2\sin(45°) + \sin(-60°) \approx 3.04819$$

The phasor notation can be written as:

$$\tilde{V} = 6.2443 + j3.04819 = \sqrt{6.2443^2 + 3.04819^2}\angle\tan^{-1}\frac{3.04819}{6.2443}$$

$$\tilde{V} = 6.94861\angle 26.0194$$

Back to the time domain, we get the answer:

$$v(t) = 6.94861\cos(200t + 26.0194°)$$

24.4 Footnotes

25 Impedance

25.1 Definition

Impedance, $\tilde{Z}$, is the quantity that relates voltage and current in the frequency domain. (The tilde indicates a phasor[1]. An overscore or arrow may also be used.)

$$\tilde{Z} = \frac{\tilde{V}}{\tilde{I}} = \frac{V\angle\phi_V}{I\angle\phi_I} = \frac{V}{I}\angle\phi_V - \phi_I$$

In rectangular form,

$$\tilde{Z} = R + jX$$

where R is the resistance and X is the reactance. Impedance is generally a function of frequency, i.e.

$$\tilde{Z}(\omega) = R(\omega) + jX(\omega)$$

NOTE: $\omega = 2\,\pi\,f$

  where f is the frequency in cycles per second (f=50 or 60 Hertz usually, depending on the country concerned. Aircraft systems often use 400 Hertz.)

25.1.1 Reactance

Reactance (symbol X) is the resistance to current flow of a circuit element that can store energy (i.e. a capacitor or an inductor), and is measured in ohms.

The reactance of an inductor of inductance L (in Henries), through which an alternating current of angular frequency w flows is given by:

$$X_L = \omega L$$

The reactance of a capacitor of capacitance C (in Farads) is given similarly:

$$X_C = 1/(\omega C)$$

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1   Chapter 24 on page 223

The two formulae for inductive reactance and capacitive reactance create interesting counterpoints. Notice that for inductive reactance, as the frequency of the AC increases, so does the reactance. Hence, higher frequencies result in lower current. The opposite is true of capacitive reactance: The higher the frequency of AC, the less reactance a capacitor will present.

Similarly, a more inductive inductor will present more reactance, while a capacitor with more capacitance will yield less reactance.

25.2 Resistors

Resistors have zero reactance, since they do not store energy, so their impedance is simply

$$\tilde{Z} = R$$

25.3 Capacitors

Capacitors have zero resistance, but do have reactance. it is stored in the power of a circuit or it can be also stored in a motor running off a AC current. Their impedance is

$$\tilde{Z} = \frac{1}{j\omega C}$$

where C is the capacitance in farads. The reactance of one microfarad at 50 Hz is -3183 ohms, and at 60 Hz it is -2653 ohms. In much more basic terms storing energy would be equivalent to a battery the power source is active and stays in this manner without any loss of power, this is what is regarded as a means for reversing electricity in the process of keeping that current.

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25.4 Inductors

Like capacitors, inductors have zero resistance, but have reactance. Their impedance is

$$\tilde{Z} = j\omega L$$

where L is the inductance in henries. The reactance of one henry at 50 Hz is 314 ohms, and at 60 Hz it is 377 ohms.

25.5 Circuit Analysis Using Impedance

Analysis in the frequency domain proceeds exactly like DC analysis, but all currents and voltages are now phasors (and so have an angle). Impedance is treated exactly like a resistance, but is also a phasor (has an imaginary component/angle depending on the representation.)

(In the case that a circuit contains sources with different frequencies, the principle of superposition[2] must be applied.)

Note that this analysis only applies to the steady state[3] response of circuits. For circuits with transient characteristics, circuits must be analyzed in the Laplace domain, also known as s-domain analysis.

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2   Chapter 15 on page 181
3   Chapter 26 on page 231

26 Steady State

26.1 Steady State

That can be said to be the condition of "rest", after all the changes/alterations were made. This may imply, for examples, that nothing at all happens, or that a "steady" current flows, or that a circuit has "settled down" to final values - that is until the next disturbance occurs.

If the input signal is not time invariant, say if is a sinosoid, the steady state will not be invariant either. The response of a systematic convergence can be considered to be composed of a transient response: the response to a disturbance, and the steady state response, in the absence of disturbance.

The transient part of the response tends to zero as time since a disturbance tends to infinity, so the steady state can be considered to be the response remaining as T -> infinity.

. In this case we make an assumption for error we can determine by calculation the extent of statistics how much power there is according to the formulae. Deducing the theory of certain parts of a sinuous making plausible solution in understanding the intricate mechanism of a steady state solution.

26.2 Chapter 3: Transient Analysis

27 RC Circuits

28 RL Circuits

29 LC Circuits

30 RCL Circuits

30.1 Chapter 4: Analog Circuits

31 Analog Circuits

As explained later, digital signals can only take one of two values at any one point. Analog signals, however, can take any value within a range. In modern electronics, many traditionally analog circuits are being replaced with digital ICs for various reasons:

- Reduced cost:
  - Digital ICs can be programmed, meaning many different analog circuits can each be replaced with the same IC, reducing cost. For example, the same DSP chip might replace many different analog filters.
  - Digital ICs can be easily expanded to put multiple functions on the same chip. For example, a DSP chip replacing multiple analog filters at the same time.
  - Digital ICs can be reprogrammed without modifying the circuit, simplifying prototyping and field upgrades.
- Increased versatility:
  - A digital IC can have its settings changed arbitrarily while it is being operated, these settings can even be changed by software. The equivalent in an analog circuit might require expensive and complicated switching techniques.
- Numeric precision: once a signal is converted to digital data, distortion and circuit noise are no longer a significant issue. A cheap modern watch driven by a digital circuit (such as a quartz oscillator and a counter) is more precise than any analog or mechanical clock.
- Ease of storage: digital data, once recorded, does not degrade as easily as analog data.

Digital circuits are also becoming more prevalent where there are no analog analogues, such as computers. Although analogue computers exist, their utility is severely limited by comparison.

Analog circuits are still more suitable for many functions. One important category is interfaces. Digital circuits are usually inferior to analog circuits for receiving and transmitting signals.

- A common digital interface, the differential line, needs an analog circuit to function well. The receiver must filter out common mode interference by computing the analog difference between the two lines. Most digital interfaces are designed as analog, only a few legacy interfaces (which have poor performance) use entirely digital circuits.
- Many radio signals are simply too high frequency to work with existing digital circuits. Radio modulators, demodulators, mixers, transmitters, and receivers are still analog. Some signals are even too high frequency for transistor circuits of any kind to amplify efficiently, such as microwave signals, which are still transmitted using vacuum tubes.
- Signals must be conditioned before conversion to digital to avoid aliasing: analog filters remove unwanted parts of signals.
- Many devices, such as monitors, require analog control. Even LCD monitors require analog circuits, although they need not be as sophisticated as CRT analog circuits.

- Audio equipment requires analog circuits. Speakers must be driven by analog signals, microphones produce analog signals. Signal of a microphone must be conditioned before conversion to digital, this usually entails sophisticated analog circuits such as preamplifers, compressors, and filters.

32 Vacuum Tubes

32.1 Passive Versus Active Components

Passive components have no gain and are not valves

- **Voltage Regulator:** an **active component** which accepts a range of voltages and outputs one constant voltage.

32.2 Vacuum Tube equals Thermonic Valve

A Vacuum Tube is a container (usually of glass) from which the air is removed. Inside the tube are two or more "Elements".

- Cathode: (electron emitter) has an electrically heated filament (which you can usually see glow red) which spits out electrons that travel through the vacuum to the Anode (electron acceptor).

- Anode: Is a conductive (usually metal) plate that is connected to a positive voltage. The negative electrons flow from the Cathode to the Anode.

A vacuum tube with just Cathode and Anode elements is a DIODE. Current will flow only when the Anode has a positive voltage relative to the Cathode.

- Grid(s): metal gratings or grids are placed between the Cathode and Anode to produce devices that can amplify signals.

NOTE: A tube with 3 elements (one grid) is a TRIODE, with 2 grids a TETRODE, with 3 grids a PENTODE.

A Grid between the cathode and anode controls the flow of electrons. By applying a negative voltage to the grid it is possible to control the flow of electrons. This is the basis of the Vacuum Tube amplifier.

A problem with Vacuum Tubes is they are big, bulky, and often meant for applications involving a lot of power. They are very powerful which usually being a Vacuum. However it is possible to scale up vacuum tubes to very high powers, and many high-powered transmitters for broadcast FM and TV use vacuum power tubes.

Vacuum tube based amplifiers have largely been replaced by semiconductor transistor based amplifiers, as they are low power and much more compact.

The voltage difference in the direction from the cathode to the anode is known as the forward bias and is the normal operating mode. If the voltage applied to the Anode becomes negative relative to the Cathode, no electrons will flow. In electronics vacuum electron tube or valve

is a device that controls current. Through a vacuum in sealed container. Vacuum tubes rely on thermionic emission of electrons from hot filament.

32.3 Klystron

A klystron is a vacuum tube used for production of microwave energy. This device is related to but not the same as a magnetron. The klystron was invented after the magnetron.

Klystrons work using a principle known as velocity modulation.

The klystron is a long narrow vacuum tube. There is an electron gun (heater, cathode, beam former) at one end and an anode at the other. In between is a series of donut shaped resonant cavity structures positioned so that the electron beam passes through the hole.

The first and last of the resonant cavities are electrically wired together.

At the cathode the electron beam is relatively smooth. There are natural slight increases and decreases in the electron density of the beam. As the beam passes through the holes of the resonant cavities, any changes in the electron beam cause some changes in the resting electro magnetic (EM) field of the cavities. The EM fields of the cavities begin to oscillate. The oscillating EM field of the cavities then has an effect on the electrons passing through, either slowing down or speeding up their passage.

As electrons are affected by the EM field of the first cavity they change their speed. This change in speed is called velocity modulation. By the time the electrons arrive at the last cavity there are definite groups in the beam. The groups interact strongly with the last cavity causing it to oscillate in a more pronounced way. Some of the last cavity's energy is tapped off and fed back to the first cavity to increase its oscillations. The stronger first cavity oscillations produce even stronger grouping of the electrons in the beam causing stronger oscillations in that last cavity and so on. This is positive feedback.

The output microwave energy is tapped of for use in high power microwave devices such as long range primary RADAR systems.

The klystron is a coherent microwave source in that it is possible to produce an output with a constant phase. This is a useful attribute when combined with signal processing to measure RADAR target attributes like Doppler shift.

Related microwave vacuum tubes are the Travelling Wave Tube (TWT) and the Travelling Wave Amplifier (TWA). A Hybrid device, which combines some aspects of these devices and the klystron, is a device called a Twicetron.

32.4 Magnetron

Magnetrons are used to produce microwaves.

This is the original device used for production of microwaves and was invented during the Second World War for use in RADAR equipment.

Magnetrons work using a principle known as velocity modulation.

A circular chamber, containing the cathode, is surrounded by and connected to a number of resonant cavities. The walls of the chamber are the anode. The cavity dimensions determine the frequency of the output signal. A strong magnetic field is passed through the chamber, produced by a powerful magnet. The cathode is similar to most thermionic valves, except heavy, rigid construction is necessary for power levels used in most Magnetrons. Early, experimental designs used directly heated cathodes. Modern, high powered designs use a rigid, tubular cathode enclosing a heater element.

Naturally excited electrons on the surface of the cathode are drawn off, into the chamber, toward the outer walls or anode. As the electrons move out, they pass through a magnetic field that produces a force perpendicular to the direction of motion and direction of the magnetic field. The faster the electrons move, the more sideways force is produced. The result is that the electrons rotate around the central cathode as they move toward the outside of the chamber.

As electrons move past the entrances to the resonant cavities a disturbance is made to the electro magnetic (EM) field that is at rest in the cavities. The cavity begins to oscillate. When another electron moves past the cavities, it also interacts with the internal EM field. The motion of the electron can be slowed or sped up by the cavity field. As more electrons interact with the cavity EM fields, the internal cavity oscillations increase and the effect on the passing electrons is more pronounced.

Eventually, bands of electrons rotating together develop within the central chamber. Any electrons that fall behind a band are given a kick by the resonant cavity fields. Any electrons going too fast have their excess energy absorbed by the cavities. This is the velocity modulation effect. The frequency of the resonance and electron interaction is in the order of GHz. (10^9 cycles per second)

In order to have a signal output from the magnetron, one of the cavities is taped with a slot or a probe to direct energy out into a waveguide for distribution.

Magnetrons for RADARs are pulsed with short duration and high current. Magnetrons for microwave ovens are driven with a continuous lower current.

The magnetrons for WWII bombers, operated by the RAF, were sometimes taped into a shielded box so that the aircrew could heat their in-flight meals, hence the first microwave ovens.

32.5 Cathode Ray Tube

A cathode ray tube or CRT is a specialized vacuum tube in which images are produced when an electron beam strikes a phosphorescent surface. Television sets, computers, automated teller machines, video game machines, video cameras, monitors, oscilloscopes and radar displays all contain cathode-ray tubes. Phosphor screens using multiple beams of electrons have allowed CRTs to display millions of colors.

The first cathode ray tube scanning device was invented by the German scientist Karl Ferdinand Braun in 1897. Braun introduced a CRT with a fluorescent screen, known as the cathode ray oscilloscope. The screen would emit a visible light when struck by a beam of electrons.

32.5.1 TV Tubes

TV tubes are basically cathode ray tubes. An electron beam is produced by an electrically-heated filament, and that beam is guided by two magnetic fields to a particular spot on the screen. The beam is moved so very quickly, that the eye can see not just one particular spot, but all the spots on the screen at once, forming a variable picture.

Colours are produced by having 3 or more differently coloured screen spots activated at once to a variable degree.

The 2 magnetic fields are one for the vertical deflection, one for the horizontal deflection, and they are provided to the beam by external coils.

32.5.2 Oscilloscope Tubes

Oscilloscope tubes are basically the same as TV tubes, but the beam is guided by two electrostatic fields provided by internal pieces of metal. It is a necessity because an oscilloscope uses a very large range of synchronisation frequencies for the deflection, when a TV set uses fixed frequencies, and it would be too difficult to drive large coils on a so large band of frequency. They are much deeper for the same screen size as a TV tube because the deflection angle is little. A TV tube has a deflection angle of 90° for the be

32.6 External Links

w:Vacuum tube[1]

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1   http://en.wikipedia.org/wiki/Vacuum%20tube

33 Diodes

33.1 Diode

Theoretically, a diode allows current flow in only one direction. An ideal diode acts as a perfect insulator for currents flowing in one direction and as a perfect conductor for currents flowing through it in the other direction. The direction in which the diode allows current to flow is called the forward bias direction and that in which current is resisted is called reverse bias direction. Diode has a symbol as shown
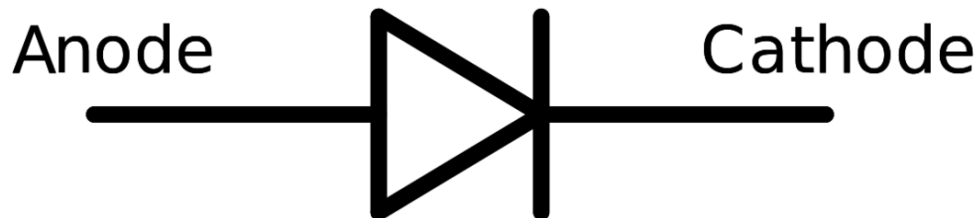
Figure 153

33.1.1 Construction

The modern semiconductor diode consists of two regions of semiconductor each having impurities of different types such that one side has excess holes (p-region) and the other has excess electrons (n-region). Such a junction of p and n regions is called a pn junction diode. The p-region has about twice as much area as the n-region to compensate for the lesser mobility of holes compared to electrons.

+ o-- [P | N]--o - .Theoretically, a diode allows current flow in only one direction the most common type today is a crystalline piece of material with a p junction connected to two electrical terminals.

33.2 Operation

33.2.1 I V Curve
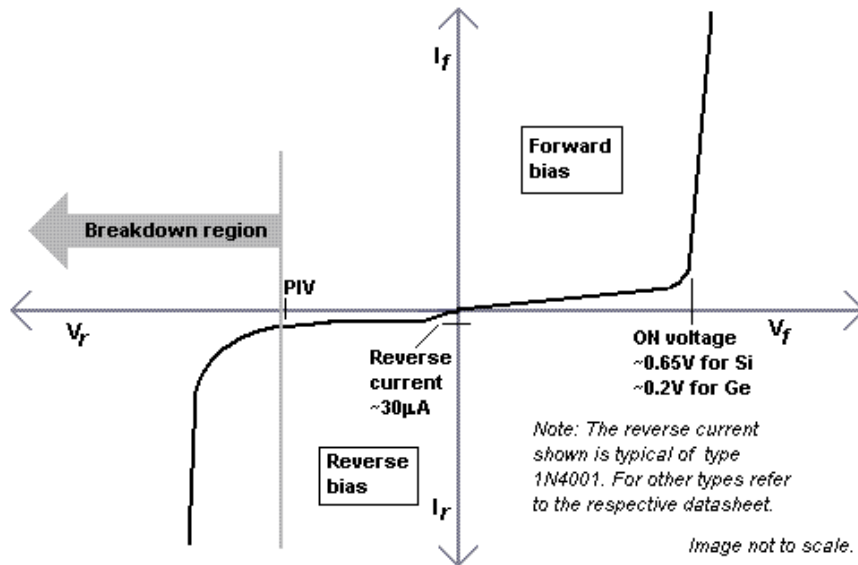
Figure 154

As seen in the graph above the diode actually works in both the forward region and the backward region. In the forward region the value of I and V are positive and in the backward region I and V are negative.

33.2.2 Forward Region

Current and Voltage are positive

When $V < V_d$. $I = 0$. Diode does not conduct

Khi $V = V_d$. $I = 1mA$. Diode starts to conduct . $V_d = 0.3v|Ge$, $0.6v|Si$

V_d is called Forward Break Over Voltage

Khi $V > V_d$. Diode conducts current . Current is calculated by $I = I_o[e^{(\frac{V_d}{nV_T})}t - 1\ ]$

33.2.3 Backward Region

Current and Voltage are Negative

When the value of voltage is more negative than the Peak Inverse Voltage (PIV) Voltage the Diode will be destroyed

33.2.4 Ideal Diode

The real diode approaches the ideal diode in the sense that the reverse current is extremely small (less than 1fA) at least for a significant part of the characteristic, and the forward current is very high (on the order of 1mA). Although a real diode does not have the characteristics as the ideal diode, in theory it is possible to make an ideal diode if the concentrations of dopants in both the regions are infinite. However, there is no way of actually doing this and experiments do not agree.

33.2.5 The Shockley equation

The diode reverse (*saturation*) current is governed by the doping concentration. The current flowing through the device varies as the voltage applied across it changes as given by the Shockley diode equation (not to be confused with Schottky):

$I_D = I_S[exp(V_D/nV_T) - 1]$

In the equation above V_T is defined as $V_T = kT/q$, where k is Boltzmann's constant, T is the temperature in Kelvin, and q is the magnitude of the charge on an electron.

In the forward bias direction, current flows with low voltage. If one draws a characteristic for this equation, a sharp increase in current can be seen at a particular voltage called the *cut-in voltage* or the *on-voltage*.

In the reverse bias mode, the diode current is approximately $-I_S$. This is called the reverse *saturation* current because it looks like the diode is saturated with charge and cannot allow more current in the reverse bias direction than this.

33.2.6 Break-down

However, a break from the above equation takes place at a point called *break-down voltage*. One could think of it as the point where the Shockley equation *breaks down* and is no longer valid. There are two reasons for breakdown to occur.

Avalanche Breakdown

This occurs as a result of excess minority carriers in a region. Minority carriers are those carriers that are in the wrong region. For example, electrons will be minority carriers in the p-region.

Zener Breakdown

This is basically due to a size difference or dopant concentration difference. One of the regions has a greater region of depletion (Reverse bias voltage induces a depletion region, which is sparse in a densely doped region and dense in a sparsely doped region.)

See also Zener diodes[1]

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1   http://en.wikibooks.org/wiki/Electronics%2FDiodes%2FZener%20diode

33.2.7 Summary

So basically, there are three modes in which a diode operates:

Forward

No current flows until a small forward voltage is reached called *cut-in* voltage.

Reverse

The diode prevents current from flowing in the opposite direction. Current is small, and voltage can be large (but not exceeding the Zener voltage.)

Breakdown

Once the diode voltage is more negative than the Zener voltage, the diode allows current to flow in the reverse direction.

When there is no voltage applied, the excess electrons of the N type semiconductor flow into the holes of the P type semiconductor. This creates a depletion region that acts as a voltage.

33.3 Diode Variations

Bridge Rectifier:

A diode circuit that 'rectifies' alternating current (AC) into direct current (DC). The bridge rectifier is a full-wave rectifier, meaning that both the positive and negative portions of the wave become positive. (In a half-wave rectifier, positive stays positive, and negative becomes zero.) The bridge rectifier has advantages over other full-wave rectifier designs, because it reduces peak-inverse voltage (PIV), the largest negative voltage across a single junction diode. By reducing the PIV, it becomes possible to use diodes with lower breakdown (Zener) voltages. This allows the use of cheaper diodes to perform the same function.
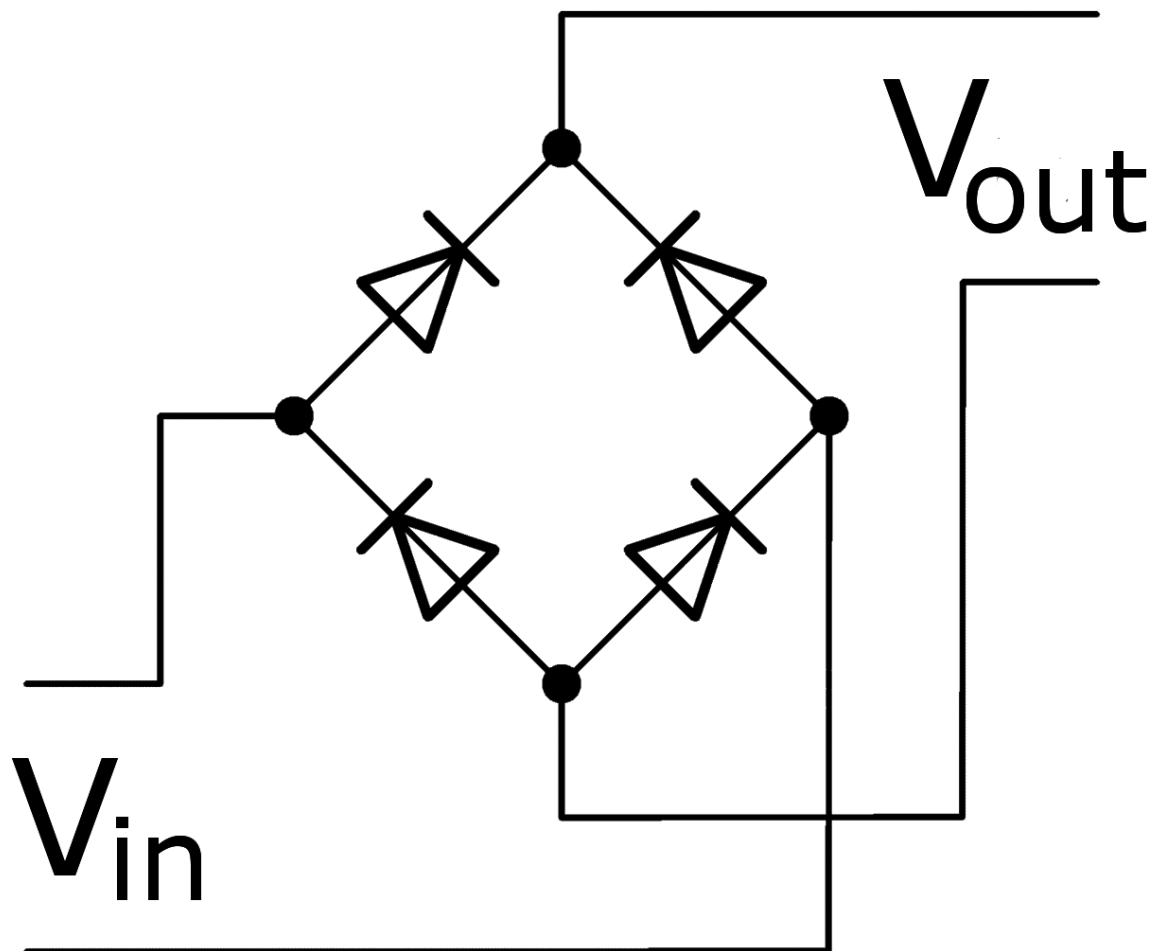
Figure 155   A bridge rectifier shown as 4 discrete diodes.

