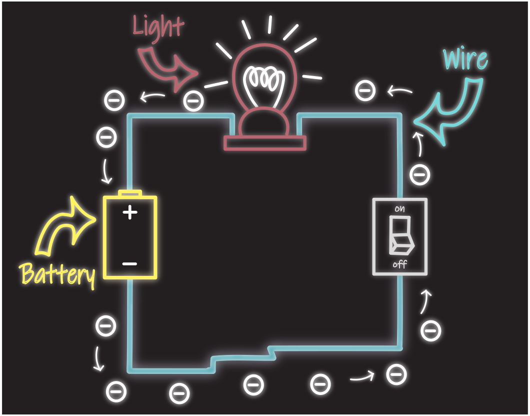
Quantum Electronics and Circuits

Brian Rashap

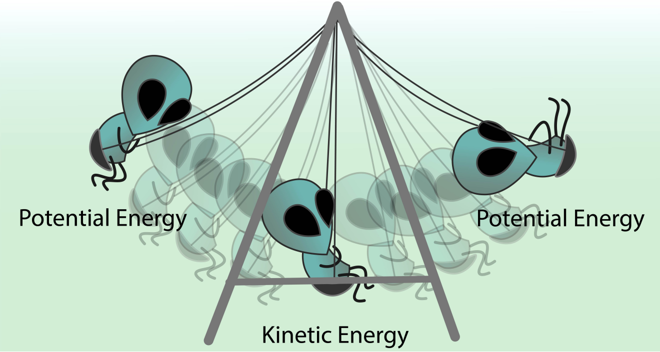
November 2025

Electrical Components and Circuits

Resistive Circuits



Energy

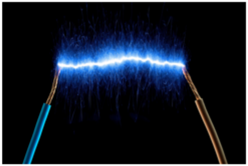


- Kinetic Energy - energy of motion
- Potential Energy - energy stored in an object

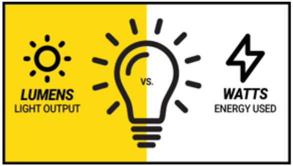
Electrical Circuit Terms

Voltage is **electric potential energy per unit charge** (V = J/C)

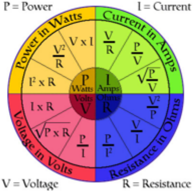
The Sub-atomic Particles			
Relative size	Name	Mass (Kg)	Charge (C)
	Proton	1.67×10^{-27}	$+1.602 \times 10^{-19}$
	Neutron	1.67×10^{-27}	0
	Electron	9.11×10^{-31}	-1.602×10^{-19}



Electric current is the **rate of charge flow** (A = C/s)