LED (Light Emitting Diode)

 A diode that emits light!
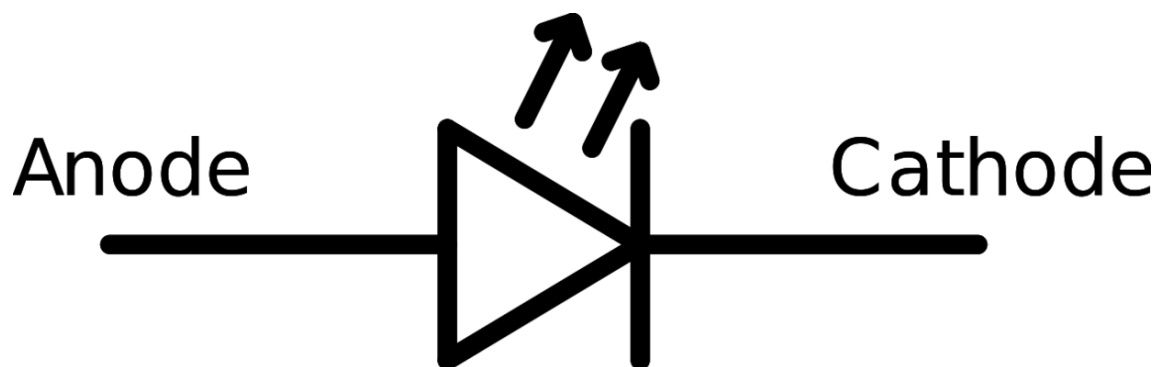
Figure 156

Schottky:

A diode made from a metal-semiconductor junction, rather than an p-type/n-type silicon junction. These diodes typically have a much lower forward voltage drop than standard diodes (around 0.2V versus 0.6V).

Anode Cathode
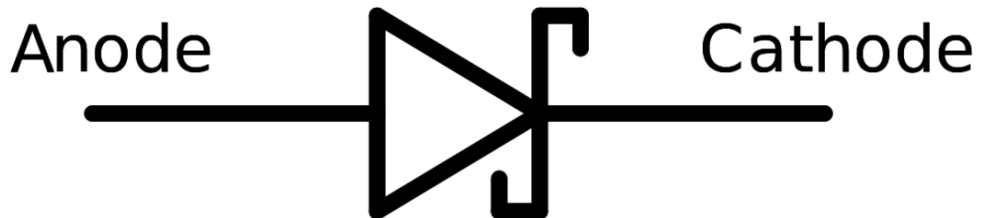
Figure 157

Zener:

A diode that is meant to be operated in the breakdown region. These diodes have lower Zener (breakdown) voltages, so that they can achieve the breakdown mode without melting. Unlike other diodes, these have very specific breakdown voltages, typically between 2 and 200 volts. See also Zener diode[2]s

Anode Cathode

Figure 158

Varicap:

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2   http://en.wikibooks.org/wiki/Electronics%2FDiodes%2FZener%20diode
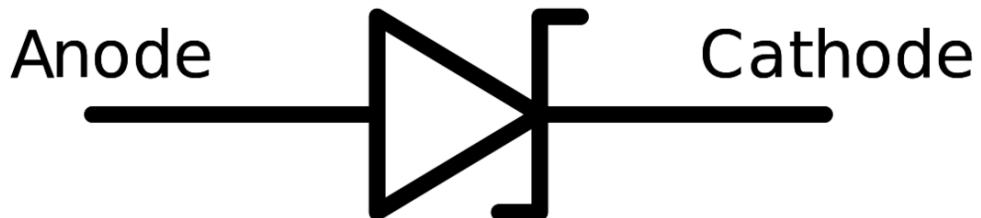
A diode that is build to use the capacity in dependance of the cross voltage. Although they rectify, they will be used in tuning circuits as a replacement of manual operated variable capacitors. They permit the use of electronic equipment to be controlled, this permits a phase-locked loop and other circuits which needs stability and electronic control. Semiconductor diodes begin conducting electricity under certain conditons.

34 Transistors

34.1 Transistor

A transistor is a solid state device made by joining three positive-type and negative-type semiconductors together. In general, all transistors have three pins: base, collector, and emitter. Transistor is a bi-polar device that is a transistor with two junctions namely BE and CE DE EE FE. In theory we take a specified formulae incorporate this with using any type of meter in figuring the mathematical solution.
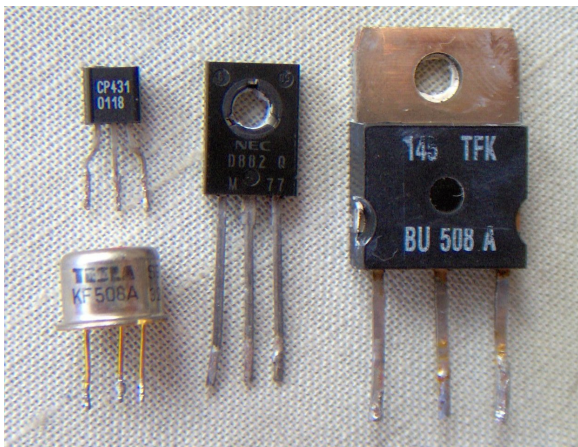
Figure 159

34.1.1 Construction

A lightly doped region called base is sandwiched between two regions called the emitter and collector respectively. The collector handles large quantities of current, hence its dopant concentration is the highest. The emitter's dopant concentration is slightly lesser, but its area is larger to provide for more current than the collector. The collector region should be heavily doped because electron-hole pairs recombine in that region, while the emitter is not such a region. We can have two varieties in this kind of transistor.

34.1.2 NPN Transistor

An NPN transistor is made by joining one positive-type semiconductor in between two negative-type semiconductors. Here a lightly doped p-type semiconductor (semiconductor with more holes than electrons) is sandwiched between two well-doped n-type regions. It is

like two pn-junctions facing away. An IEEE symbol for the NPN transistor is shown here. The arrow between the base and emitter is in the same direction as current flowing between the base-emitter junction. Power dissipated in the transistor is

$P = V_{CE}I_C$, where V_{CE} is the voltage between the collector and the emitter and I_C is the collector current.
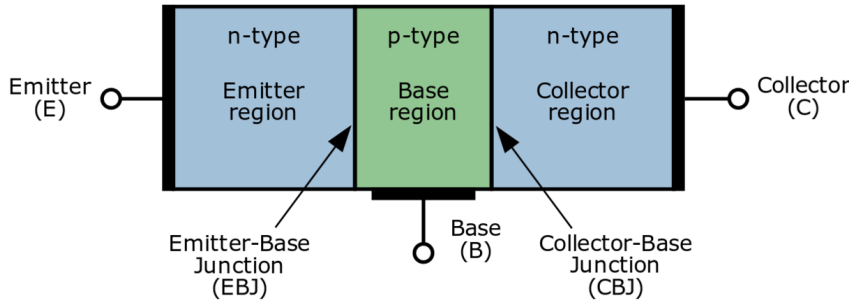
Figure 160
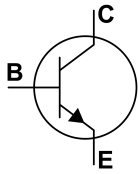
34.1.3 PNP Transistor

A PNP transistor is made by sandwiching a negative-type semiconductor in between two positive-type semiconductors.
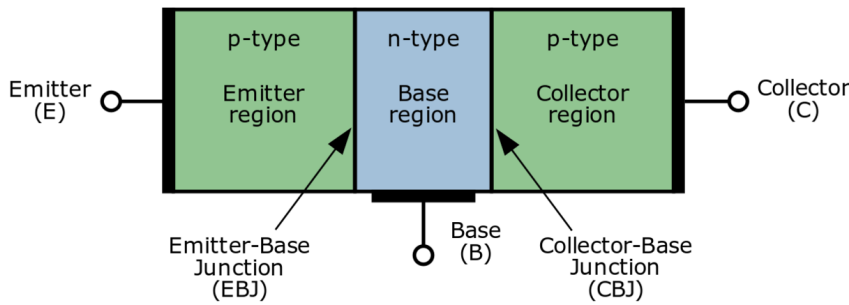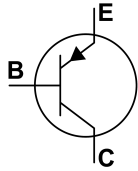
Figure 162

34.2 Transistor Operation

34.2.1 Amplifier

A transistor conducts current when the base voltage is greater than BE junction's voltage. Current is non zero.

$$I_B \neq 0$$

$$I_E = \alpha I_B$$

$$I_C = \beta I_B$$

34.2.2 Switch

A transistor conducts current when the base voltage is greater than BE junction's voltage. Current is non zero. This corresponds to a closed switch. A transistor does not conduct current when the base voltage is less than BE junction's voltage. Current is zero. This correspond to an open switch.

34.3 External links

w:Transistor[1]

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1   http://en.wikipedia.org/wiki/Transistor

35 FET

35.1 Field Effect Transistor

The most common transistors today are FETs (Field Effect Transistor). These transistors are characterized as having a conductance between source and drain dependent on the voltage applied between the gate and the source terminals. The dependence is linear if the gate to drain voltage is also high along with the gate to source voltage. It turns into a square-law relationship if the gate to drain voltage is not enough.

35.2 Current Voltage Characteristics

35.3 Disadvantages

One of the issues that comes up in circuit design is that as chips get smaller the insulator gets thinner and it starts to look like Swiss cheese. As a result the insulator starts acting like a conductor. This is known as leakage current. One solution is to replace the insulator by a material with a higher dielectric coefficent.

Two types: enhancement and depletion. Enhancement is the standard MOSFET, in which a channel must be induced by applying voltage. Depletion MOSFETs have the channel implanted, and applying voltage causes the channel to cease being conductive.

FET transistors respond to the difference in voltage bias between the gate and the source.

MOSFET (Metal-Oxide-Semiconductor FET): standard FET

JFET (Junction Fet): When voltage is applied between the source and drain current flows. Current only stops flowing when a voltage is applied to the gate.

MESFET (MEtal-Semiconductor FET): p-n junction is replaced with Scottky junction. Not made with Silicon.

HEMT (High Electron Mobility Transfer): A MESFET

PHEMT (Pseudomorphic HEMT):

36 MOSFET

36.1 Complementary Metal Oxide Semiconductor

CMOS , Complementary Metal Oxide Semiconductor is not a type of transistor. It is a logic family, based on MOS transistors.

36.2 Construction & Operation

CMOS is made of two FETs blocking the positive and negative voltages. Since only one FET can be on at a time, CMOS consumes negligible power during any of the logic states. But when a transition between states occurs, power is consumed by the device. This power consumed is of two types.

Short-circuit power

For a very short duration, both transistors are on and a very huge current flows through the device for that duration. This current accounts for about 10% of the total power consumed by the CMOS.

Dynamic power

This is due to charge stored on the parasitic capacitance of the output node of the device. This parasitic capacitance depends on the wire's area, and closeness to other layers of metal in the IC, besides the relative permittivity of the quartz layer separating consecutive metal layers. It also depends (to a much smaller extent) upon the *input capacitance* of the next logic gate. This capacitance delays the rise in the output voltage and hence the rise or fall in the output of a gate is more like a that in a resistor-capacitor (RC) network. Thus the dynamic power consumed due to switching action in one gate is given by:

$P_d = CV_d^2 f$

37 Amplifiers

37.1 Circuit Models for Amplifiers

Amplifier are generally put in four categories

1. voltage amplifier,
2. current amplifier,
3. transresistance amplifier and
4. transconductance amplifier.

These models apply irrespective of the complexity of the internal circuit of the amplifier. The values of the model parameters can be found either by analyzing the amplifier circuit or by performing measurements at the amplifier temlinals.

The model for a voltage amplifier is shown in figure 1. Real amplifiers have input and output resistance. This is reflected in the model.
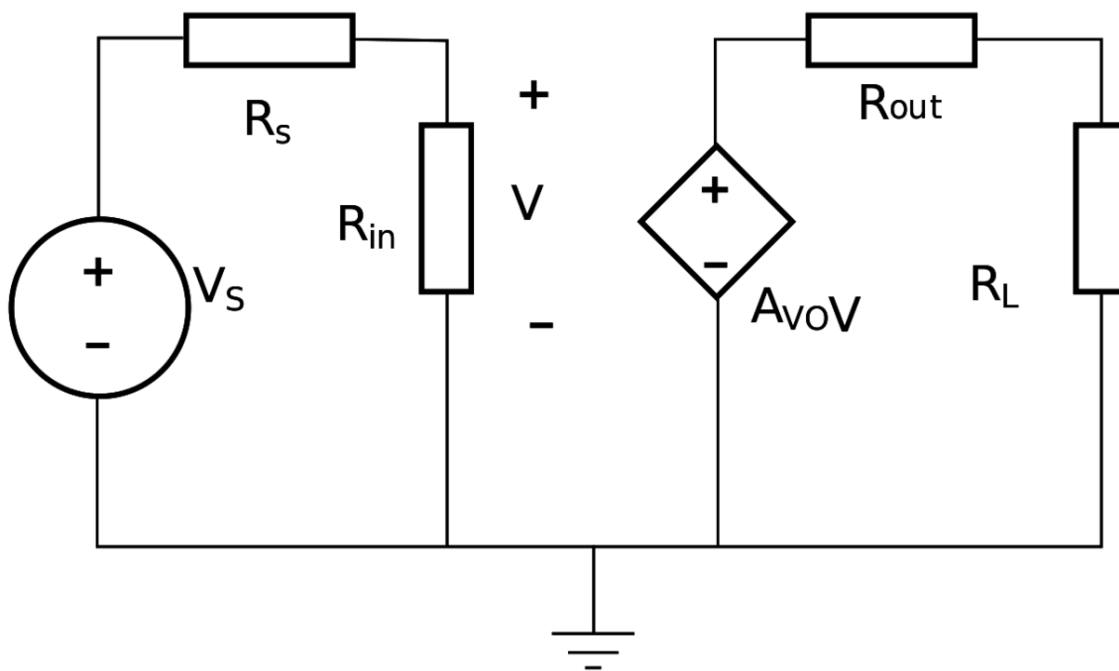
Figure 164

Figure 1: A Voltage Amplifier.

37.2 Gain

Gain is the increase in the strength of a signal and is often expressed in decibel[1]s (dB). An increase of 3 dB is about equal to doubling in a linear scale. A gain of more than 1 is called amplification, while a gain of less than 1 is called Attenuation.

Gain is given different symbols depending of the type. For No load gains

Voltage gain is A_{vo},

Current gain A_{io},

Transconductance G_m

Transresistance R_m.

Using the model, the gain with a load can be calculated.

37.3 Transistor amplifiers

37.3.1 Common Emitter
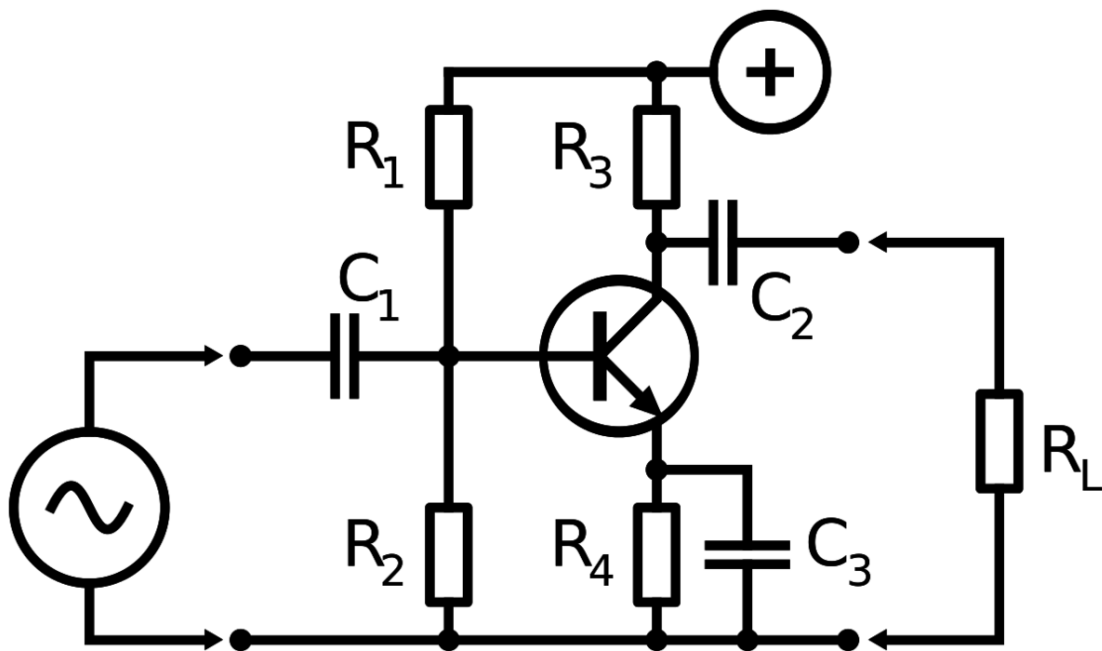
Figure 165

QUALITATIVE CHARACTERISTICS

- Current Gain: ..... HIGH

---

1   http://en.wikipedia.org/wiki/decibel

- Voltage Gain: ..... HIGH
- Power Gain: ..... HIGH
- Input Impedance: ... AVERAGE
- Output Impedance:... AVERAGE

```
QUANTITATIVE CHARACTERISTICS

Input Resistance(base): Zb=β×re'

-> β: Current Gain (Ic/Ib), where 'Ic' is Colector DC current and 'Ib' is DC
Base current;
-> re': Base-Emitter dynamic resistor (Ut/Ie), where Ut is thermal
voltage(≈25mV at 25°C) and
'Ie' is DC emitter current;
```

Input Resistance(general): Zg= Zb || R1 || R2, where R1 and R2 are the same as
the picture above.

37.3.2 Common Collector
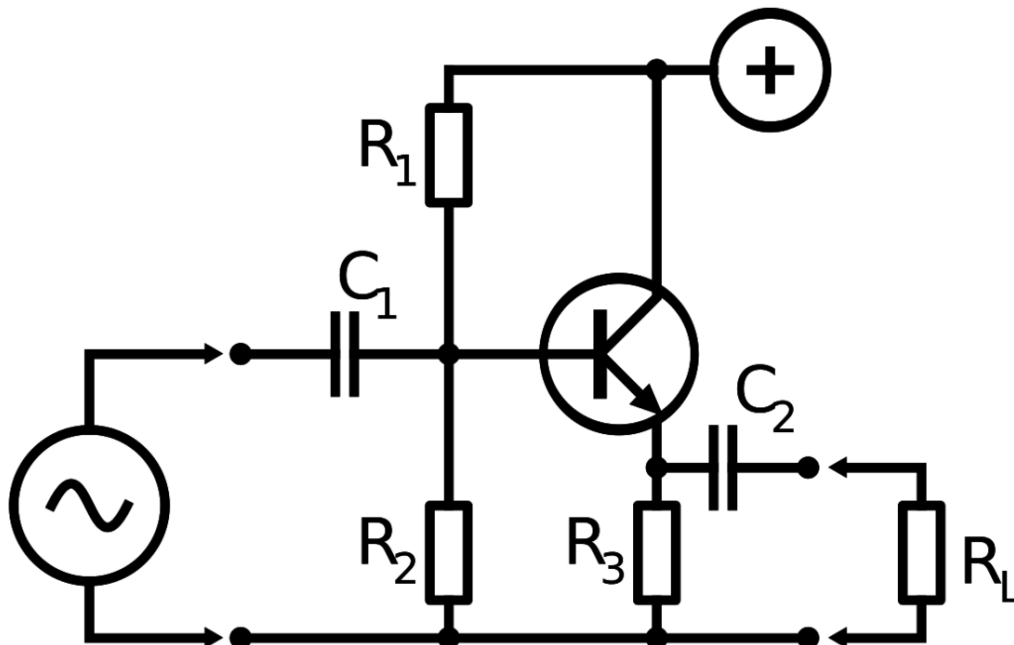
Figure 166

```
QUALITATIVE CHARACTERISTICS

Current Gain: ..... HIGH
Voltage Gain: ..... ≈1
Power Gain:   ..... LOW
Input Resistance: ... HIGH
Output Resistance:... LOW
```

37.3.3 Common Base
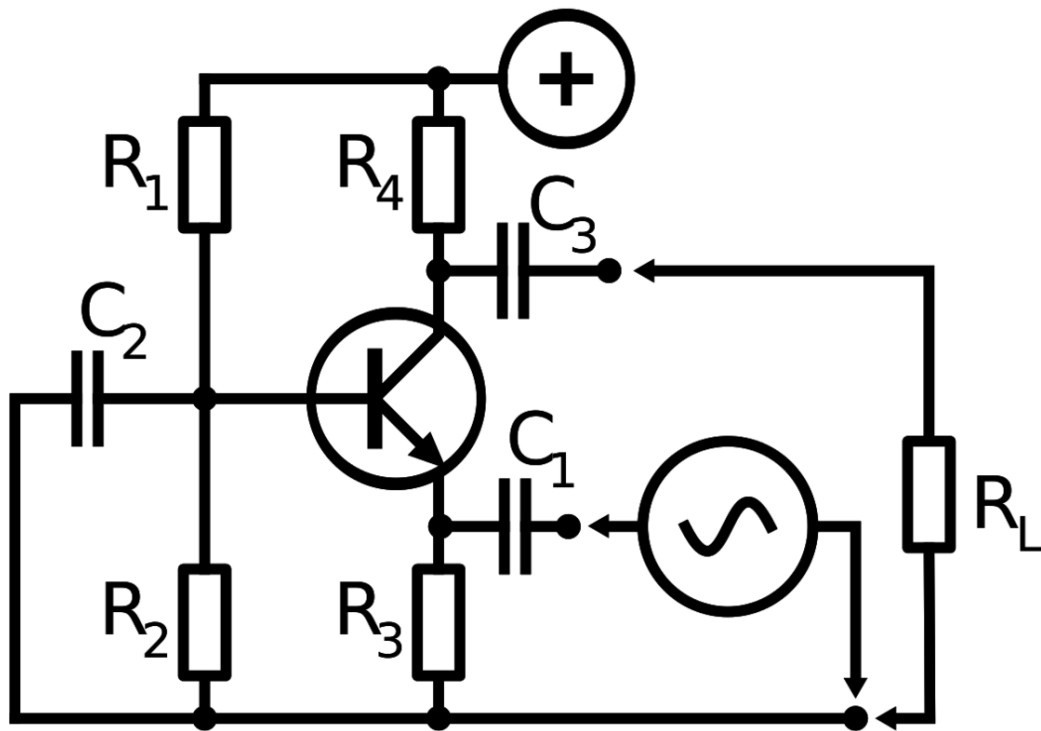
Figure 167

```
QUALITATIVE CHARACTERISTICS

Current Gain: ..... ≈1
Voltage Gain: ..... HIGH
Power Gain:   ..... AVERAGE
Input Resistance: ... LOW
Output Resistance:... HIGH
```

37.4 FET Configurations

As with BJT configurations, there are three FET configurations, each one corresponding to one of the terminals of the transistor.

37.4.1 Common Source
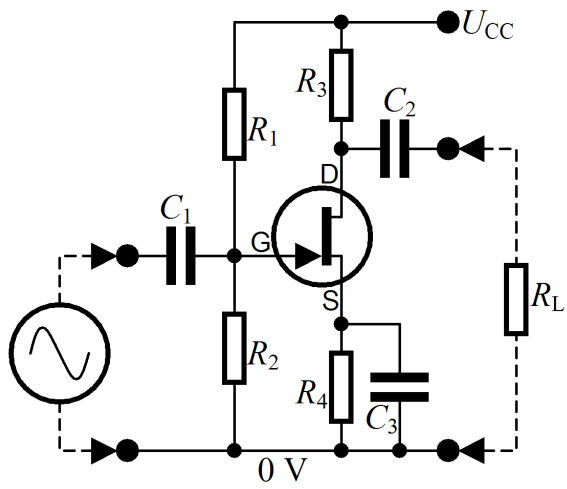
Figure 168   Common Source Amplifier
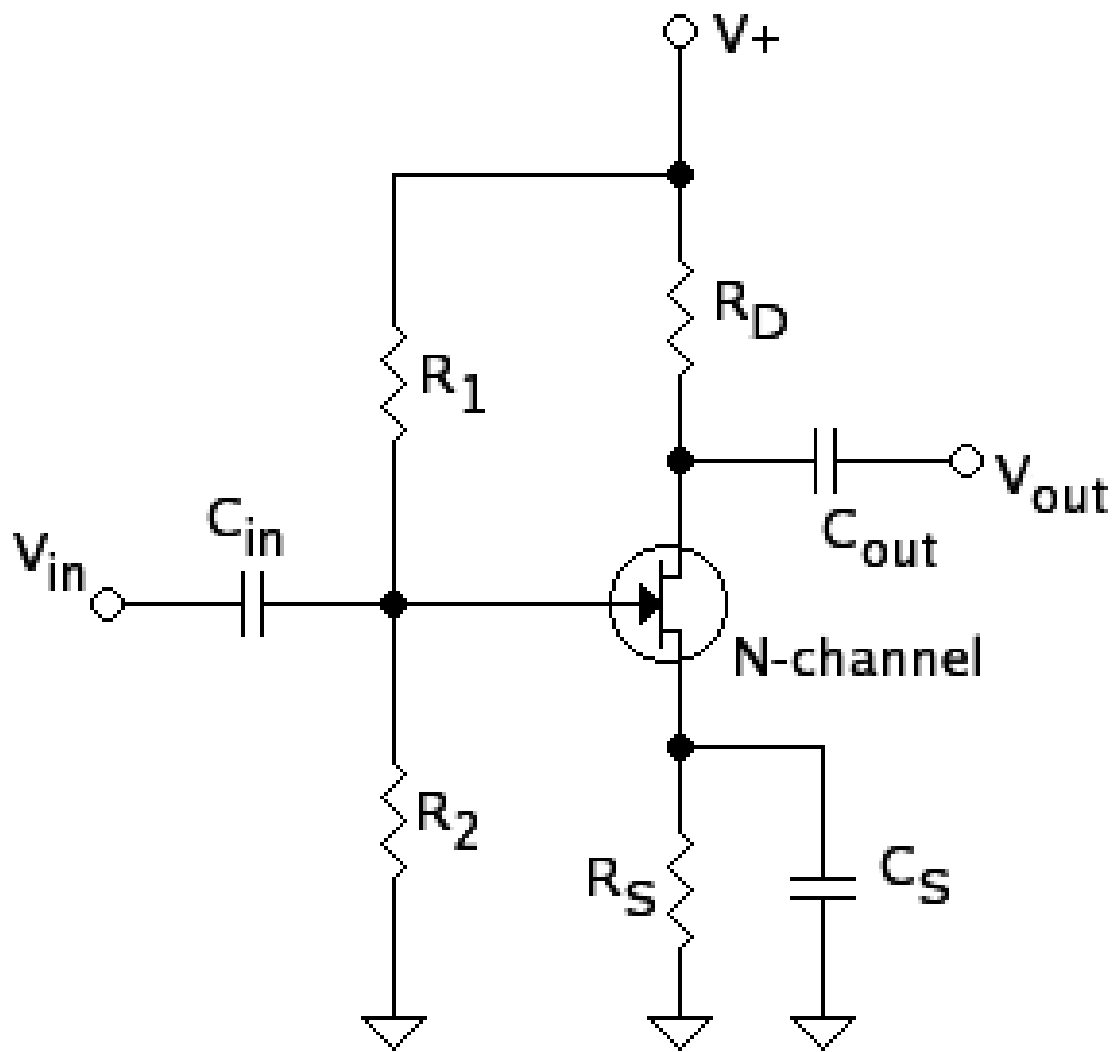
Figure 169

37.4.2 Common Drain
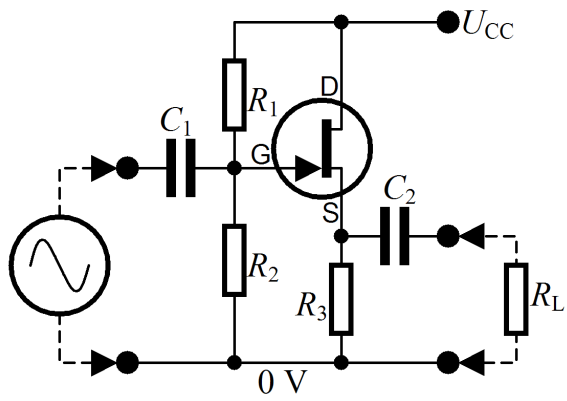
Figure 170   Common Drain Amplifier
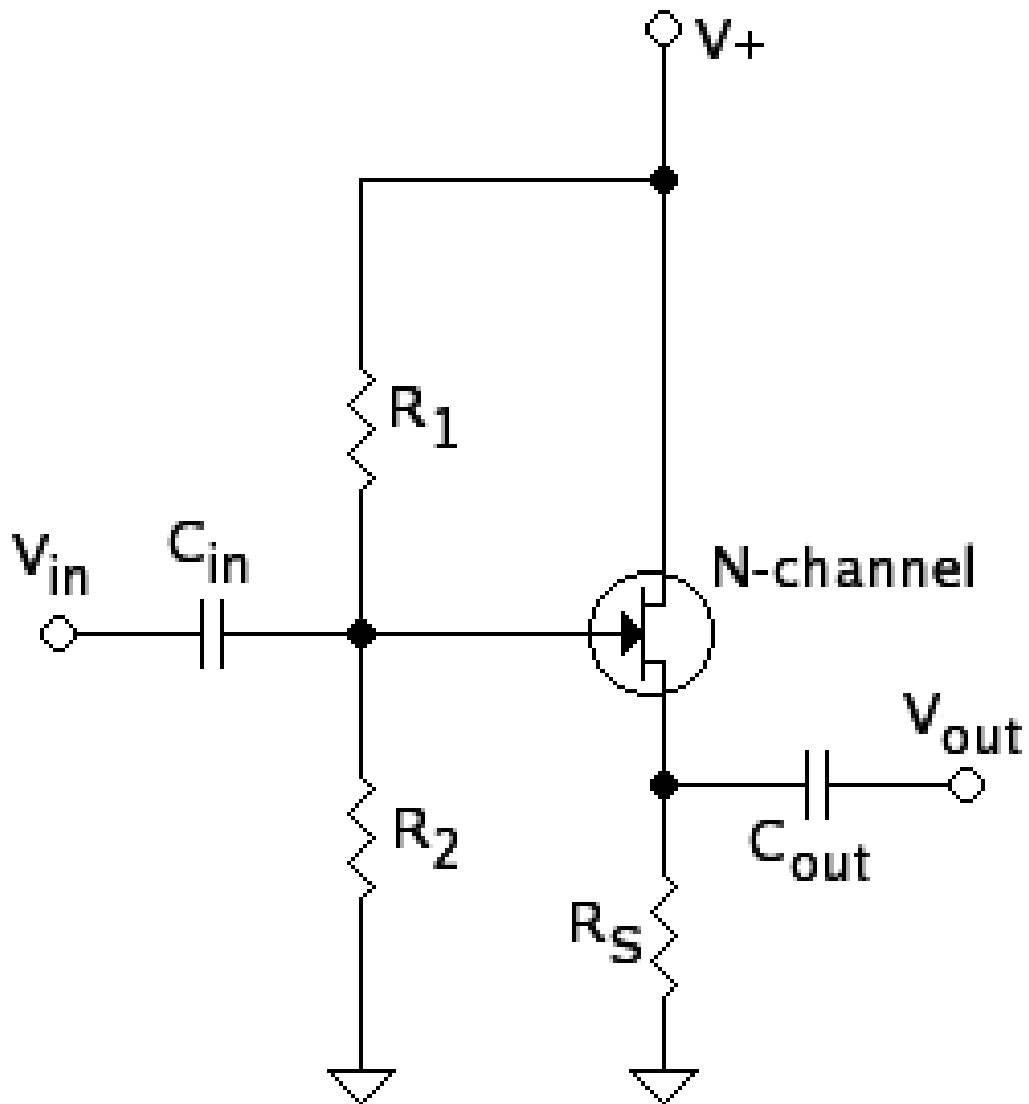
Figure 171

37.4.3 Common Gate
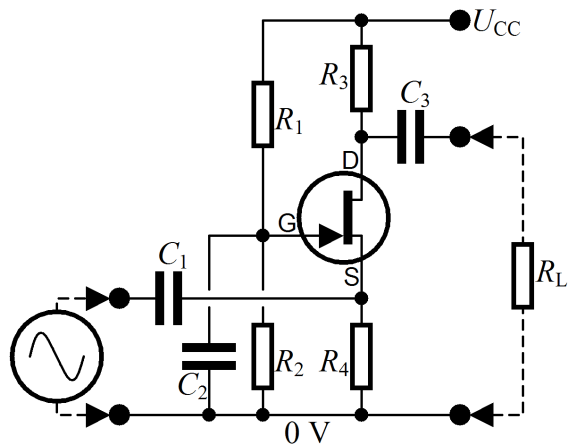
Figure 172   Common Gate Amplifier
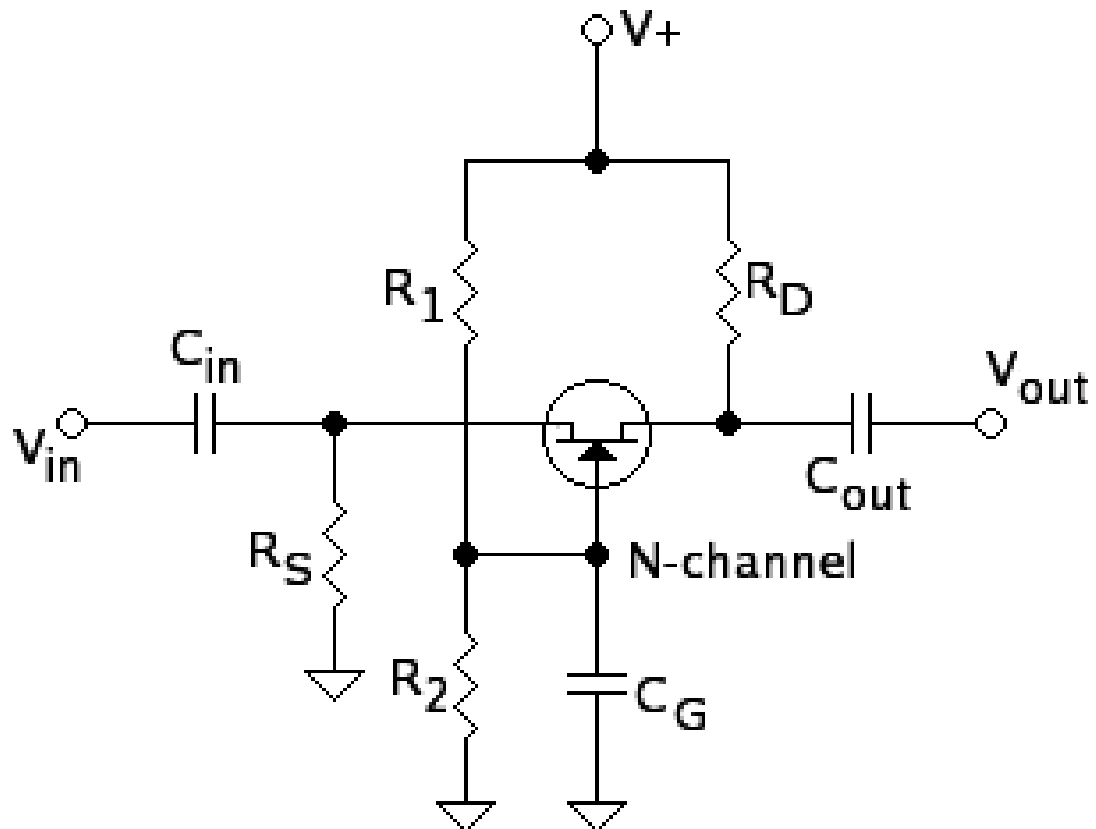
Figure 173

37.5 Biased Voltage Class

Transistors may be biased in a variety of classes. A trade off of linearity and power consumption is usually made where a Class A

Class A

The transistor is "on" all the time. We say 360 degrees of conduction, representing an entire period of the sine waveform. Ideally, this class produces very little distortion, however consumes a lot of power and is also least preferred.

This is the most linear of the classes, meaning the output signal is a truer representation of what was imputed. Here are the characteristics of the class: 1.The output device (transistor) conducts electricity for the entire cycle of input signal. In other words, they reproduce the entire waveform in its entirety. 2.These amps run hot, as the transistors in the power amp are on and running at full power all the time. 3.There is no condition where the transistor(s) is/are turned off. That doesn't mean that the amplifier is never or can never be turned off; it means the transistors doing the work inside the amplifier have a constant flow of electricity through them. This constant signal is called "bias". 4.Class A is the most inefficient of all power amplifier designs, averaging only around 20%.

Because of the way they are usually designed, Class A amplifiers are very inefficient. They do not need to be built in this way, but for every watt of output power, they can typically waste 4-5 watts as heat. They are usually very large, heavy and because of the 4-5 watts of heat energy released per watt of output, they run very hot, needing lots of ventilation (not at all ideal for a car, and rarely acceptable in a home). This is not due to the amplifier type, but the fact that even many design engineers do not fully understand how they work and often copy their designs from previous ones. The upside is that these amps are the most enjoyed of all amplifiers. When properly designed, the Class A amp gives the best representation of musical detail, with no clipping of the waveform. As a result the sound is cleaner and more linear; that is, it contains much lower levels of distortion.

They are the most accurate of all amps available, but at greater cost to manufacture, calling for tight tolerances and additional components for cooling and heat regulation.

Class AB

The transistor is "on" for slightly more than half the cycle (>180 degrees) of a sine wave and is the most common configuration used in push-pull audio power amplifiers. In push-pull amplifiers, Class AB produces mostly odd order distortion, however it is far more power efficient than Class A. Odd order distortion is not considered pleasing to hear in audio power amplifiers. This distortion can easily be removed with the addition of a simple negative feedback loop into the system as shown by the diagram below:
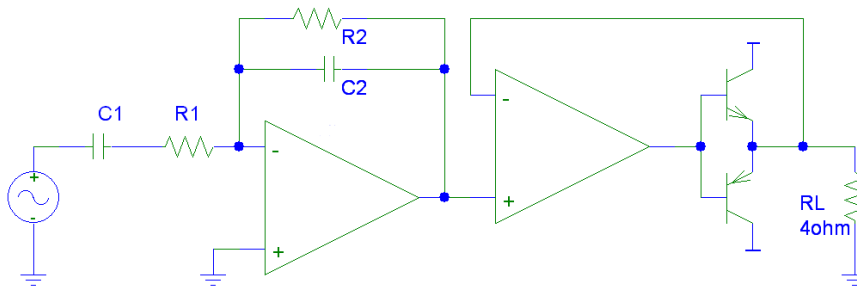
Figure 174   Class AB Amp

This type of amplifier is extremely easy to build and is the industry standard for audio amplifiers.

Issues with this type of amplifier include poor efficiency, size and cost. A typical class ab amplifier will have a power efficiency of 40-80%. Because of this they require large heat sinks to cool the transistors, this also increases the cost of the amplifier due to the extra material to create these heat sinks.

This is the compromise of the bunch. Class AB operation has some of the best advantages of both Class A and Class B built-in. Its main benefits are sound quality comparable to that of Class A and efficiency similar to that of Class B. Most modern amp designs employ this topology.

Its main characteristics are: In fact, many Class AB amps operate in Class A at lower output levels, again giving the best of both worlds The output bias is set so that current flows in a specific output device for more than a half the signal cycle but less than the entire cycle. There is enough current flowing through each device to keep it operating so they respond instantly to input voltage demands. In the push-pull output stage, there is some overlap as each output device assists the other during the short transition, or crossover period from the positive to the negative half of the signal.

There are many implementations of the Class AB design. A benefit is that the inherent non-linearity of Class B designs is almost totally eliminated, while avoiding the heat-generating and wasteful inefficiencies of the Class A design. And as stated before, at some output levels, Class AB amps operate in Class A. It is this combination of good efficiency (around 50) with excellent linearity that makes class AB the most popular audio amplifier design.

There are quite a few excellent Class AB amps available. This is the design I recommended for most general-use applications in home and car. Usually, parts choice rivals that of Class A amps, and dollar for dollar these are some of the best values in stereo amplification. There can be some variation in design principle, but generally these are well-designed amps since their function is very well-understood by audio designers.

Class B

The transistor is "on" for only half the cycle (exactly 180 degrees) of a sine wave and is also very typically used in push-pull amplifier circuits. Ideally this class produces mostly odd order distortion. In audio applications it is believed that odd order distortion is not

pleasing to hear. It is difficult to build a low distortion Class B amplifier and hence Class AB is almost universal.

In this amp, the positive and negative halves of the signal are dealt with by different parts of the circuit. The output devices continually switch on and off. Class B operation has the following characteristics: The input signal has to be a lot larger in order to drive the transistor appropriately. This is almost the opposite of Class A operation There have to be at least two output devices with this type of amp. This output stage employs two output devices so that each side amplifies each half of the waveform. [li Either both output devices are never allowed to be on at the same time, or the bias (remember, that trickle of electricity?) for each device is set so that current flow in one output device is zero when not presented with an input signal. Each output device is on for exactly one half of a complete signal cycle.

These amps run cooler than Class A amps, but the sound quality is not as pure, as there is a lot of "crossover" distortion, as one output device turns off and the other turns on over each signal cycle.

This type of amplifier design, or topology, gives us the term "push-pull," as this describes the tandem of output devices that deliver the audio signal to your speakers: one device pushes the signal, the other pulls the signal. They can be less expensive, because one can use two cheap output devices instead of one high-quality one in the design.

As I mentioned before, the input signal has to be lot larger, meaning that from the amplifier input, it needs to be "stepped up" in a gain stage, so that the signal will allow the output transistors to operate more efficiently within their designed specifications. This means more circuitry in the path of your signal, degrading sound even before it gets to the output stage

Class C

The transistor is "on" less than half the cycle of a sine wave. We say <180 of conduction. This class produces both even and odd order distortion, however is very efficient.

Class D

The class D amp has been developed after the short-comings of past generations, including classes A, B, AB, and C. Many people mistake the D as standing for digital. Although it is a "switching" amp, meaning it turns "on" and "off" at a specific frequency, it is a wrong assumption. D was simply the next letter in the alphabet. Consuming the least power out of its previous generations, the class D amps are generally smaller, making them ideal for mobile devices. It is because of their power efficiency, small size, and cheaper costs that the class D amps are quickly becoming the new industry standard for audio electronic. Companies such as Advanced Analog[2], Texas Instruments[3] as well as other companies have released 50W stereo class d amplifiers that are the size of a penny and did not require any sort of heat sinking, something that was not possible with other types of amplifiers.

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2   `http://www.analogictech.com`
3   `http://www.ti.com`
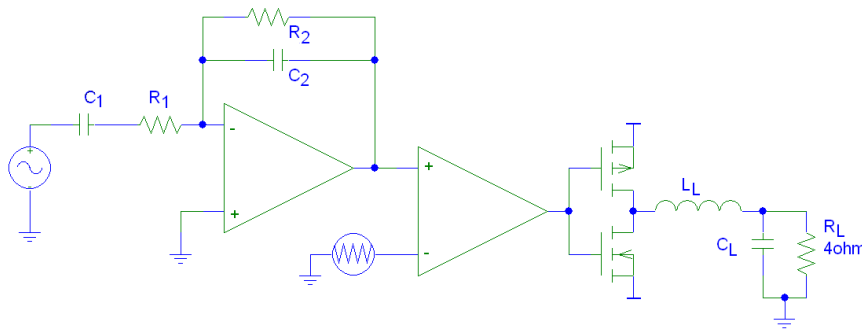
Figure 175   class d amplifier

The basic design includes two MOSFET transistors[4] in series, one pFET and one nFET being driven by a pulse width modulated (PWM) signal. Because of the properties of MOSFET transistors they are either fully on or fully off. When the transistor is off and the current is zero (so the amount of power wasted heating up the transistor is zero), or the transistor is fully on and the voltage across it is very close to zero (so the amount of power wasted heating up the transistor is again, very close to zero).

Because an analog signal needs to be transformed into a PWM signal a certain amount of distortion can occur, but the amount of distortion can be minimized. Because a PWM signal is very much like a digital signal, the sampling theorem[5] states that if the sampling frequency is more than half the maximum frequency of the source it can be reproduced exactly. For audio signals the maximum frequency heard by humans is roughly 20kHz, so a PWM generator would only need to provide a minimum switching frequency of 40kHz. Because of the availability of faster components many class d amplifier designers will use switching frequencies closer to 400kHz to further reduce the distortion.

Issues of concern with a class d amplifier include electromagnetic emissions. Due to the presence of a medium frequency signal[6] in the circuit, steps must be taken to reduce the emission of these signals that could interfere with other electronic devices.

Class E

(oops, class D again?) Switching amplifier These amplifiers are erroneously called "digital" amplifiers by the press and many audio "experts." Here's the skinny on Class D: While some Class D amps do run in true digital mode, using coherent binary data, most do not. They are better termed "switching" amplifiers, because here the output devices are rapidly switched on and off at least twice for each cycle. Depending on their switching frequency, they may be "switched on" or "off" millions of times a second. Class D operation is theoretically 100% efficient, but in practice, they are closer to 80-90% efficiency. This efficiency gain is at the cost of high-fidelity.

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4   http://en.wikibooks.org/wiki/Semiconductors%2FMOSFET_Transistors
5   http://en.wikibooks.org/wiki/Analog_and_Digital_Conversion%2FSampling_Theorem
6   http://en.wikibooks.org/wiki/Electronics%2FFrequency_Spectrum

Think of Class D amps as being similar to a switchable power supply, but with audio signals controlling, or modulating, the switching action. To do this, you use a technology called Pulse Width Modulation (or PWM, a technology found in many CD players).

According to experts, audio signals can be used to modulate a PWM system to create a high power audio amplifier at fairly low voltages using very small components. Class D audio uses a fixed, high frequency signal having pulses that vary in width based on input signal amplitude. So, for example, a deep bass note creates a large pulse in the carrier signal. This can be translated into a musical signal by the on/off nature of the output devices.

Class D amplifiers are generally used for non-high-fidelity, or subwoofer applications.

There is a fifth (and, nominally, a sixth) class of amplifier, but they are rarely seen in practice in the consumer market. One is the Class G and the other Class H. These are similar in design to Class AB topologies, but both feature two power supplies that switch on or off, depending on the musical signal imputed. Using two power supplies improves efficiency enough to allow significantly more power for a given size and weight. Class G is becoming common for pro audio designs. Class H amps are designed to use the same topology as Class G, but it provides just enough voltage for optimum operation of the output devices. Again, its an attempt to increase efficiency, but at the expense of fidelity ultimately.

Class F

Class S

37.6 Amplifier
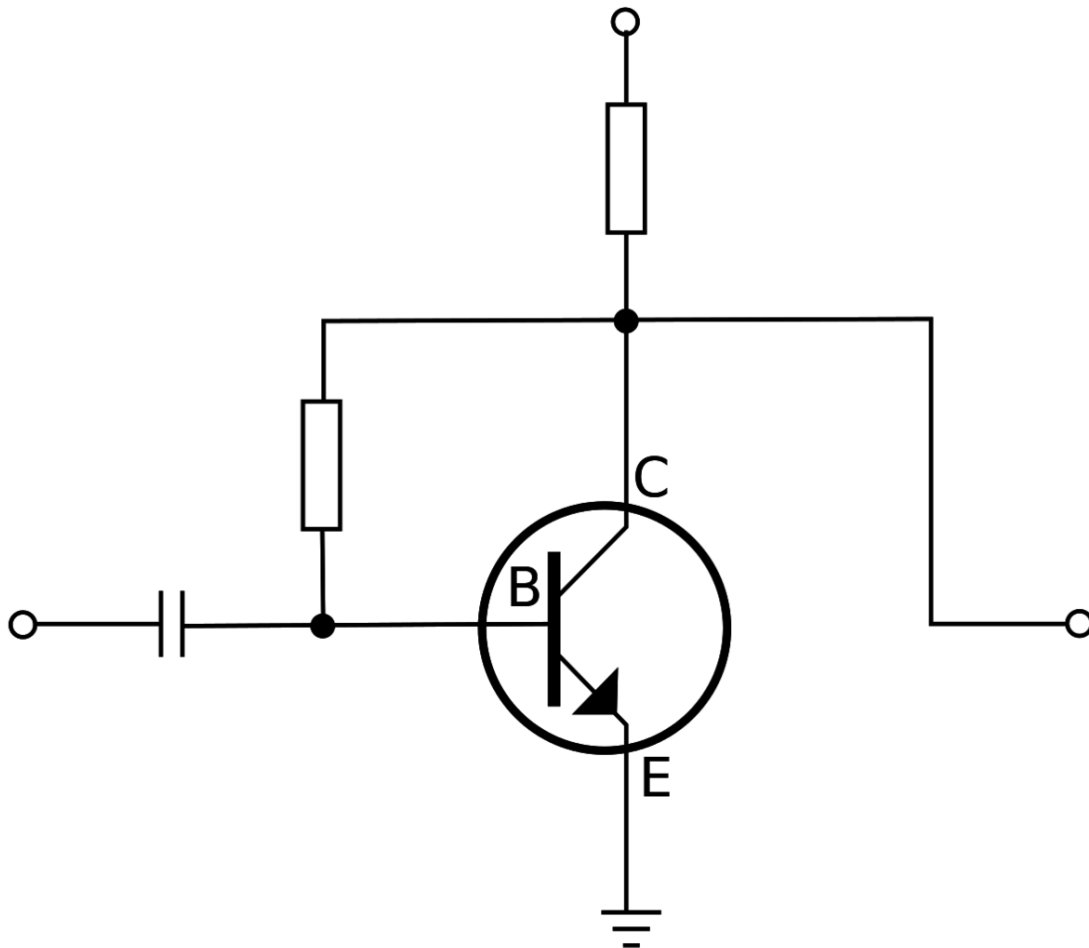
Figure 176

38 Operational amplifiers

39 Analog multipliers

39.1 Analog multipliers

An analog multiplier is a circuit with an output that is proportional to the product of two inputs:

$$v_{out} = K v_1 \cdot v_2$$

where K is a constant value whose dimension is the inverse of a voltage. In general we might expect that the two inputs can be both positive or negative, and so can be the output. Anyway, most of the implementations work only if both inputs are strictly positive: this is not such a limit because we can shift the input and the output in order to have a core working only with positive signals but external interfaces working with any polarity (within certain limits according to the particular configuration).

Two possible implementations will be shown. Both will be using operational amplifiers, but the first one will use diodes to get the needed relationships, the second one MOSFET transistors.

39.2 Diode Implementations

As known, using operational amplifiers and diodes it's quite easy to obtain the logarithm and the exponential of a certain input. Remembering the property of logarithms:

$$\log(a \cdot b) = \log a + \log b$$

we can multiply two signals first calculating their logarithm, then summing them and finally calculating the exponential of such a sum. From the point of view of mathematics, such an approach works as long as the two inputs are positive, because the logarithm of a negative number does not exist (in the real domain). We'll see that this limit is valid for the actual circuit as well, even if the reason will be more "physical". The block diagram of this implementation is the following:
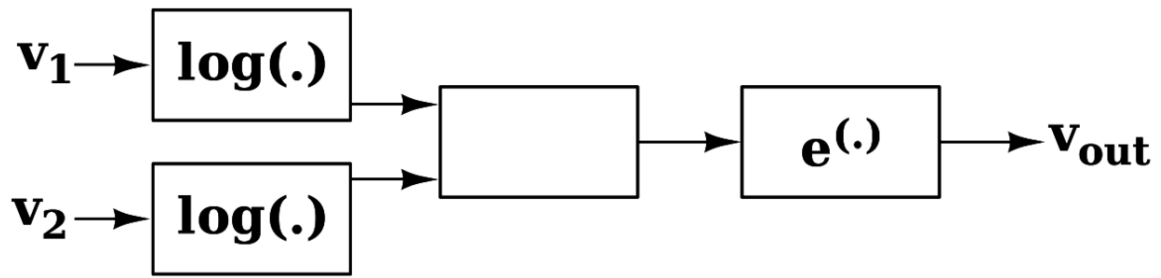
Figure 177

If we simply append the circuits for logarithm, sum and exponential we get the following configuration:
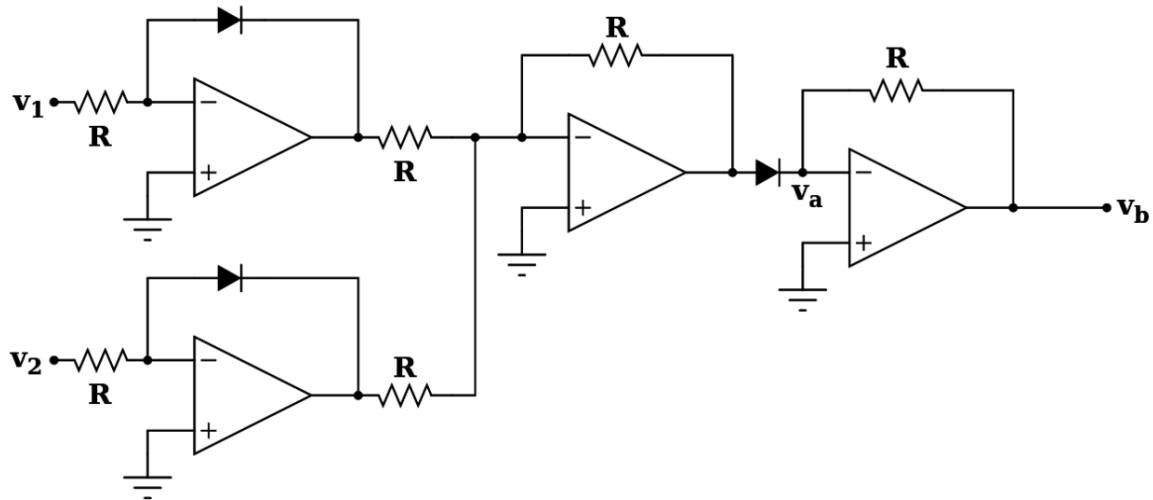
Figure 178

for a quick overview on the behavior of the circuit, we'll assume that all the resistors R have the same value. It is obviously possible to use different values to get different results, but we will not consider it here. Let us use the following notation for the relationship between current and voltage on a diode:

$$i = I_s \left(e^{\frac{v}{V_T}} - 1 \right)$$

where $V_T \simeq 0.6V$ is the threshold voltage and I_s is the current flowing through the diode if it's inverse-polarized. If we analyze the circuit without introducing any approximation we get:

$$v_a = -\left[-V_T \ln\left(\frac{v_1}{RI_s} + 1 \right) - V_T \ln\left(\frac{v_2}{RI_s} + 1 \right) \right] = V_T \ln\left[\left(\frac{v_1}{RI_s} + 1 \right) \left(\frac{v_2}{RI_s} + 1 \right) \right]$$

so the final output is:

$$v_b = -RI_s \left(e^{\frac{v_a}{V_T}} - 1 \right) = -\frac{v_1 \cdot v_2}{RI_s} - (v_1 + v_2)$$

as it is clear, in the output there is the multiplication we were looking for, but there is another term we don't want. It can't be simply considered an error because it might be as great as the multiplication element, so it has to be removed. Anyway this is an easy task, since it is necessary only to add another stage to sum exactly $v_1 + v_2$, so we will have no error. The complete multiplier circuit is the following:
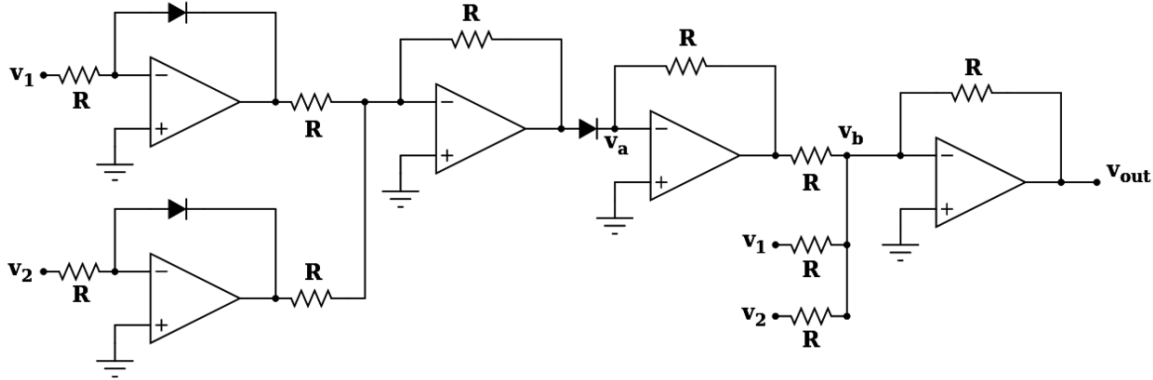
Figure 179

where the output voltage is given by:

$$v_{out} = -\left(-\frac{v_1 \cdot v_2}{RI_s} - (v_1 + v_2) + (v_1 + v_2) \right) = \frac{v_1 \cdot v_2}{RI_s}$$

that's exactly what we wanted. The circuit works as long as the following relationship is verified:

$$v_1, v_2 > -RI_s$$

so the inputs can be zero or sightly negative but, since RI_s will be a small voltage, we are allowed to rewrite the relation simply as $v_1, v_2 \geq 0$. From the mathematical point of view this is due to the fact that we can't calculate the logarithm of a negative number, from a physical point of view the limit is due to the fact that we can obtain only very small currents (almost zero) inverse-polarizing the diodes.

In practical applications, the diodes are replaced with BJTs connected so to work like a diode.

39.3 MOS implementation
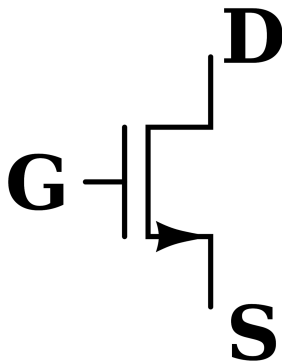
Figure 180

Since it is possible to use a MOSFET transistor as a voltage controlled resistor, we can use this feature to create an analog multiplier. Let us refer to picture on the right. With the letter we indicate the different pins: **D** rain, **S** ource and **G** ate. MOS are symmetrical devices, so we could replace the drain with the source without affecting the behavior of the device. Anyway we'll call *source* the lowest voltage pin and *drain* the point with the highest voltage. When the voltage between gate and source is less than the voltage between drain and source, i.e. $V_{GS} < V_{DS}$, the relationship between current and voltage is the following:

$$I_{DS} = K[2(V_{GS} - V_T)V_{DS} - V_{DS}^2] \simeq 2K(V_{GS} - V_T)V_{DS}; \qquad V_{GS} < V_{DS}$$

assuming we can always use this relationship, the analog multiplier configuration is the following:
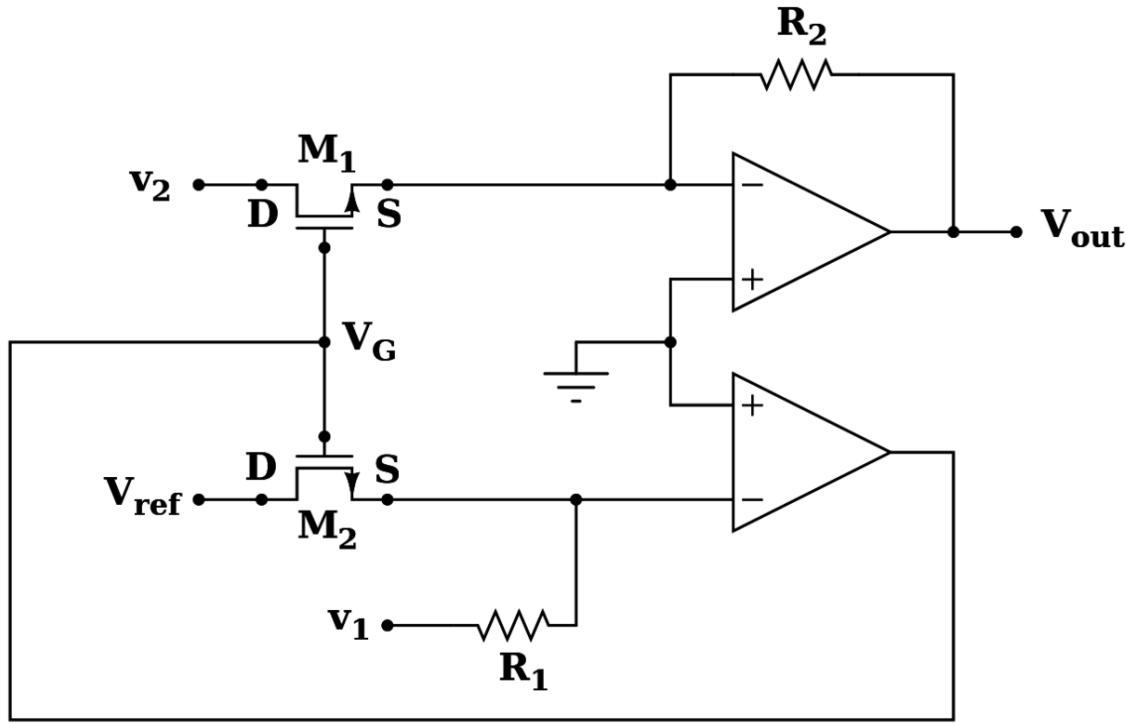
Figure 181

where source and drain of both devices are pointed out. If v_2 and V_{ref} are positive, then the sources will remain there because that points are virtually connected to ground by the operational amplifiers. The current flowing through R_1 is defined: one side of the resistor has the voltage v_1, the other one is grounded. That same current will flow through the MOS M_1, thus defining the voltage V_G. The current is given by:

$$\frac{v_1}{R_1} = -I_{DS1} = -2K(V_{GS1} - V_{T1})V_{DS1}$$

but $V_{GS1} = V_G$ and $V_{DS1} = V_{ref}$. replacing and calculating we get:

$$V_G = V_{T1} - \frac{v_1}{2KR_1V_{ref}}$$

considering the other MOS M_2 we have:

$$I_{DS2} = 2K(V_{GS2} - V_{T2})V_{DS2}$$

where $V_{GS2} = V_G$ and $V_{DS2} = v_2$. Replacing we get:

$$I_{DS2} = -\frac{v_1 v_2}{R_1 V_{ref}}$$

from which we finally get the output voltage:

$$v_{out} = \frac{R_2}{R_1} \frac{v_1 v_2}{V_{ref}}; \qquad V_{ref}, v_1, v_2 > 0$$

and this is what we wanted. The difference between the previous configurations are:

- the MOS implementation is simpler and requires fewer devices
- in the calculations for the diode configuration we did not introduce any approximation, while the MOS configuration we did.

In other words, the diode implementation is more complicated but it works fine for a wider range on inputs.

39.4 Chapter 4: Digital Circuits

40 Digital Circuits

40.1 Overview

In Digital circuits there are two parts one is Digital the other is circuits.

Digital

means a description of system which operates on digits or numbers.

The numbers that a digital system operates upon are binary numbers.One binary digit just have two values '0' and '1'. This '0' or '1' are analogous to 'off' and 'on', 'false' and 'true', etc. The Binary digIT is known as 'bit'. In day to day activities we use numbers and every digit of that number can be between 0 - 9. We use combination of such digital to for numbers bigger than 9. Similarly we can use combination of bits, i.e. combination of 1 & 0, to form bigger binary numbers.

Circuit can be any electric circuit and Digital circuit is a circuit which is designed to implement the description of digital circuit.

Digital circuits are developed using a special type of mathematics called 'Boolean Algebra'.

41 Boolean Algebra

41.1 Boolean Algebra

Boolean Algebra was created by George Boole (1815 - 1864) in his paper *An Investigation of the Laws of Thought, on Which Are Founded the Mathematical Theories of Logic and Probabilities* , published in 1854. It had few applications at the time, but eventually scientists and engineers realized that his system could be used to create efficient computer logic. The Boolean system has two states: **True** (T) or **False** (F). This can be represented in several different ways as on or off, one or zero, yes or no, etc. These states are manipulated by three fundamental operations called *logical operators* : **AND** , **OR** and **NOT** . These operators take certain inputs and produce an output based on a predetermined table of results. For example, the AND operator takes two (or more) inputs and returns an 'on' result only when both (or all) inputs are 'on'.

- In these tables T means "True", or "Yes", or 1 (in electronics), and
- F means "False", or "No" or 0 (in electronics).
- For example, the 1st line of the AND table says that if A is F and B is F then the result also is F. This is also said often as If A is 0 and B is also 0, then A AND B = 0 times 0 = 0
- Also at the bottom of the AND table 1 times 1 is 1.
- Looking at the OR table, use plus instead of times: 0 plus 0 is 0, where again 0 is F and 1 is T. Only 0 and 1 exist, therefore if the result of the addition is more than 1, then change it to 1.

Truth Tables

AND

A	B	$A \wedge B$
F	F	F
F	T	F
T	F	F
T	T	T

OR

A	B	$A \vee B$
F	F	F
F	T	T
T	F	T
T	T	T

NOT

A	$\bar{A}$
F	T
T	F

These simple operators are good because they allow us to create very simple logic circuits: if user put in a quarter AND the Coke button is pressed, drop a Coke

There are ways, however, to combine these expressions to make much more complex but useful digital circuits. By using multiple operators on the same inputs, it is possible to create much more complex outputs. An expression like: A and B or C would have a truth table of the following:

A and B or C

A	B	C	X
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

This truth table follows the rules If A and B are true, or C is true, then X is true

Exercise: Go through each case in the table and check it using the above statement.

41.1.1 Formal Mathematical Operators

AND is represented by $\wedge$ or $\cdot$ that is A AND B would be $A \wedge B$ or $A \cdot B$.

OR is represented by $\vee$ or $+$ that is A OR B would be $A \vee B$ and $A + B$.

NOT is represented by $\neg$ or $^-$ that is NOT A is $\neg A$ or $\bar{A}$.

If these three operators are combined then the NOR and NAND can be created. So A NOR B is $\neg(A \vee B)$ or $\overline{A + B}$. NAND is $\neg(A \wedge B)$ or $\overline{A \cdot B}$. Other notations are valid as well, and many different combinations of them arise in mathematics and engineering. No universal standard has been agreed upon. However, most sources will make explicit the particular notation used.

41.1.2 Boolean Algebra Laws

Boolean Algebra, like regular algebra, has certain rules. These rules are Associativity, Distributivity, Commutativity and De Morgan's Laws. Associativity, Commutativity and Distributivity only apply to the AND and OR operators. Some of these laws may seem trivial in normal Algebra but in other algebras they are not.

Associativity

Associativity is the property of algebra that the order of evaluation of the terms is immaterial.

•

$$A \vee (B \vee C) = (A \vee B) \vee C$$

$$A \wedge (B \wedge C) = (A \wedge B) \wedge C$$

Or

$$A + (B + C) = (A + B) + C$$

$$A.(B.C) = (A \cdot B) \cdot C$$

Wikipedia:Associativity[1]

Distributivity

Distibutivity is the property that an operator can be applied to the terms within the brackets.

$$A \wedge (B \vee C) = (A \wedge B) \vee (A \wedge C)$$

Or

$$A.(B + C) = (A \cdot B) + (A \cdot C)$$

Wikipedia:Distributivity[2]

Commutativity

Commutativity is the property that order of application of an operator is immaterial.

$$A \wedge B = B \wedge A$$

$$A \vee B = B \vee A$$

Or

---

1   http://en.wikipedia.org/wiki/Associativity
2   http://en.wikipedia.org/wiki/Distributivity

$$A \cdot B = B \cdot A$$

$$A + B = B + A$$

Wikipedia:Commutativity[3]

De Morgan's Law

De Morgan's Law is a consequence of the fact that the not or negation operator is not distributive.

$$\neg(P \wedge Q) = (\neg P) \vee (\neg Q)$$

$$\neg(P \vee Q) = (\neg P) \wedge (\neg Q)$$

Or

$$\overline{P \cdot Q} = \bar{P} + \bar{Q}$$

$$\overline{P + Q} = \bar{P} \cdot \bar{Q}$$

Notes

It is important to note that

$$A \wedge B \vee C \neq A \wedge (B \vee C)$$

Or

$$A \cdot B + C \neq A \cdot (B + C)$$

This can be seen as either AND having a higher precedence or the fact that Associativity does not hold between AND and OR or that it is an invalid application of distributivity.

Another way of looking at this is the possible application of our understanding of normal algebra rules using the second notation. Where clearly the analogy between OR being addition and AND being multiplication is made. We would never make this error if this were high school algebra.

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3   http://en.wikipedia.org/wiki/Commutativity

Rules

All of these Laws Result in a number of rules used for the reduction of Boolean Algebra.

1. $A \wedge A = A$
2. $A \vee A = A$
3. $A \wedge 1 = A$
4. $A \vee 1 = 1$
5. $A \wedge 0 = 0$
6. $A \vee 0 = A$
7. $A \wedge \neg A = 0$
8. $A \vee \neg A = 1$
9. $\neg(\neg A) = A$
10. $A \vee \neg A \wedge B = A \vee B$
11. $\neg A \vee A \wedge B = \neg A \vee B$

Or

1. $A \cdot A = A$
2. $A + A = A$
3. $A \cdot 1 = A$
4. $A + 1 = 1$
5. $A \cdot 0 = 0$
6. $A + 0 = A$
7. $A \cdot \bar{A} = 0$
8. $A + \bar{A} = 1$
9. $\bar{\bar{A}} = A$
10. $A + \bar{A} \cdot B = A + B$
11. $\bar{A} + A \cdot B = \bar{A} + B$

41.1.3 Examples

Simplify the following Expressions.

1. $B \wedge A \wedge \neg A$
2. $A \wedge \neg B \vee A \wedge B$

Or

1. $B \cdot A \cdot \bar{A}$
2. $A \cdot \bar{B} + A \cdot B$

For number 1 using rule 7. We get.

$$B \wedge 0 = 0$$

Or

$$B \cdot 0 = 0$$

Which happens to be rule 5 so the answer is zero. In number 2 we can take out A. Given

$$A \wedge (\neg B \vee B)$$

Or

$$A \cdot (\bar{B} + B)$$

The Expression within brackets is rule 8. So the answer is A.

41.1.4 See also

Wikipedia: Boolean logic[4]

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4   http://en.wikipedia.org/wiki/Boolean%20logic

42 TTL

42.1 Introduction

TTL stands for **Transistor-Transistor Logic** . It is the system based on combining transistors in such a way that they can be used for logic gates. Transistors have the capability of becoming parts of very complex devices when combined. An average microprocessor uses upwards of 40 million transistors. Transistors in microprocessors, however, are microscopic as opposed to the discrete components used in consumer electronics and circuitboards.

42.2 The NOT Gate

The NOT gate works by inverting the input. The TTL version of the NOT gate contains one transistor, seen below:
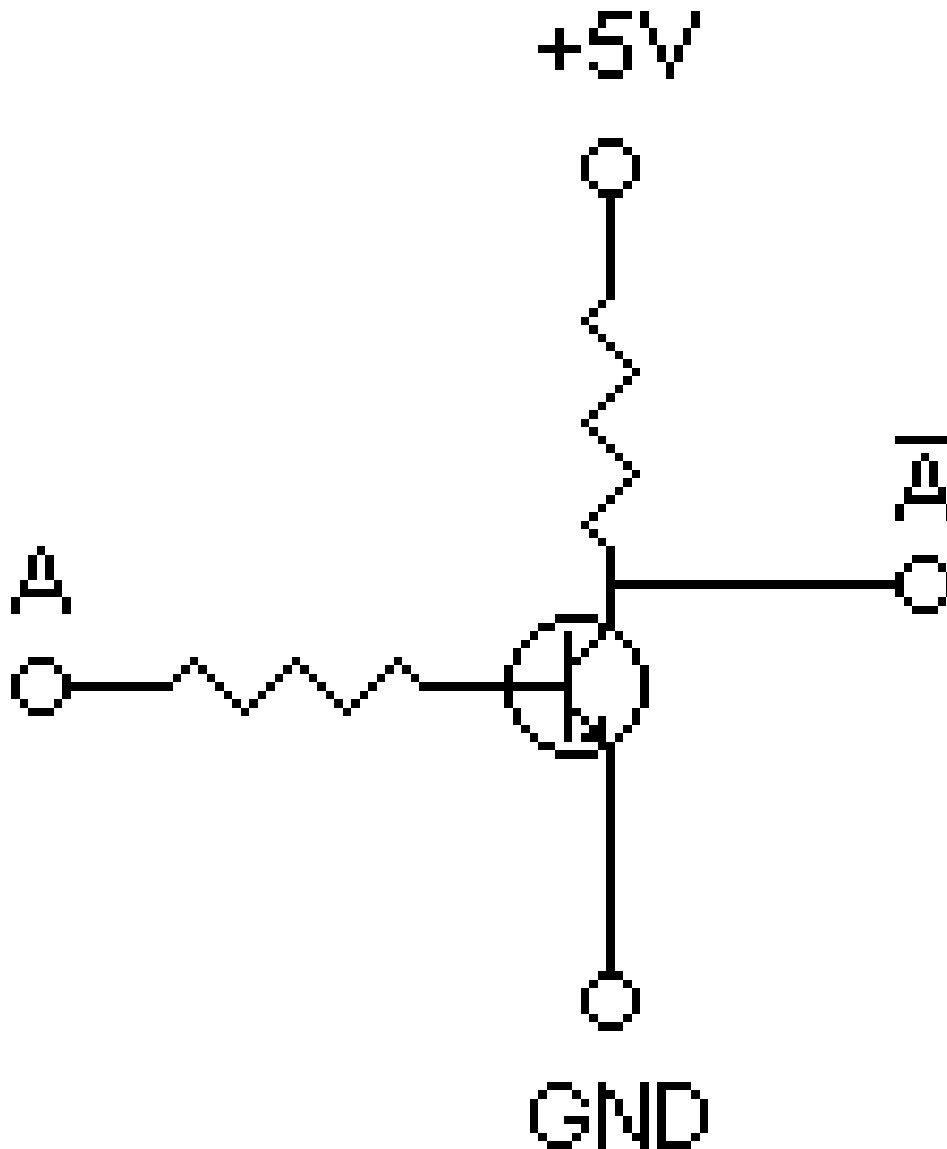
Figure 182

When the input, A, is **high** (+5V), the base of the transistor is saturated, allowing current to flow from the collector of the transistor to the emitter. Since this is possible, the current does not take the higher resistance path through the output (assuming it has a resistive load attached to it such as an LED). When the input is **low** (0V), the current has no choice but to flow out of the inverted A output (the A with the line overtop to indicate it is negated). The two resistors in the circuit are for limiting current as to not destroy the transistor, and sometimes may not even be required depending on the transistor.

(note: this image is considered *Resistor-Transistor Logic* The proper TTL representation is below.)
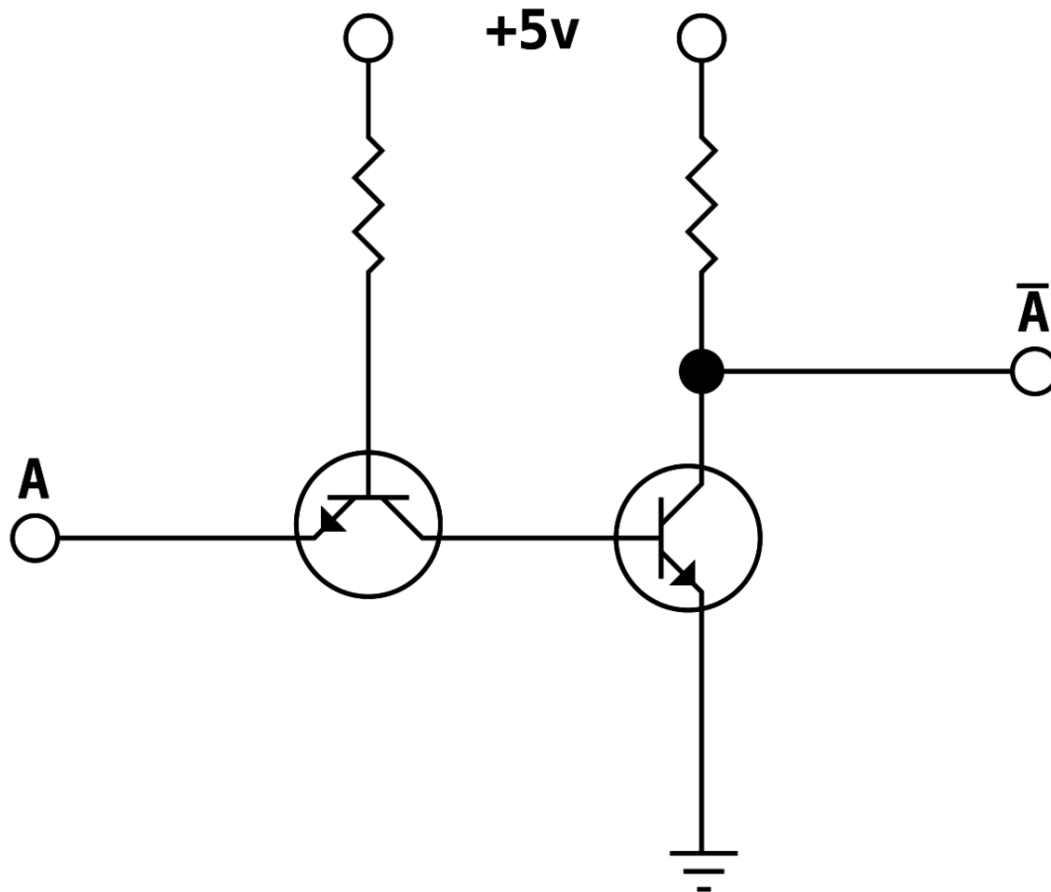
Figure 183   TTL Inverter (NOT Gate)

To further explain, the NOT gate has been integrated into a circuit by connecting it to a current probe and a battery. When the switch for the input of the not gate is not hit, the current flows in the path indicated by the red diagram below. The current flows through the resistor because the transistor does not conduct when the base is not saturated.:
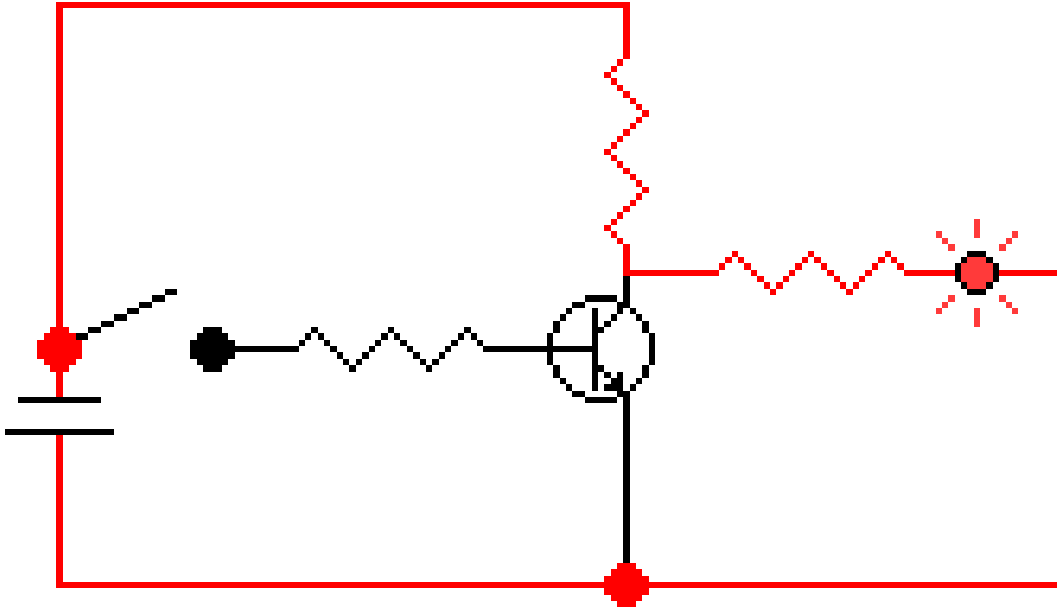
Figure 184

However, when the switch is hit, making the input **high** , the circuit is shorted and current flows directly from one terminal of the battery through the transistor, to the other terminal. This is illustrated further in the next figure:
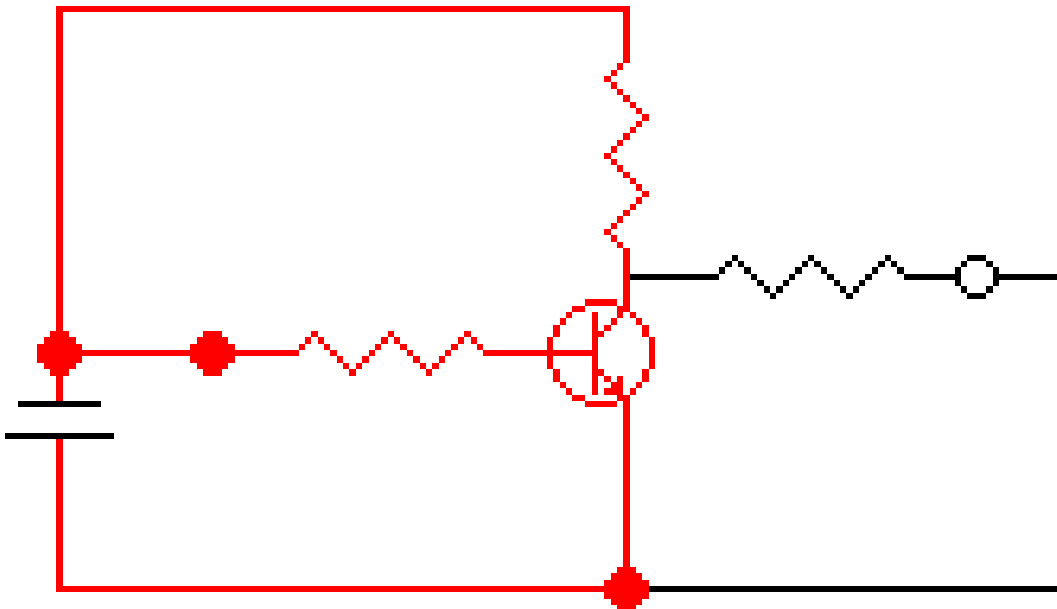
Figure 185

In real logic gates, several more transistors are used in order to stabilize the input and output. Although this may seem like a large hike in complexity and price, creating transistors in ICs is a lot cheaper and easier to do, as they do not have to even have a shell or casing, and are a lot smaller.

43 CMOS

43.1 CMOS

CMOS stands for **C** omplementary **M** etal-**O** xide-**S** emiconductor. Metal-Oxide-Semiconductor refers to the construction method of the component Field-Effect Transistors (MOSFETs), and Complementary means that CMOS uses both n-type (nMOS) and p-type (pMOS) transistors. Older designs had used only n-type transistors, and are referred to as NMOS logic.

n-type MOSFETs are active (conductive) when their input voltage is high, while p-type MOSFETs are active when their input voltage is low.

All CMOS gates are arranged in two parts: the pull-up network (PUN), built from p-type transistors and connect to source; and the pull-down network (PDN), built from n-type transistors and connected to ground (also called drain). The two parts are logical duals of each other, so that if the PUN is active, then the PDN is inactive, and vice-versa. In this way there can never be a direct path between source and ground (in any steady state).

The biggest advantage of CMOS over NMOS is that CMOS has a rapid change from both hi-to-low and from low-to-hi. NMOS transitions only slowly from low-to-hi (because it uses a resistor in place of a PUN), and since overall circuit speed must take into account the worst case, NMOS circuits must be much slower.
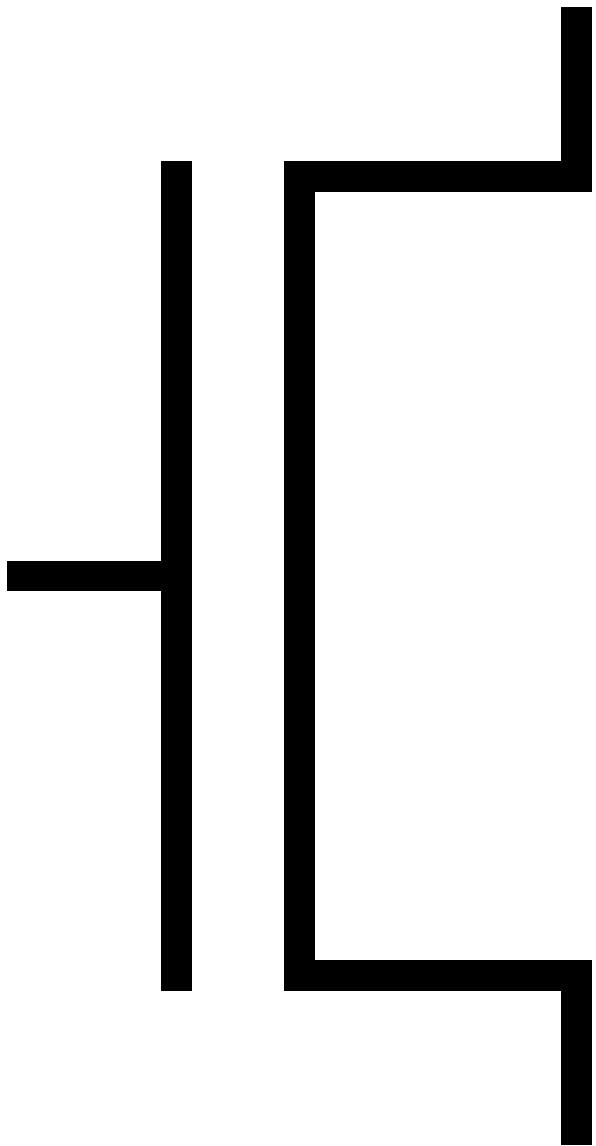
Figure 186
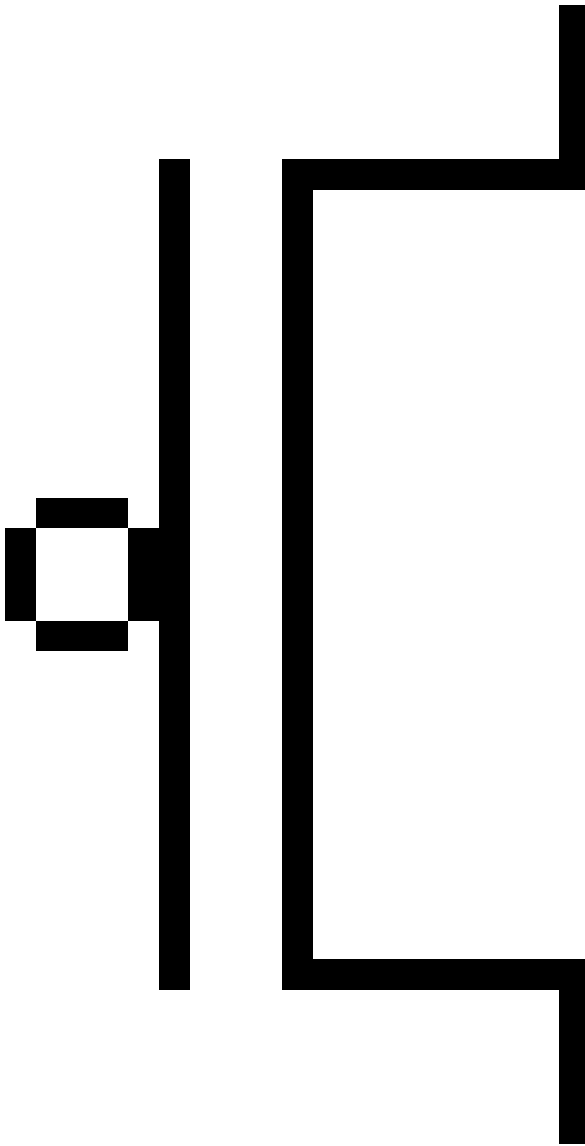
Figure 187

43.2 Logic Gates

43.2.1 NOT

The simplest CMOS circuit: the NOT gate, or inverter. Although uncomplicated, it demonstrates the basic structure of a CMOS gate; a series of inputs (in this case, one) which are connected to the transistors, the PUN (consisting of a single p-type transistor) connected to source, the PDN (consisting of a single n-type transistor) connected to ground, and the output which is fed from both the PUN and PDN.

When the input voltage is high, the p-type transistor will be inactive, and the n-type transistor will be active. This creates a connection between ground and the gate output,

pulling the gate's output to low. Conversely, when the input voltage is low, the p-type transistor will be active instead, creating a connection between the output and source, pulling the gate's output to high.
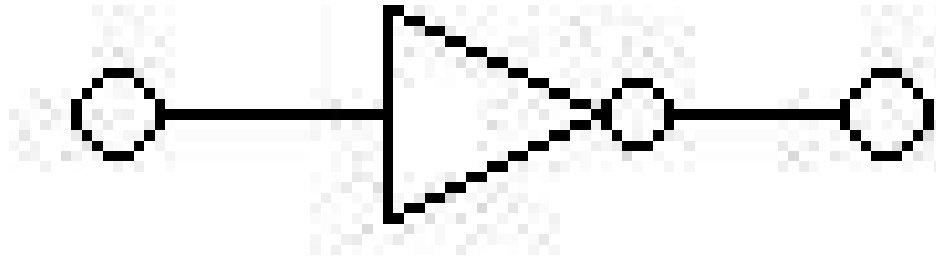
Figure 188

Input	Output
0	1
1	0

43.2.2 NAND

The PUN for NAND consists of a pair of p-type transistors in parallel, one with the A input feeding it and one with the B input feeding it. Therefore the PUN is active, and the output of the gate is high, as long as either of these inputs is low.

The PDN for NAND consists of a pair of n-type transistors in series, also each fed by one of the two inputs. Therefore the PDN is active, and the output of the gate is low, only if both of the inputs are high.it uses the logic a bar(OR)b bar

Input 1	Input 2	Output
0	0	1
0	1	1
1	0	1
1	1	0

43.2.3 AND

A CMOS AND gate is constructed by driving a NOT gate from the output of a NAND gate.

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

43.2.4 NOR

"Upside down" relative to the NAND gate, the NOR gate is made from a PUN of two p-type transistors in series and a PDN of two n-type transistors in parallel.

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	0

43.2.5 OR

As AND is to NAND, OR is to NOR. CMOS OR is constructed by feeding the output of NOR to a NOT gate.

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	1

43.2.6 XNOR

To build an XNOR gate, first we will need easy access to the inverted inputs. This is accomplished with a pair of NOT gates. The original inputs are A and B, and their inverted forms we will call NOT-A and NOT-B. Both the PUN and PDN are made of four of the appropriate type of transistor, in two parallel sets, of series of two transistors each. In the PUN there is one series fed by A and B and the other is fed by NOT-A and NOT-B; in the PDN one series is fed by A and NOT-B and the other is fed by NOT-A and B.

All told, this takes 12 transistors (4 in the PUN, 4 in the PDN, and 2 for each inverter). There are more efficient designs for the XNOR circuit, but they require a more detailed analysis than we will go into here. Instead of serving as an example of an actual XNOR design, this section should instead help to suggest the methods one could use to generate a CMOS circuit for any arbitrary boolean function.

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	1

43.2.7 XOR

If you've been following along, you may guess that an XOR gate is made by attaching a NOT onto the end of the XNOR; while this will produce *a* correct circuit, it is not the *most* correct

(or efficient) circuit. Instead, we could use the same 12 transistors and simply shuffle around the wires. This is left as an exercise for the reader. it uses the logic a.bbar(OR)abar.b

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	0

44

44.1 Elements of Digital Circuits

45 Transistors

45.1 Transistor

A transistor is a solid state device made by joining three positive-type and negative-type semiconductors together. In general, all transistors have three pins: base, collector, and emitter. Transistor is a bi-polar device that is a transistor with two junctions namely BE and CE DE EE FE. In theory we take a specified formulae incorporate this with using any type of meter in figuring the mathematical solution.
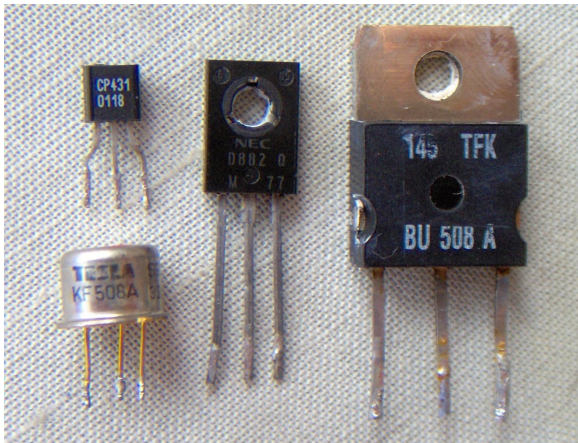
Figure 189

45.1.1 Construction

A lightly doped region called base is sandwiched between two regions called the emitter and collector respectively. The collector handles large quantities of current, hence its dopant concentration is the highest. The emitter's dopant concentration is slightly lesser, but its area is larger to provide for more current than the collector. The collector region should be heavily doped because electron-hole pairs recombine in that region, while the emitter is not such a region. We can have two varieties in this kind of transistor.

45.1.2 NPN Transistor

An NPN transistor is made by joining one positive-type semiconductor in between two negative-type semiconductors. Here a lightly doped p-type semiconductor (semiconductor with more holes than electrons) is sandwiched between two well-doped n-type regions. It is like two pn-junctions facing away. An IEEE symbol for the NPN transistor is shown here. The arrow between the base and emitter is in the same direction as current flowing between the base-emitter junction. Power dissipated in the transistor is

$P = V_{CE}I_C$, where V_{CE} is the voltage between the collector and the emitter and I_C is the collector current.
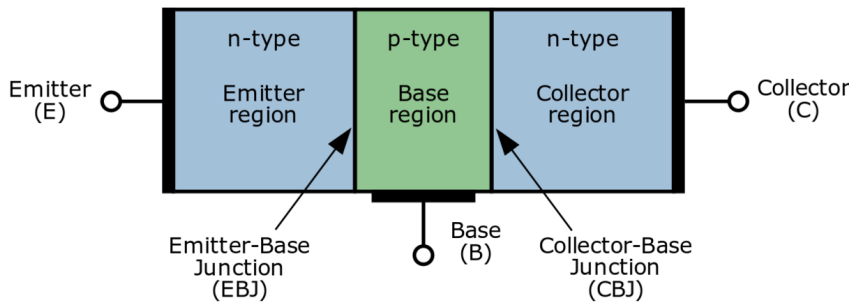
Figure 190
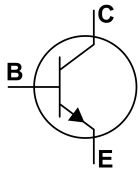
45.1.3 PNP Transistor

A PNP transistor is made by sandwiching a negative-type semiconductor in between two positive-type semiconductors.
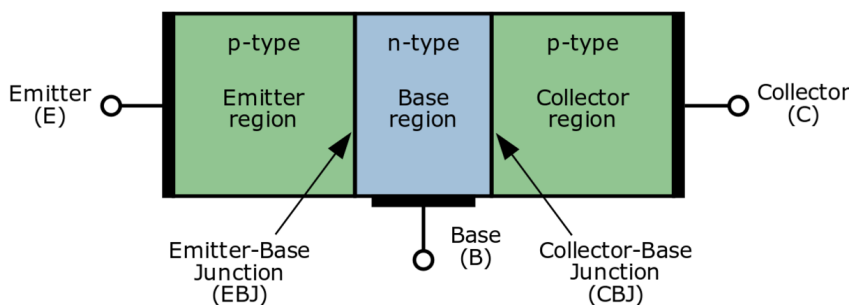
Figure 192

45.2 Transistor Operation

45.2.1 Amplifier

A transistor conducts current when the base voltage is greater than BE junction's voltage. Current is non zero.

$$I_B \neq 0$$

$$I_E = \alpha I_B$$

$$I_C = \beta I_B$$

45.2.2 Switch

A transistor conducts current when the base voltage is greater than BE junction's voltage. Current is non zero. This corresponds to a closed switch. A transistor does not conduct current when the base voltage is less than BE junction's voltage. Current is zero. This correspond to an open switch.

45.3 External links

w:Transistor[1]

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1   http://en.wikipedia.org/wiki/Transistor
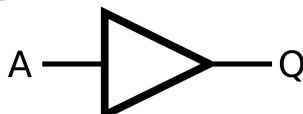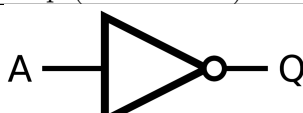
46 Basic gates

46.1 Basic Gates

There are 5 basic gates used in performing logic operations in Digital Electronic namely BUFFER gate, NOT gate, AND gate, OR gate, XOR gate . Each Logic Gate has A Symbol for easy to identify , a Mathematical Expression to identify mathmatic logic operation and a Truth Table to completely describe operation of the Logic Gate
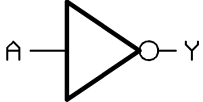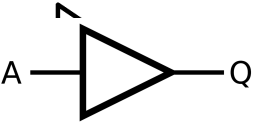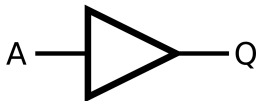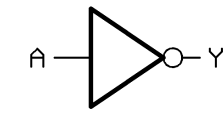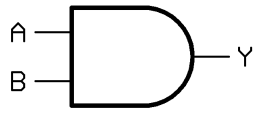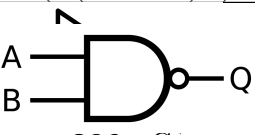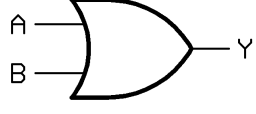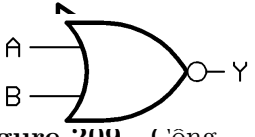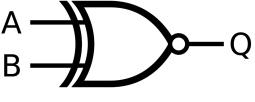
46.2 Five Basic Logic Gates

Digital gates	Symbol	Logic Operation	Mathematic Expression
BUFFER	**Figure 194** Cổng Tiếp (Buffer Gate)	Y = BUFFER A	Y = A
NOT	**Figure 195**	Y = NOT A	$Y = \bar{A}$
AND	**Figure 196**	Y = A AND B	Y = A . B
OR	**Figure 197**	Y = A OR B	Y = A + B
XOR	**Figure 198**	Y = A XOR B	$Y = A \oplus B$

The Truth Table of the five basic logic gates above

A	B	Q = A	Q = NOT A	Q = A AND B	Q = A OR B	Q = A XOR B
0	0	0	1	0	0	0
0	1	0	1	0	1	1
1	0	1	0	0	1	1
1	1	1	0	1	1	0
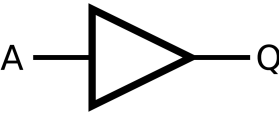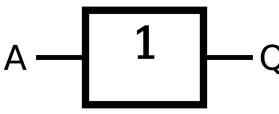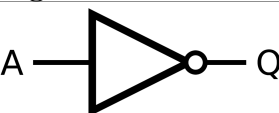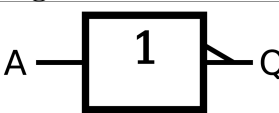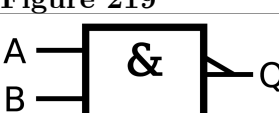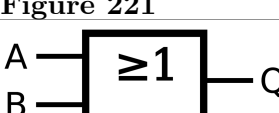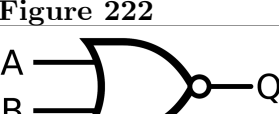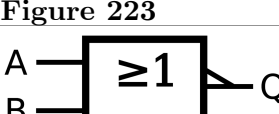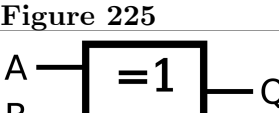
46.3 Complement of Basic Logic gates

Basic Gates	Combination Gates	Symbol	Mathematical Expression
BUFFER	**Figure 199**	**Figure 200** Công **Figure 201** NOT (NOT Gate)	Q = is NOT NOT A Y = A
NOT	**Figure 202**	Công **Figure 203** **Figure 204** Cổng NOT (NOT Gate) NOT (NOT Gate)	Y = is NOT A
NAND	**Figure 205**	**Figure 206** Công **Figure 207** NOT (NOT Gate)	Q = NOT A AND B
NOR	**Figure 208**	**Figure 209** Công **Figure 210** NOT (NOT Gate)	Y = NOT A OR B
XNOR	**Figure 211**	**Figure 212** **Figure 213**	Q = NOT A XOR B

The Truth table of the combination gates above

A	B	Q = A	Q = NOT A	Q = A NAND B	Q = A NOR B	Q = A XNOR B
0	0	0	1	1	1	1
0	1	0	1	1	0	0
1	0	1	0	1	0	0
1	1	1	0	0	0	1

46.4 Summary

Gates	Function	Symbol	
		ANSI	**IEC**
../Buffer/[1]	$Q = A$	A ———▷——— Q **Figure 214**	A —[1]— Q **Figure 215**
../NOT gate/[2] **(Inverter)**	$Q = \overline{A}$	A ———▷○— Q **Figure 216**	A —[1]◿— Q **Figure 217**
../AND gate/[3]	$Q = A \cdot B$	A, B ——D—— Q **Figure 218**	A, B —[&]— Q **Figure 219**
../NAND gate/[4] **(NOT−AND)**	$Q = \overline{A \cdot B}$	A, B ——D○— Q **Figure 220**	A, B —[&]◿— Q **Figure 221**
../OR gate/[5]	$Q = A + B$	A, B ——⟩⟩—— Q **Figure 222**	A, B —[≥1]— Q **Figure 223**
../NOR gate/[6] **(NOT−OR)**	$Q = \overline{A + B}$	A, B ——⟩⟩○— Q **Figure 224**	A, B —[≥1]◿— Q **Figure 225**
../XOR gate/[7] **(Exclusive-OR)**	$Q = A \oplus B$	A, B ——⟫⟩—— Q **Figure 226**	A, B —[=1]— Q **Figure 227**

1   http://en.wikibooks.org/wiki/..%2FBuffer%2F
2   http://en.wikibooks.org/wiki/..%2FNOT%20gate%2F
3   http://en.wikibooks.org/wiki/..%2FAND%20gate%2F
4   http://en.wikibooks.org/wiki/..%2FNAND%20gate%2F
5   http://en.wikibooks.org/wiki/..%2FOR%20gate%2F
6   http://en.wikibooks.org/wiki/..%2FNOR%20gate%2F
7   http://en.wikibooks.org/wiki/..%2FXOR%20gate%2F
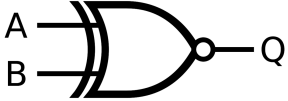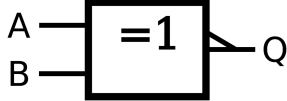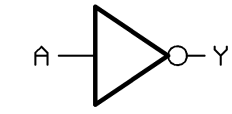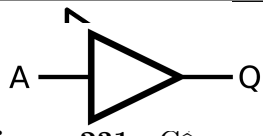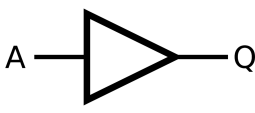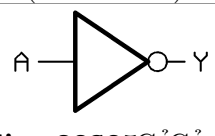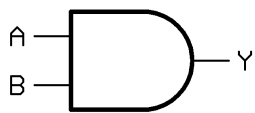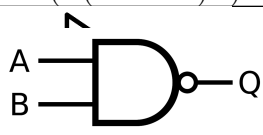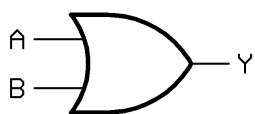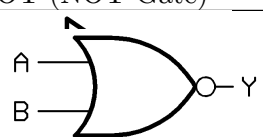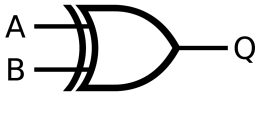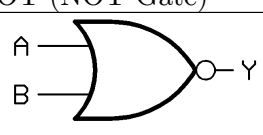
../XNOR gate/[8] **(NOT−exclusive−OR)**	$Q = \overline{A \oplus B}$	A, B → Q **Figure 228**	A, B → Q **Figure 229**

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8   http://en.wikibooks.org/wiki/..%2FXNOR%20gate%2F

A	B	Q = A	Q = NOT A	Q = A AND B	Q = A OR B	Q = A XOR B	Q = A NAND B	Q = A NOR B	Q = A XNOR B
0	0	0	1	0	0	0	1	1	1
0	1	0	1	0	1	1	1	0	0
1	0	1	0	0	1	1	1	0	0
1	1	1	0	1	1	0	0	0	1

47 Combination gates

47.1 Complement of Basic Logic gates

Basic Gates	Combination Gates	Symbol	Mathematical Expression
BUFFER	Figure 230	Figure 231 Cổng NOT (NOT Gate) Figure 232	Y = is NOT NOT A Y = A
NOT	Figure 233	Figure 234 Cổng NOT (NOT Gate) Figure 235	Y = is NOT A
NAND	Figure 236	Figure 237 Cổng NOT (NOT Gate) Figure 238	Y = NOT A AND B
NOR	Figure 239	Figure 240 Cổng NOT (NOT Gate) Figure 241	Y = NOT A OR B
XNOR	Figure 242	Figure 243 Figure 244	Y = NOT A NOR B

Truth table of the combination gates

A	B	Q = A	Q = NOT A	Q = A NAND B	Q = A NOR B	Q = A XOR B
0	0	0	1	1	0	0
0	1	0	1	1	0	1
1	0	1	0	1	0	1
1	1	1	0	0	1	0

47.2 XOR

(A AND B) OR (A OR B) = A XOR B

(A.B) + (A+B) = A+B

48 Flip Flops

48.1 Flip Flop

A **flip-flop** is a device very like a latch[1] in that it is a bistable multivibrator, having two states and a feedback path that allows it to store a bit of information. The difference between a latch and a flip-flop is that a latch is asynchronous, and the outputs can change as soon as the inputs do (or at least after a small propagation delay). A flip-flop, on the other hand, is *edge-triggered* and only changes state when a control signal goes from high to low or low to high. This distinction is relatively recent and is not formal, with many authorities still referring to flip-flops as latches and vice versa, but it is a helpful distinction to make for the sake of clarity.

There are several different types of flip-flop each with its own uses and peculiarities. The four main types of flip-flop are : SR, JK, D, and T.

48.1.1 RS Flip Flop

An **SR latch** (Set/Reset) is an asynchronous device: it works independently of control signals and relies only on the state of the S and R inputs. In the image we can see that an SR flip-flop can be created with two NOR gates that have a cross-feedback loop. SR latches can also be made from NAND gates, but the inputs are swapped and negated. In this case, it is sometimes called an $\overline{\textbf{S}}\overline{\textbf{R}}$ **pt latch** .

An SR (Set/Reset) flip-flop is perhaps the simplest flip-flop, and is very similar to the SR latch[2], other than for the fact that it only transitions on clock edges. While as theoretically valid as any flip-flop, synchronous edge-triggered SR flip-flops are extremely uncommon because they retain the illegal state when both S and R are asserted. Generally when people refer to SR flip-flops, they mean SR latches.

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1   http://en.wikibooks.org/wiki/Digital%20Circuits%2FLatches
2   http://en.wikibooks.org/wiki/Digital%20Circuits%2FLatches%23SR%20latch
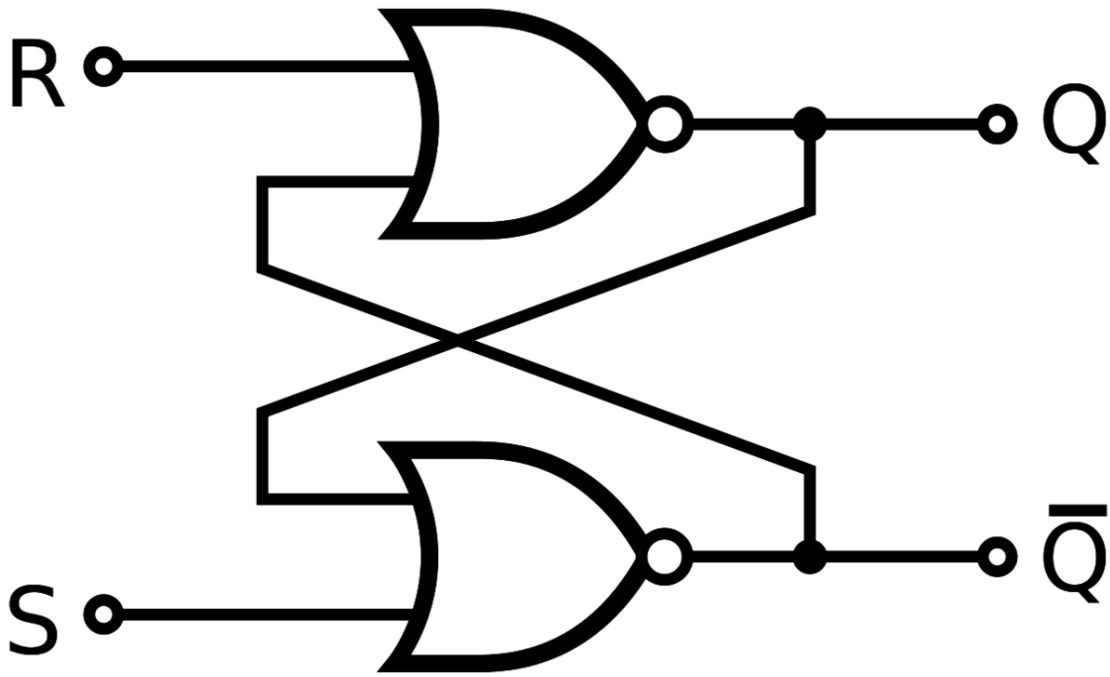
Figure 245 An SR latch made from two NOR gates.
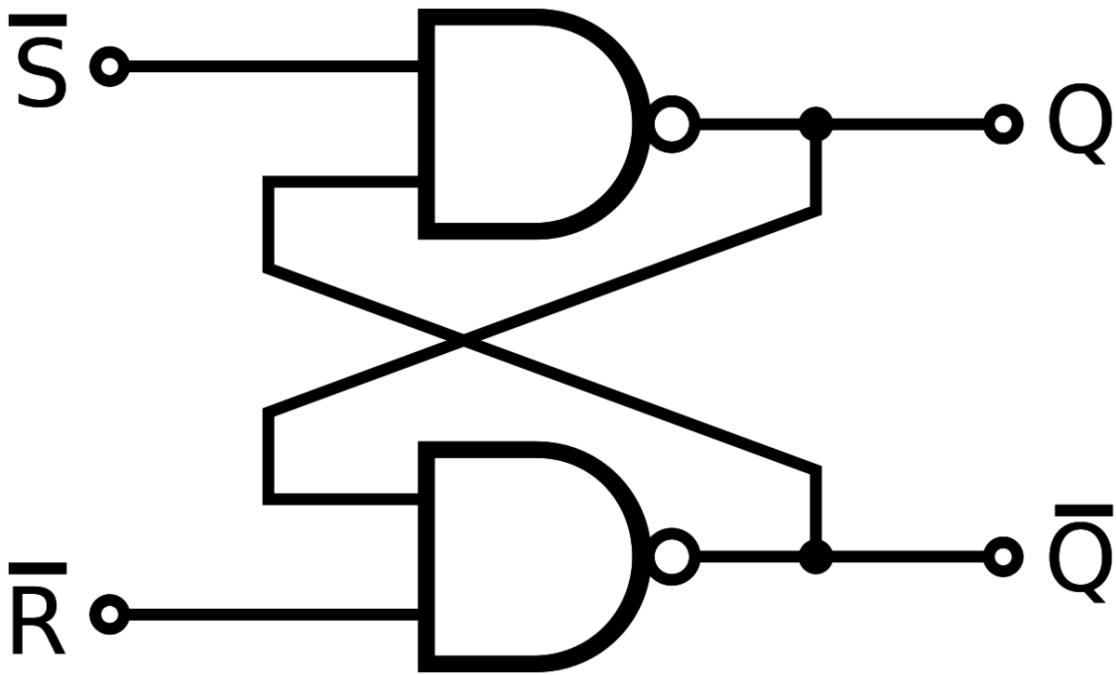
Figure 246 An $\overline{S}\overline{R}$pt latch made from two NAND gates.
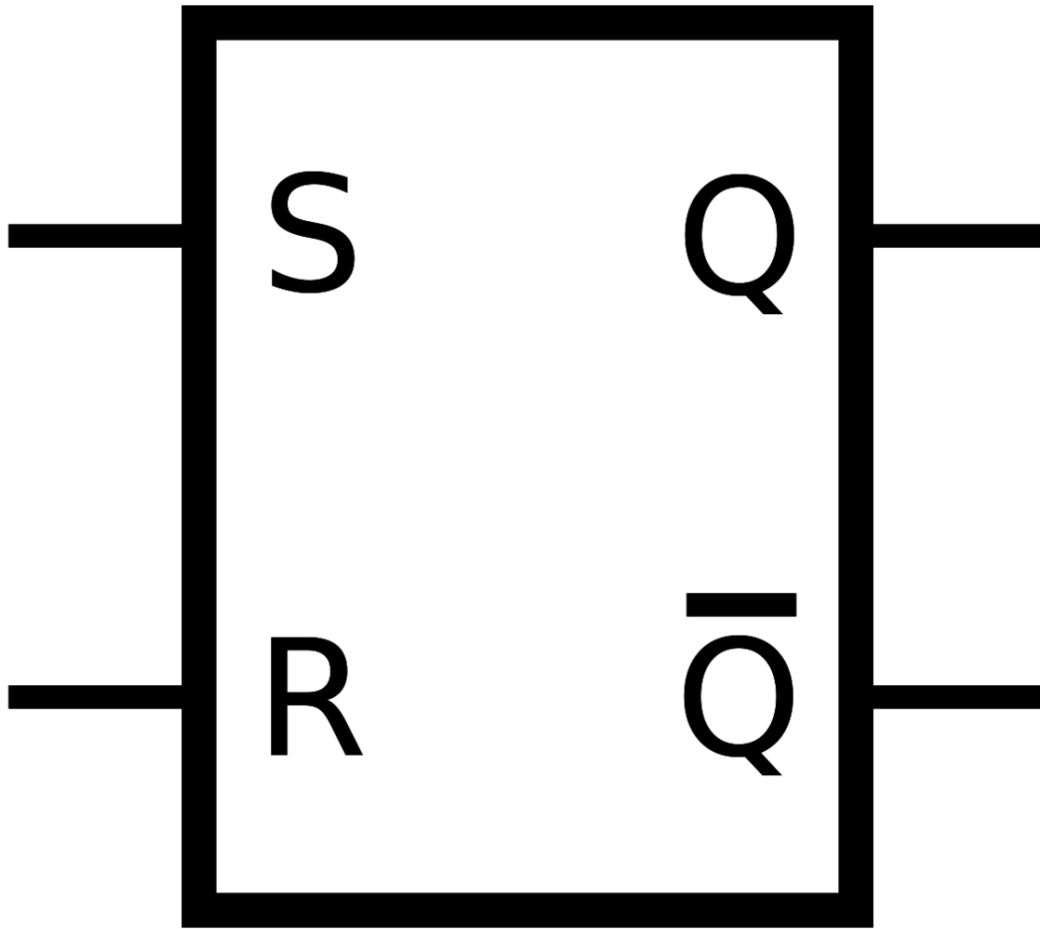
Figure 247 Circuit symbol for an SR latch.

S	R		Q	$\overline{Q}$
0	0		**Latch**	
0	1		0	1
1	0		1	0
1	1		Metastable	

When a high is applied to the *Set* line of an SR latch, the Q output goes high (and $\overline{Q}$ low). The feedback mechanism, however, means that the Q output will remain high, even when the S input goes low again. This is how the latch serves as a memory device. Conversely, a high input on the *Reset* line will drive the Q output low (and $\overline{Q}$ high), effectively resetting the latch's "memory". When both inputs are low, the latch "latches" – it remains in its previously set or reset state.

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When both inputs are high at once, however, there is a problem: it is being told to simulataneosuly produce a high Q and a low Q . This produces a "race condition" within the cirucit - whichever flip flop succeeds in changing first will feedback to the other and assert itself. Ideally, both gates are identical and this is "metastable", and the device will be in an undefined state for an indefinite period. In real life, due to manufacturing methods, one gate will always win, but it's impossible to tell which it will be for a particular device from an assembly line. The state of $S = R = 1$ is therefore "illegal" and should never be entered.

When the device is powered up, a similar condition occurs, because both outputs, Q and Q +1pt‾, are low. Again, the device will quickly exit the metastable state due to differences between the two gates, but it's impossible to predict which of Q and Q1pt‾ will end up high. To avoid spurious actions, you should always set SR flip-flops to a known initial state before using them - you must not assume that they will initialise to a low state.

S	R	Q$_{next}$	Comment	Q / Q$_{next}$	S	R
0	0	0	Hold state	0	0	0
0	1	0	Reset	0	1	1
1	0	1	Set	1	0	0
1	1	1	Metastable	0	1	X

48.2 Gated Flip Flop

48.2.1 Gated SR latch

In some situations it may be desirable to dictate when the latch can and cannot latch. The **gated SR latch** is a simple extension of the SR latch which provides an *Enable* line which must be driven high before data can be latched. Even though a control line is now required, the SR latch is not synchronous, because the inputs can change the output even in the middle of an enable pulse.

When the *Enable* input is low, then the outputs from the AND gates must also be low, thus the Q and $\overline{Q}$ outputs remain latched to the previous data. Only when the enable input is high can the state of the latch change, as shown in the truth table. When the enable line is asserted, a gated SR latch is identical in operation to an SR latch.

The *Enable* line is sometimes a clock signal, but is usually a read or write strobe[3].

Figure 248

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3   http://en.wikibooks.org/wiki/Digital%20Circuits%2FGlossary%23S
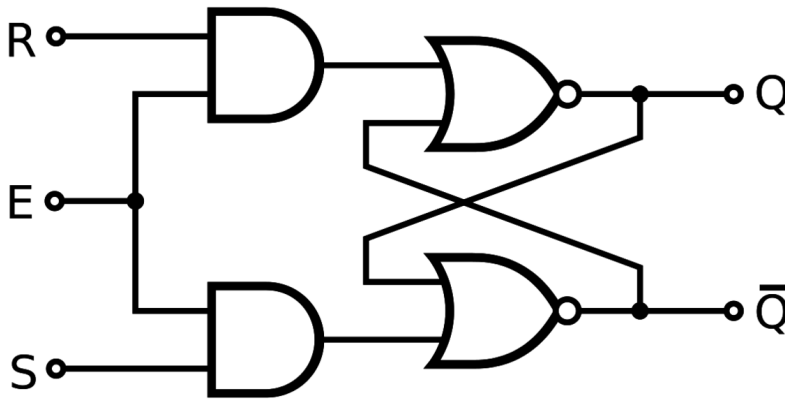
Enable	S	R		Q	$\bar{Q}$
0	0	0		Latch	
0	0	1		Latch	
0	1	0		Latch	
0	1	1		Latch	
1	0	0		Latch	
1	0	1		0	1
1	1	0		1	0
1	1	1		Metastable	

48.2.2 Gated D latch

The **D latch** (D for "data") or **transparent latch** is a simple extension of the gated SR latch that removes the possibility of invalid input states.

Since the gated SR latch allows us to latch the output without using the S or R inputs, we can remove one of the inputs by driving both the *Set* and *Reset* inputs with a complementary driver: we remove one input and automatically make it the inverse of the remaining input.

The D latch outputs the D input whenever the *Enable* line is high, otherwise the output is whatever the D input was when the *Enable* input was last high. This is why it is also known as a transparent latch - when *Enable* is asserted, the latch is said to be "transparent" - it signals propagate directly through it as if it isn't there.
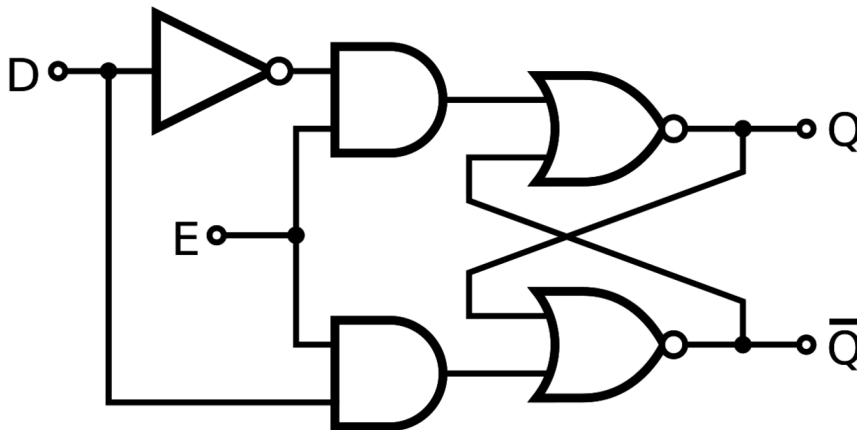
Figure 249

Enable	D		Q	Q̄1pt
0	0		Latch	
0	1		Latch	
1	0		0	1
1	1		1	0

D latches are often used in I/O ports of integrated circuits and are available as discrete devices, often multiply packaged. An example is the 74HC75, part of the 7400 series of ICs, containing four separate D latches.

48.3 Clock - Controlled Flip Flops

48.3.1 D flip-flop

The D flip-flop is the edge-triggered variant of the transparent latch. On the rising (usually, although negative edge triggering is just as possible) edge of the clock, the output is given

the value of the D input *at that moment* . The output can only change at the clock edge, and if the input changes at other times, the output will be unaffected.

D flip-flops are by far the most common type of flip-flops and some devices (for example some FPGAs) are made entirely from D flip-flops. They are also commonly used for shift-registers and input synchronisation.
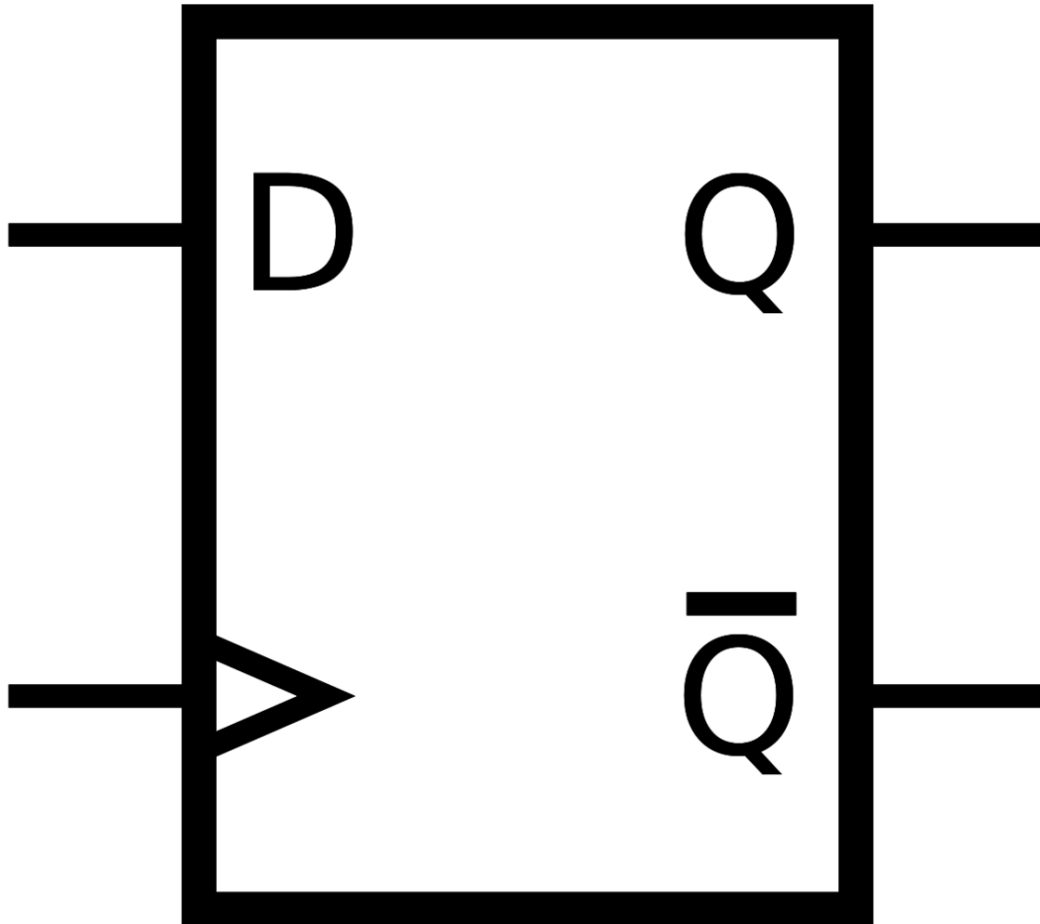
Figure 250 Symbol for a D flip-flop.

	Clock	D		$\mathbf{Q}_{\text{next}}$	Comment
	0	0		Express D at Q	
	1	1		Express D at Q	
Otherwise	X	Q_{prev}		Hold state	

48.3.2 JK Flip-flop

The JK flip-flop is a simple enhancement of the SR flip-flop where the state J=K=1 is not forbidden. It works just like a SR FF where J is serving as set input and K serving as reset. The only difference is that for the formerly "forbidden" combination J=K=1 this flip-flop now performs an action: it inverts its state. As the behavior of the JK flip-flop is completely predictable under all conditions, this is the preferred type of flip-flop for most logic circuit designs. But there is still a problem i.e. both the outputs are same when one tests the circuit practically. This is because of the internal toggling on every propagation elapse completion. The main remeady is going for master-slave jk flip-flop,this ff overrides the self(internal) recurring toggling through the pulsed clocking feature incorporated.
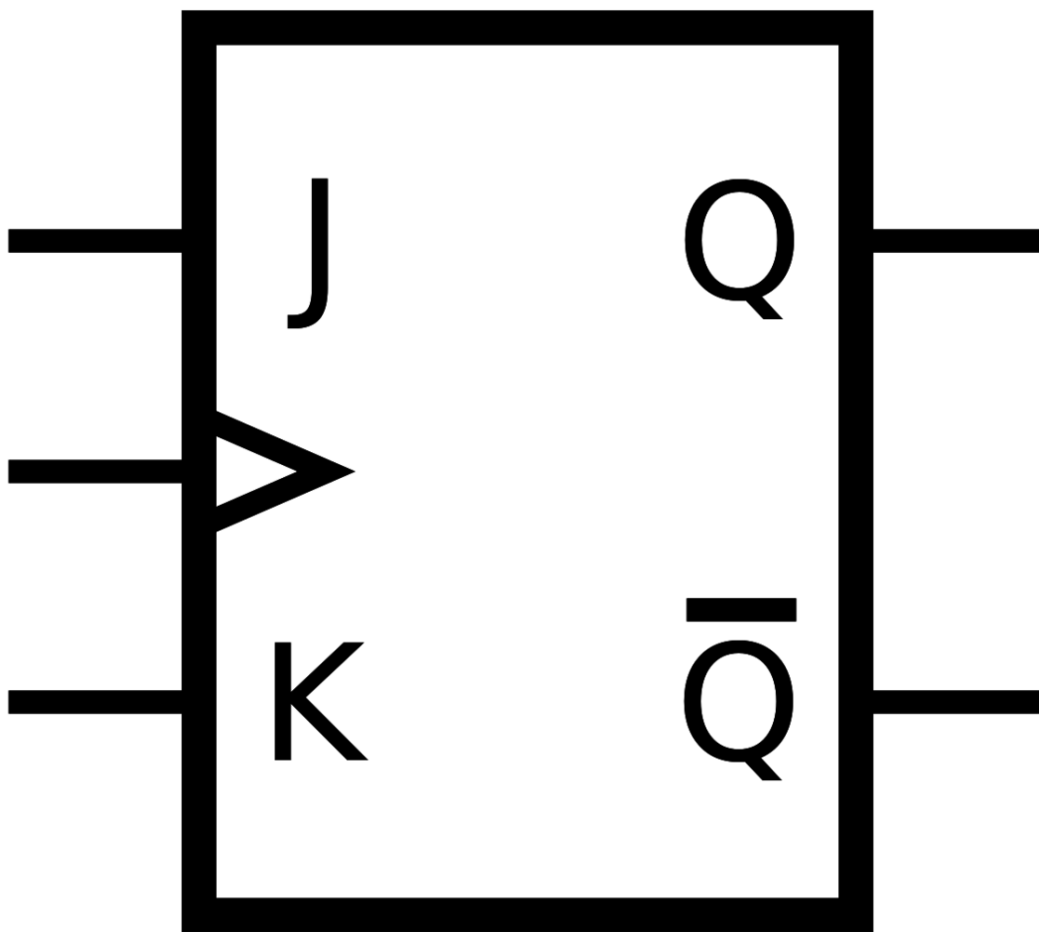
Figure 251   Symbol for a JK flip-flop

J		Q$_{\text{next}}$	Comment
K			
0 Hold state		0	Q$_{\text{prev}}$
0 Reset		1	0
1 Set		0	1
1 Toggle		1	Q1pt$\overline{}_{\text{prev}}$

Q		J	K	Comment
Q$_{\text{next}}$				
0 Hold state		0	0	X
0 Set		1	1	X
1 Reset		0	X	1
1 Hold state		1	X	0

|}

48.3.3 T flip-flops

A **T flip-flop** is a device which swaps or "toggles" state every time it is triggered if the T input is asserted, otherwise it holds the current output. This behavior is described by the characteristic equation:

$$Q_{next} = T \oplus Q = T\overline{Q} + \overline{T}Q$$

and can be described either of the following tables:
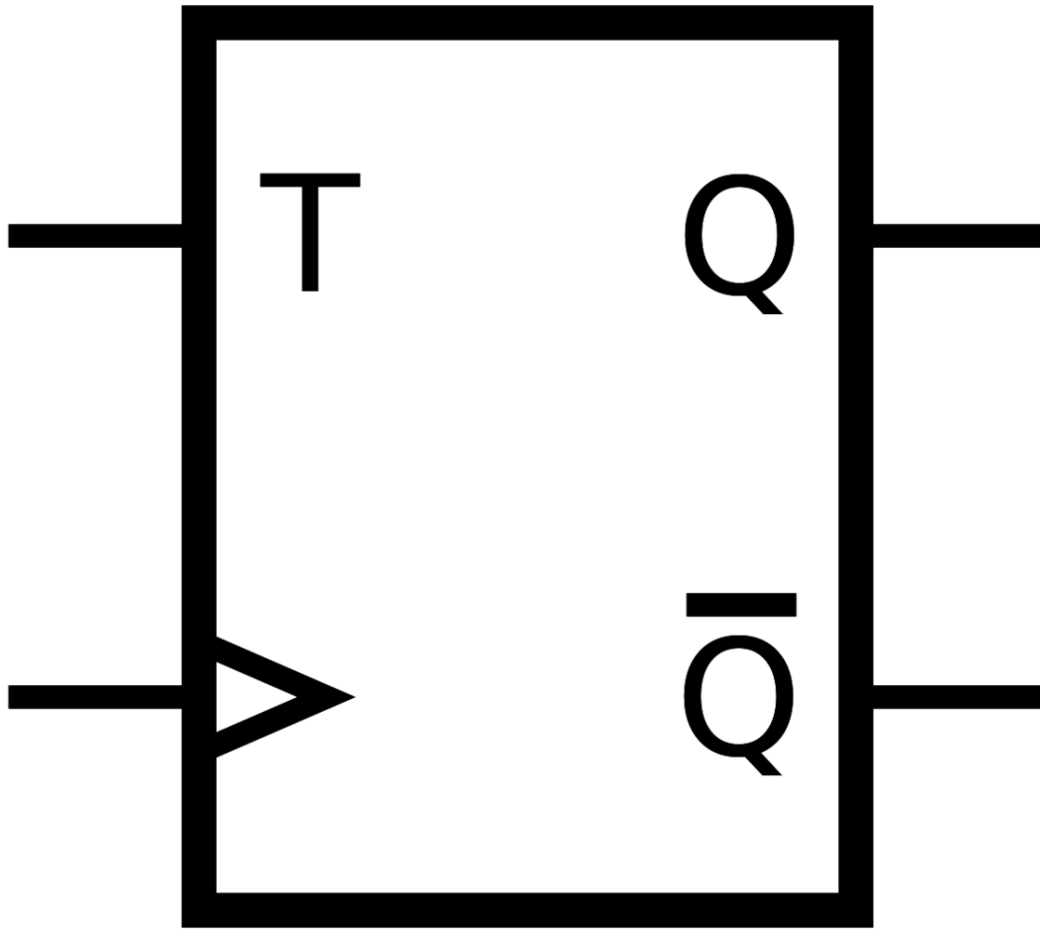
Figure 252   A circuit symbol for a T-type flip-flop: T is the toggle input and Q is the stored data output.

Q	Q_next		T
0	0		0
0	1		1
1	1		0
1	0		1

T	Q	Q_next	Comment
0	0	0	Hold state
0	1	1	Hold state
1	0	1	Toggle
1	1	0	Toggle

When T is held high, the toggle flip-flop divides the clock frequency by two; that is, if clock frequency is 4 MHz, the output frequency obtained from the flip-flop will be 2 MHz. This 'divide-by' feature has application in various types of digital counters[4]. A T flip-flop can also be built using a JK flip-flop (J & K pins are connected together and act as T) or D flip-flop (T input and Q_{prev} are connected to the D input through an XOR gate).

---

4   http://en.wikibooks.org/wiki/Digital%20Circuits%2FCounters

49 Counters

49.1 Overview

A counter is a device that generates some patterned binary value depending on a clock or some other pulsed input. There are three simple types of counters ripple and synchronous.[[

49.2 Types of Counters

49.2.1 Ring Counters

If the output of a shift register is fed back to the input. a ring counter results. The data pattern contained within the shift register will recirculate as long as clock pulses are applied. For example, the data pattern will repeat every four clock pulses in the figure below. However, we must load a data pattern. All 0's or all 1's doesn't count. Is a continuous logic level from such a condition useful?

We make provisions for loading data into the parallel-in/ serial-out shift register configured as a ring counter below. Any random pattern may be loaded. The most generally useful pattern is a single 1.

Loading binary 1000 into the ring counter, above, prior to shifting yields a viewable pattern. The data pattern for a single stage repeats every four clock pulses in our 4-stage example. The waveforms for all four stages look the same, except for the one clock time delay from one stage to the next. See figure below.

The circuit above is a divide by 4 counter. Comparing the clock input to any one of the outputs, shows a frequency ratio of 4:1. How may stages would we need for a divide by 10 ring counter? Ten stages would recirculate the 1 every 10 clock pulses.

An alternate method of initializing the ring counter to 1000 is shown above. The shift waveforms are identical to those above, repeating every fourth clock pulse. The requirement for initialization is a disadvantage of the ring counter over a conventional counter. At a minimum, it must be initialized at power-up since there is no way to predict what state flip-flops will power up in. In theory, initialization should never be required again. In actual practice, the flip-flops could eventually be corrupted by noise, destroying the data pattern. A "self correcting" counter, like a conventional synchronous binary counter would be more reliable.

The above binary synchronous counter needs only two stages, but requires decoder gates. The ring counter had more stages, but was self decoding, saving the decode gates above. Another disadvantage of the ring counter is that it is not "self starting". If we need the

decoded outputs, the ring counter looks attractive, in particular, if most of the logic is in a single shift register package. If not, the conventional binary counter is less complex without the decoder.

The waveforms decoded from the synchronous binary counter are identical to the previous ring counter waveforms. The counter sequence is (QA QB) = (00 01 10 11).

49.2.2 Ripple Counters

Ripple counters are the simplest type of counters. They are nothing more than toggle flip flops connected in a chain to divide each others output frequency by two. The result is a binary count. They are called ripple counters because the new count ripples through them. The major disadvantage of ripple counters is that because of new count "rippling" through the flip flops all the bits of the count arrive at different times.

49.2.3 Synchronous Counters

Synchronous counters are simple state machines made out of flip flops and logic gates. They have two parts, a register made out of flip flops and a decoder made out of logic gates. A register is a simple group of flip flops that are all clocked at the same time. In this way they can hold the counters output value until the next clock cycle. The decoder, decodes the current count and generates the correct value for the next count to the flop flops. For example in a simple up counter the decoder would always output the current count plus one. The major advantage of Synchronous Counters is that all the bits of their output change at the same time.

50 Adders

50.1 Intro

When adding one number A with another number B the operation will produce a Sum S and a Carry C.The Operation of an adder is Shown below.

50.2 Digital Adder

50.2.1 Half adder

If there are two binary number A and B . The operation of adding two numbers can be shown below

A + B = S C

0 + 0 = Sum 0 Carry 0

0 + 1 = Sum 1 Carry 0

1 + 0 = Sum 1 Carry 0

1 + 1 = Sum 0 Carry 1

The operation of Half Adder can be summarized in the Truth Table below

A	B	C	S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

From above, In term of logic gate XOR will produce a sum of two input . logic gate AND produce carry

$$S = A \oplus B$$

$$C = A \cdot B$$

Half Adder can constructed from AND gate and XOR gate as shown below
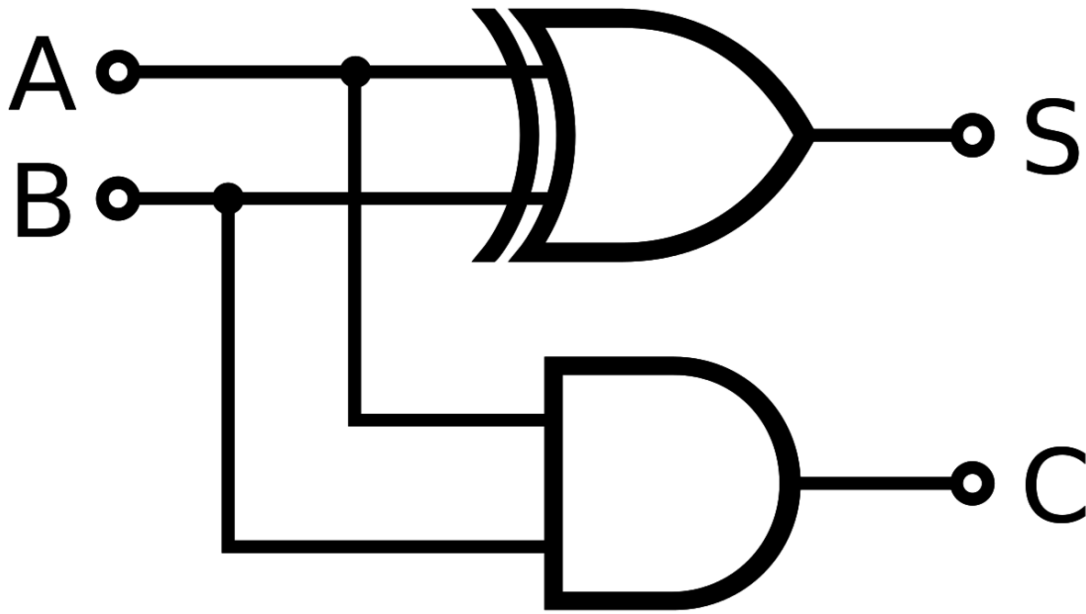
Figure 253   Half adder circuit diagram

```
          -----------
 A ------|           |
         |   Half    |-----  S = A ⊕ B
         |   Adder   |
         |           |-----  C = A · B
 B ------|_____|
```
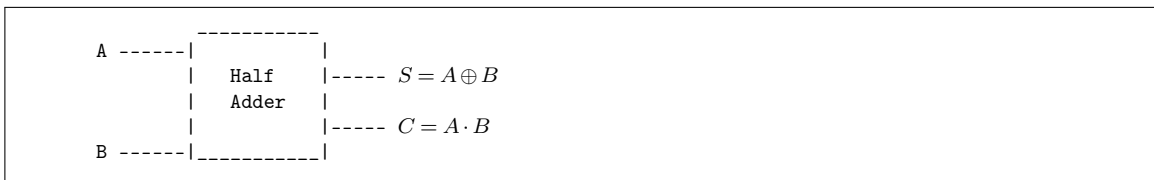
50.2.2 Full adder

A **full adder** is a logical circuit that performs an addition operation on three one-bit binary numbers. The full adder produces a sum of the two inputs and carry value. It can be combined with other full adders (see below) or work on its own.

Input			Output	
A	B	C_i	C_o	S
0	0	0	0	0
0	1	0	0	1
1	0	0	0	1
1	1	0	1	0
0	0	1	0	1
0	1	1	1	0
1	0	1	1	0
1	1	1	1	1

$$S = (A \oplus B) \oplus C_{in}$$

$$C_{out} = (A \cdot B) + (C_{in} \cdot (A \oplus B))$$
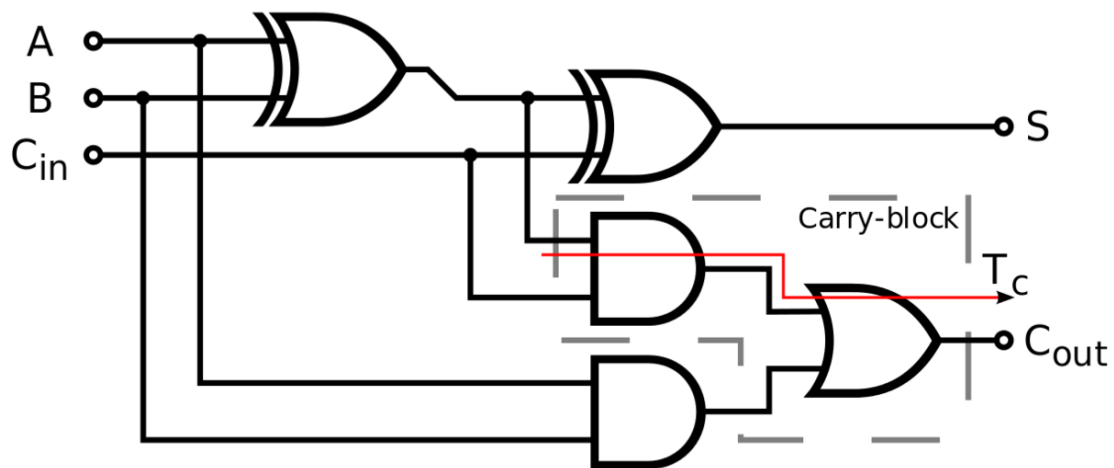
Figure 254 Full adder circuit diagram
Inputs: {A, B, CarryIn} → Outputs: {Sum, CarryOut}
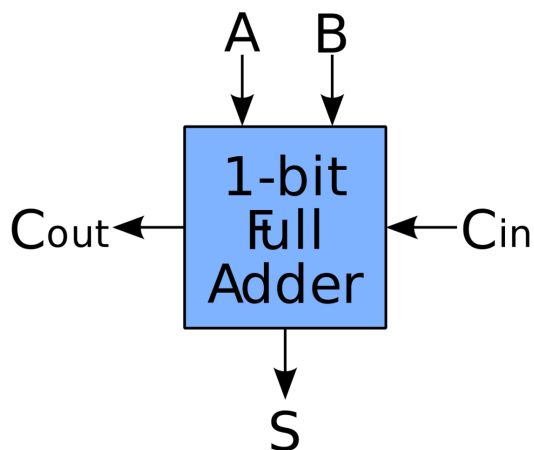
Figure 255 Schematic symbol for a 1-bit full adder

Note that the final OR gate before the carry-out output may be replaced by an XOR gate without altering the resulting logic. This is because the only difference between OR and XOR gates occurs when both inputs are 1; for the adder shown here, this is never possible. Using only two types of gates is convenient if one desires to implement the adder directly using common IC chips.

A full adder can be constructed from two half adders by connecting A and B to the input of one half adder, connecting the sum from that to an input to the second adder, connecting C_i to the other input and OR the two carry outputs. Equivalently, S could be made the

three-bit XOR of A , B , and C_i , and C_o could be made the three-bit majority function[1] of A , B , and C_i .

50.3 Multiple-bit adders

50.3.1 Ripple carry adder

It is possible to create a logical circuit using multiple full adders to add N -bit numbers. Each full adder inputs a C_{in} , which is the C_{out} of the previous adder. This kind of adder is a *ripple carry adder* , since each carry bit "ripples" to the next full adder. Note that the first (and only the first) full adder may be replaced by a half adder.

The layout of ripple carry adder is simple, which allows for fast design time; however, the ripple carry adder is relatively slow, since each full adder must wait for the carry bit to be calculated from the previous full adder. The gate delay[2] can easily be calculated by inspection of the full adder circuit. Each full adder requires three levels of logic. In a 32-bit [ripple carry] adder, there 32 full adders,so the critical path (worst case) delay is $32 * 3 = 96$ gate delays.

50.3.2 Carry look-ahead adders

To reduce the computation time, engineers devised faster ways to add two binary numbers by using carry lookahead adder[3]s. They work by creating two signals (P and G) for each bit position, based on whether a carry is propagated through from a less significant bit position (at least one input is a '1'), a carry is generated in that bit position (both inputs are '1'), or if a carry is killed in that bit position (both inputs are '0'). In most cases, P is simply the sum output of a half-adder and G is the carry output of the same adder. After P and G are generated the carries for every bit position are created. Some advanced carry look ahead architectures are the Manchester carry chain[4], Brent-Kung adder[5], and the Kogge-Stone adder[6].

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1   http://en.wikibooks.org/wiki/majority%20function
2   http://en.wikibooks.org/wiki/gate%20delay
3   http://en.wikibooks.org/wiki/carry%20lookahead%20adder
4   http://en.wikibooks.org/wiki/Manchester%20carry%20chain
5   http://en.wikibooks.org/wiki/Brent-Kung%20adder
6   http://en.wikibooks.org/wiki/Kogge-Stone%20adder
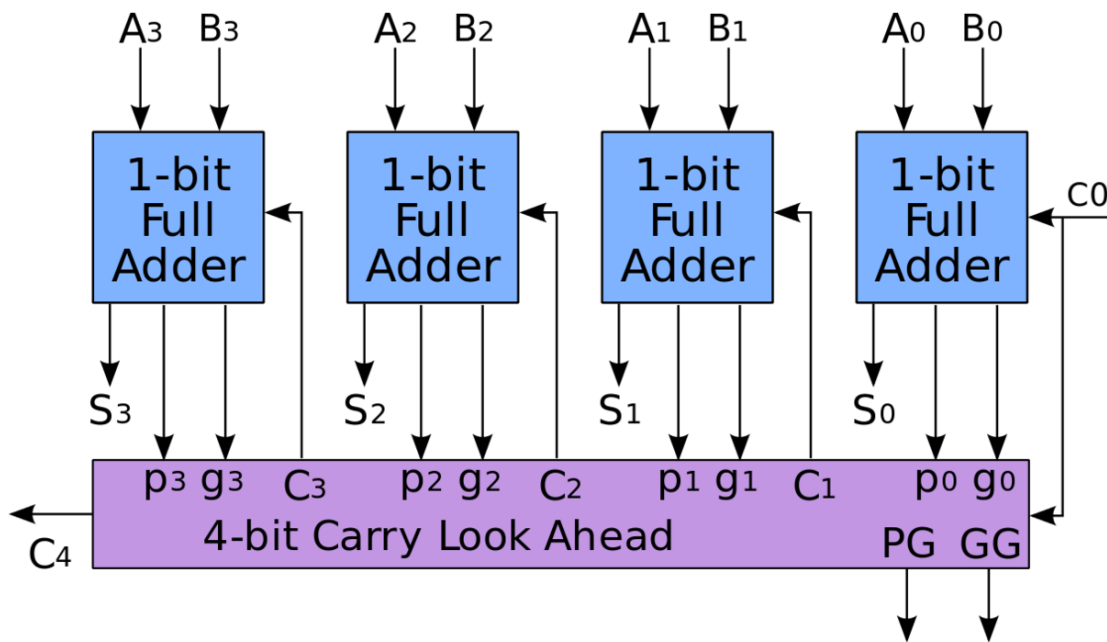
Figure 256 4-bit adder with Carry Look Ahead

Some other multi-bit adder architectures break the adder into blocks. It is possible to vary the length of these blocks based on the propagation delay of the circuits to optimize computation time. These block based adders include the carry bypass adder[7] which will determine P and G values for each block rather than each bit, and the carry select adder[8] which pre-generates sum and carry values for either possible carry input to the block.

Other adder designs include the conditional sum adder[9], carry skip adder[10], and carry complete adder[11].

50.3.3 Lookahead Carry Unit

By combining multiple carry look-ahead adders even larger adders can be created. This can be used at multiple levels to make even larger adders. For example, the following adder is a 64-bit adder that uses four 16-bit CLAs with two levels of LCUs.

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7   http://en.wikibooks.org/wiki/carry%20bypass%20adder

8   http://en.wikibooks.org/wiki/carry%20select%20adder

9   http://en.wikibooks.org/wiki/conditional%20sum%20adder

10   http://en.wikibooks.org/wiki/carry%20skip%20adder

11   http://en.wikibooks.org/wiki/carry%20complete%20adder
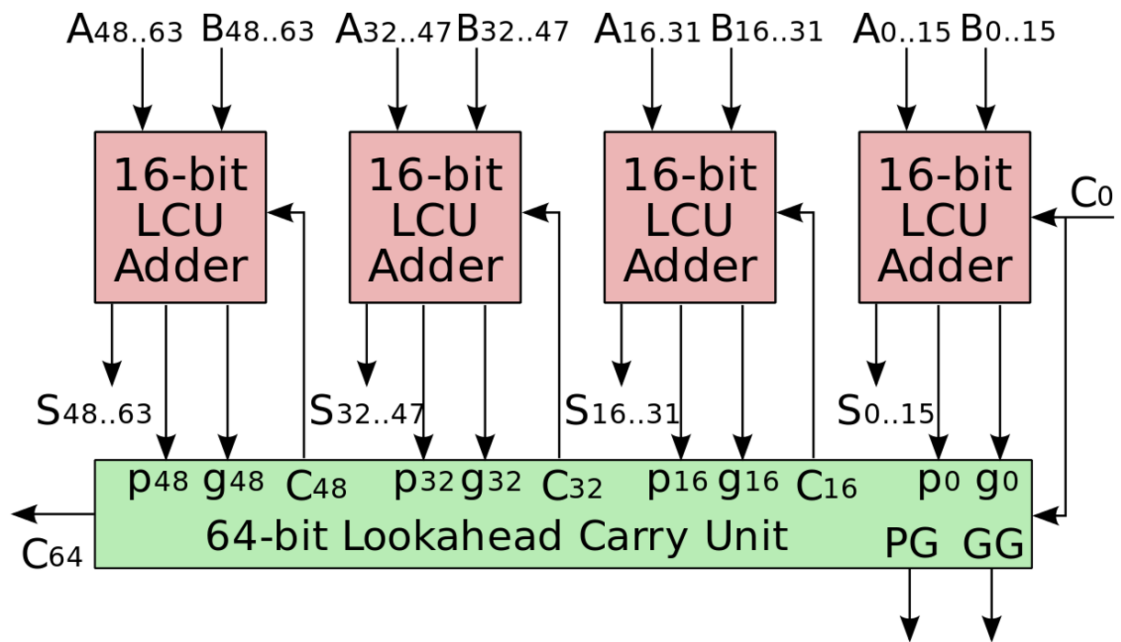
Figure 257   A 64-bit adder

50.4 Reference

1. Digital Adder on Wikipedia[12]

12   http://en.wikipedia.org/wiki/Adder_%28electronics%29

51 Decoders and Encoders

51.1 Encoders

Encoders are devices that act on data to transform it in such a way that the data acquires some new characteristics. These characteristics can vary from reduction in length to inclusion of error correction properties to use of security measures. At the most basic level, encoders can be used to reduce the size of data. Consider the following block diagram :

```
         ____
  A ---|    |
  B ---|    |-- X
  C ---|    |-- Y
       |____|
```
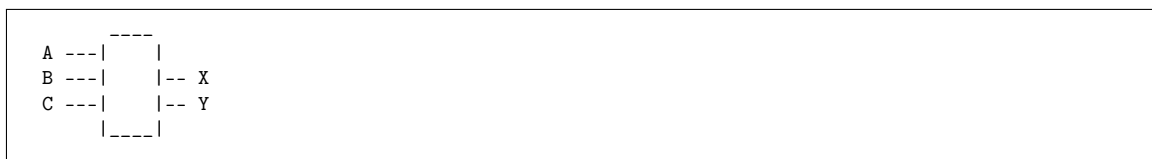
If out of ABCD only one is high at any given time, then we can only have the following possibilities for input : 000, 001, 010, 100. Thus we can make the internal circuit of the encoder in such a way that when it sees 000 it outputs 00, when it sees 001 it outputs 01, when it sees 010 it gives 10 and when it sees 100 it outputs 11

```
     _____
  ---| 000 | 00 |
  ---|-----|----|
  ---| 001 | 01 |
  ---|-----|----|
  ---| 010 | 10 |
  ---|-----|----|
  ---| 100 | 11 |
  ---|_____|____|
```
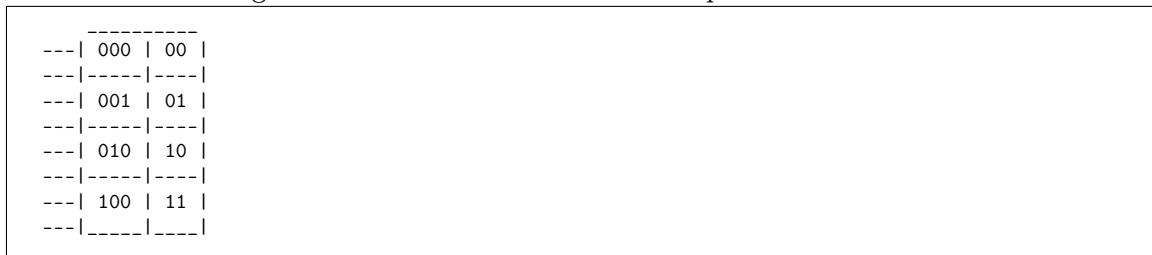
Thus we have effectively reduced the size of the data, by exploiting the fact that all possible combinations of input will never be provided at the input terminals.

The internal circuit of the encoder can be easily derived by using truth tables

```
     _____
  ---| A | B | C ||| X | Y |
  ---| 0 | 0 | 0 ||| 0 | 0 |
  ---| 0 | 0 | 1 ||| 0 | 1 |
  ---| 0 | 1 | 0 ||| 1 | 0 |
  ---| 1 | 0 | 0 ||| 1 | 1 |
  ---|___|___|___|||___|___|
```
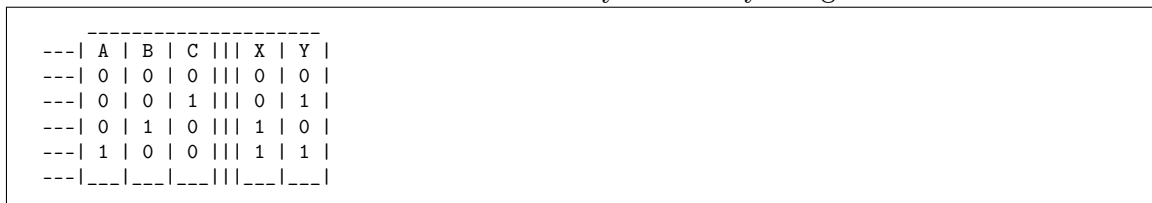
Clearly X = A + B and Y = A + C

So the circuit diagram can be :

```
A ----------[ OR ]----------X
     |    B---[ OR ]
     |
     |-------[ OR ]----------Y
          C---[ OR ]
```
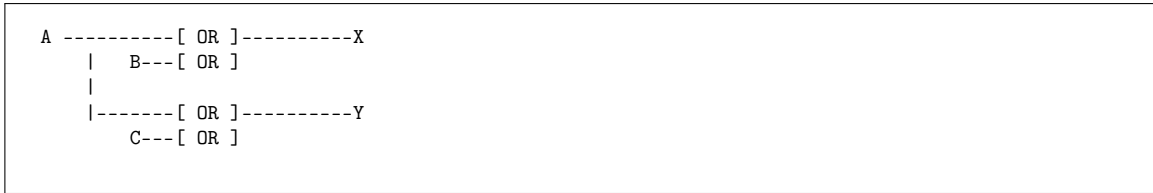
This scheme can be extended for n inputs.

This was a very basic encoder, it could act only on data when a single line was high. It is possible that multiple lines may be high, in that case one may use priority encoders which assign output based on priority, that is if two lines are high, for example A and C in the previous example, then a priority encoder will, based on a prior decision by the designer, decide to assign output to either C or A thereby assigning it a higher priority.

In some cases we don't want priority encoding, rather when faced with multiple signals, we wish to create a new code for that particular combination as well, and still obtain some reduction in size.

At other times we may wish to modify the incoming code in a manner that allows the receiver to detect any errors that may have crept in during transmission. These topics will be elaborated upon in appropriate topics.

52 Multiplexers

52.1 Overview

A multiplexer is a device that brings the concept of a rotary switch in analog electronics to the digital side. It is a device which, based on some input, will change the connection of its other inputs to its outputs. Conceptually a digital multiplexers functionality is the same as an analog one, only it handles everything digitally. Because of the mathematical concept of combinatorix they can be used to replace chain logic circuits. However, this is not done frequently because multiplexer based logic has a comparably high propagation delay.

52.2 Configuration
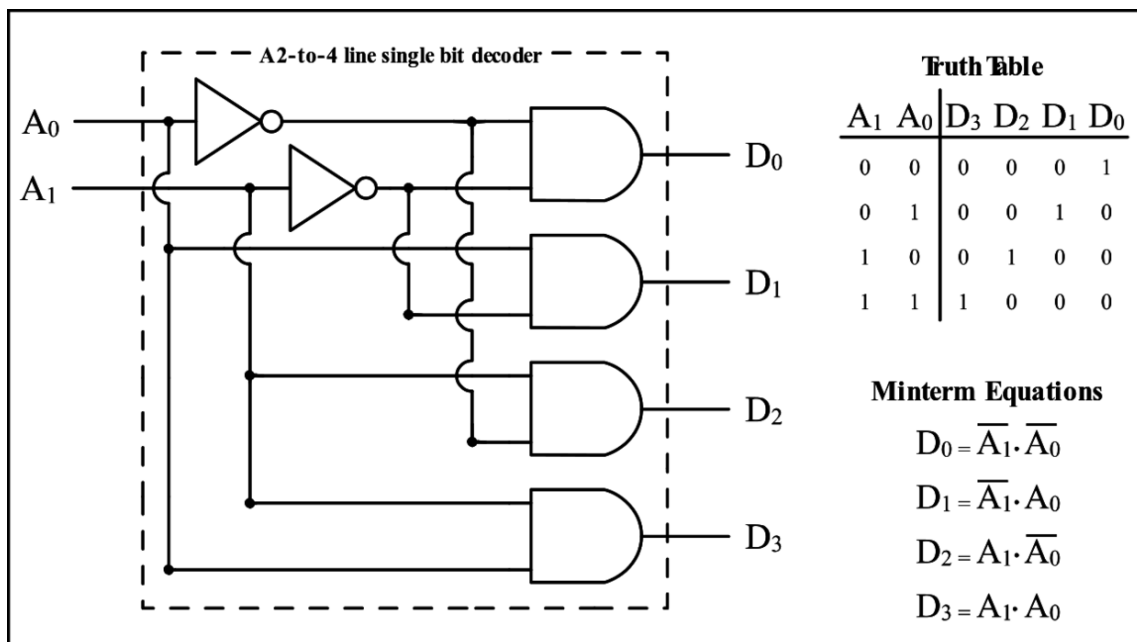
Figure 258

The circuit above has 2 Control Lines A1Ao which can be used as 2 Selectors . Depend on the value of the Selectors only one of the Output Lines can be high . The circuit above has the capability to select the output line

The operation of the circuit above can be summarized in the Truth Table below

A_1A_0	$D_3D_2D_12_0$
00	0001
01	0010
10	0100
11	1000

In general

2 Selectors can select $2^2 = 4$ output lines

3 Selectors can select $2^3 = 8$ output lines

n Selectors can select 2^n output lines

52.3 Computer Architecture

53 RAM and ROM

RAM: Random Access Memory ROM: Read Only Memory

53.1 Basics

53.1.1 Capacitors as memory

- Capacitors[1] can be charged, and when they are charged they can be discharged.
- When charged they act like a source of voltage but only for a limited time unless they are "refreshed".
- If charged they can be "refreshed" by charging them again and again to keep their voltage above a specified minimum. This procedure can be quite automatic at regular intervals and applies ONLY to capacitors that already have a voltage that is above that set minimum.
- "Writing" into a capacitor-memory means either charging that capacitor or discharging it as required. We say that a memory is "a zero" if its voltage is below a specified value, and it is "a one" if above. Putting a 1 into the memory means charging the capacitor, while putting a 0 into the memory means discharging the capacitor.
- "Reading" a capacitor-memory is equivalent to putting a voltmeter across its terminals to see whether its voltage is or is not above a given minimum.

NOTE: Modern memories use transistors, gates, diodes, etc.

Examples

Reference 1: Programmer's Reference Guide for the Commodore 64 Personal Computer, published in 1988 by Commodore Business Machines, Inc.

- part of the microprocessor 6510's characteristics:
- For a 0 the minimum is minus 0.3 Volt, and the maximum is plus 0.3 Volt.
- For a 1 the minimum is plus 2.0 Volt, and the maximum is 1 Volt above the supply voltage which usually is about 5 Volt, but whose absolute maximum is 7.0 Volt. Note that static electricity (by friction on the carpet for example) can cause a lot of damage and must be guarded against.

Reference 2: The Semiconductor Memory Data Book for Design Engineers, published in 1975 by Texas Instruments Inc.

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1   Chapter 7 on page 43

53.1.2 Bits

- Think of "one bit" as one memory unit, such as one capacitor-memory. It can have a 0 or a 1 "in it", as required; a "High" (H) usually is a 1, and a "Low" (L) usually is a 0. Bit is a shortened version of binary digit.

53.1.3 Bytes

- A byte is a group of bits. One bit can only represent "a count" of zero or one, two bits grouped together into a byte can represent a count of zero to 3, 3 bits into a byte can count up to 7 and n bits in a byte can count up to 2^n minus 1. A byte with 8 bits in it can count from 0 to 255. "Words" are bytes; they each have a stated number of bits in them.
- Bytes can also be combined; 2 bytes, each with 8 bits in it, can count up to 256 times 256 minus 1, that is 0 to 65535.

53.1.4 Words

- Words are a concept that dates back to early computer architectures, where a single "unit" of memory was different from 8 bits. Common early word sizes were often 10 bits, but sometimes six or 20 bits.
- Generally a word was defined as the size of the memory bus for internal storage (i.e. RAM or ROM), as well as the minimum independently addressable unit of memory.
- Most modern CPU architectures use independently addressable byte architecture, but some modern CPUs (like the Pentium and other x86 CPUs) perform memory and instruction tasks more efficiently if the memory is "aligned" on word boundaries.
- Terms like **word** and **longword** date back to 16-bit and 32-bit CPU architectures respectively, and to give a common framework for backward compatible software tools. More recently, the term **quadword** is used to denote a 64-bit piece of memory, although the term **octaword** is sometimes used (because it is 8-bytes being accessed at once).
- Endian architecture[2] defines how the memory is encoded within the RAM of the computer and its relationship with the byte addresses. Generally this is not an issue for most software except when you write data files meant for consumption on multiple platforms that have multi-byte components.

53.1.5 Address Bus connection

Just as the mail delivery person needs to have an address on each item to be delivered/collected, so also access to a particular byte of memory is "delivered" to a particular address, or "collected" from a particular address.

- For example a memory can have 16 address connections, labelled 0 to 15. That means that data can be fed into, or taken out of, a specific memory cell, whose address is between 0 and (2^{16} minus one), which is between 0 and 65535.

---

2   http://en.wikipedia.org/wiki/Endianness

53.1.6 Data Bus connection

After the specific address has been fed into the memory, a specific given number is fed ("written") into the data bus connection, or the content of that address is "read".

- For example a memory can have 8 data connections, labelled 0 to 7. That means that the number fed into the selected byte must be between 0 and (2^8 minus one), which is between 0 and 255.

53.1.7 Read/Write connection

There is also an input terminal connection that indicates the operation required. A 0 into that connection may indicate that the next operation will be a "write", while a 1 may indicate that it will be a "read".

53.1.8 Clock connection

A memory may require one or more clock signals, possibly "phase 1" and "phase 2", etc., which are inputs into the memory from oscillators, meaning they alternate very fast between 0 and 1 continuously. While the clock is, maybe, 0 various changes can be made, such as an address change and/or a change of data, but the actual reading or writing takes place only while the clock is, maybe, 1. Some memories include clock oscillators, possibly requiring external crystals.

53.2 RAM (Random Access Memory)

A RAM is a "Random Access Memory" - Sizes and their architecture vary considerably, users can put into any of their addressed bytes any number up to a given maximum, and that number can be replaced by another number as required, when required. Some memories supply the complements of what was put into them.

- For example a memory with 1024 bits can require only a 0 or 1 to be put into any of the 1024 cells, while another memory can require 4 bits (0 to 15) per word, but only 16 words can be retained at a time, etc.

Dynamic Read/Write Memories

  Requires frequent refreshing.

Static Read/Write Memories

  Retains the data even if control signals are absent, however such memories may use dynamic addressing

53.3 ROM (Read Only Memory)

A ROM is a "Read Only Memory". It is factory-produced, and usually its contents are fixed. A ROM can be read, but it usually cannot be written to. Usually a ROM contains very important fixed information required for the proper operation of the equipment.

Mask-Programmed Read-Only Memories

  Uses a mask during manufacture, contents cannot be altered.

Programmable Read-Only Memories

  Permits a change of each cell after manufacture, but once only.

Reprogrammable Read-Only Memories

  Permits changes to each cell after manufacture, more than once.

54 Registers

54.1 Registers

Registers can move two types of digital information: parallel and serial. Registers also have two basic ways of moving it: FIFO and LIFO. The simplest register is a FIFO, which is only one level deep and one bit wide. It is basically a single D Type Flip/Flop.

54.1.1 FIFO

A FIFO (First In First Out) is a digital device that moves data in the same way a queue would. The first chunk of information in is moved over as more is loaded in behind it. This continues until it is pushed out the end. Like a grocery line.

54.1.2 LIFO

A LIFO (Last In First Out) is a like a FIFO only the data comes out in the reverse order it came in. Data is processed like a stack data structure. Imagine putting items onto a stack, the first item taken off would be at the top of the stack. Thus, the last item in (item at the top of the stack), would be the first item out

54.1.3 Parallel

Parallel Registers take in mulitple bits at a time.

54.1.4 Shift Registers

Shift Registers are the simplest serial interfaces. They take serial data in one bit at a time and convert it to parallel form or the other way around. The first way is Serial In Parallel Out and the latter is Parallel In Serial Out. Shift Registers are used to make larger state machines like counters and UARTs.

Serial In Parallel Out

Tons of information about Serial in Parallel out circuits and how they are constructed[1]

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1   http://www.allaboutcircuits.com/vol_4/chpt_12/4.html

Parallel In Serial Out

55 ALU

56 Arithmetic and Logic Unit

Introduction

The Arithmetic and Logic Unit are not a single entity, but are actually composed of two separate units whose operation is highly dependent on the Select Input(S).

This input, is a one-bit input, that will decide whether to route the binary variables to the Arithmetic, or to the Logic Circuit.

Arithmetic Unit

Handles basic operations such as Addition and Subtraction. The Multiplication and Division operations are dependent on the basic operations, and Bit-Shifting. The Multiply and Divide operations, can also be implemented using Hardwired / Microprogrammed Control.

Logic Unit

The Logic unit, is a Hardware Unit, implemented for performing basic operations such as AND, OR, NAND, and NOT. A particular logical operation is selected using a 4:1 Demultiplexer.

The results of all the operations are routed into a data bus for memory addressing.

further reading

- Microprocessor Design/ALU[1]

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1   http://en.wikibooks.org/wiki/Microprocessor%20Design%2FALU

57 Control Unit

The Control Unit provides the Micro-Instructions that are necessary for the execution of a program. The micro instruction that should be executed next is decided based on the Current instruction fetched from memory and the bit values off the Various CPU status registers such as Negative, Zero etc.

Of the two CPU architectures in use the RISC (Reduced Instruction Set Computing) and the CISC (Complex Instruction Set Computing) have different philosophies in this regard where the RISC believes in having a larger number of more simple Micro-instructions and the CISC believes in a smaller number of more complex instructions.

57.1 further reading

w:control unit[1]

- Digital Circuits/Finite State Machines[2] describes low-level detail of state machines in general, which includes control units.
- Microprocessor Design[3] describes some very complicated control units, and how to design your own.

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1   http://en.wikipedia.org/wiki/control%20unit
2   http://en.wikibooks.org/wiki/Digital%20Circuits%2FFinite%20State%20Machines
3   http://en.wikibooks.org/wiki/Microprocessor%20Design

58 I/O

59 Input/Output

59.1 Input

For example: a computer disk can have a lot of information on it, and the user selects a particular disk for the task in hand. Then the user activates an **input** procedure to have the computer move a copy of the given required information from the disk, where the original remains, into a part of the computer's memory for further use. The original on the disk can, if desired, be deleted.

59.2 Output

For example: Some work has been done using a computer, and now the result is to be moved from the computer onto a disk, which is one of many possible **output** devices. Usually the computer's screen, which is also an **output** device, shows exactly what is being done by the user so as to ensure the information concerned ends up at the correct place, **outside** of the computer. Often a printer is used, which is another **output** device.

60 RTN

60.1 RTN (Register Transfer Notation)

Register Transfer Notation is a way of using special math notation to analize different types of computer architectures. RTN easily shows the number of transfers and clocks required for a given architecture to do a specific process.

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1   http://en.wikibooks.org/wiki/Electronics%3AComputer%20Architecture

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131	EugeneZelenko, Glenn, Hazard-Bot, Hydrargyrum, Inductiveload, JarektBot, MGA73bot2, Morpheios Melas, SchlurcherBot, Severino666, SieBot, Vdegroot	

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170 http://en.wikipedia.org/wiki/GIMP
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172 http://en.wikibooks.org/wiki/en:User:Wanderer
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144	Adrignola, Az1568, Pi zero, Wanderer, Webaware	
145	Adrignola, Az1568, Pi zero, Wanderer, Webaware	
146	Adrignola, Az1568, Pi zero, Wanderer, Webaware	
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160	Inductiveload[231]	
161	Crochet.david, E2m, Glenn, Gvf, JarektBot	
162	Inductiveload[232]	
163	Crochet.david, E2m, Glenn, Gvf, JarektBot	
164	User:Wykis[233]	
165	User:FDominec[234]	
166	FDominec	
167	FDominec	
168	BotMultichill, Inductiveload, JarektBot, Paddy, Peo	
169	Inductiveload, JarektBot, Omegatron, Paddy, WikipediaMaster, Yves-Laurent	
170	BotMultichill, FDominec, Glenn, Inductiveload, JarektBot, Paddy, Peo, WikipediaMaster	
171	Inductiveload, JarektBot, Omegatron, Paddy	
172	BotMultichill, Inductiveload, JarektBot, Paddy, Peo, TommyBee	
173	Inductiveload, JarektBot, Omegatron, Paddy	
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243 http://commons.wikimedia.org/wiki/User:Inductiveload

194	Emijrpbot, Inductiveload, Slobot, Tothwolf	
195	Inductiveload[244]	
196	Inductiveload[245]	
197	AnyFile, EDUCA33E, Emijrpbot, EugeneZelenko, Hazard-Bot, Ilmari Karonen, JarektBot, MGA73bot2, Stefan506, WikipediaMaster	
198	Inductiveload[246]	
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206	AnyFile, Emijrpbot, EugeneZelenko, Hazard-Bot, Ilmari Karonen, JarektBot, MGA73bot2, SpiderMum, Stefan506, Tothwolf, WikipediaMaster	
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214	Emijrpbot, Inductiveload, Slobot, Tothwolf	
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228	Inductiveload[263]	
229	Inductiveload[264]	
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238	Inductiveload[265]	

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245	Inductiveload[267]	
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Version 3, 29 June 2007

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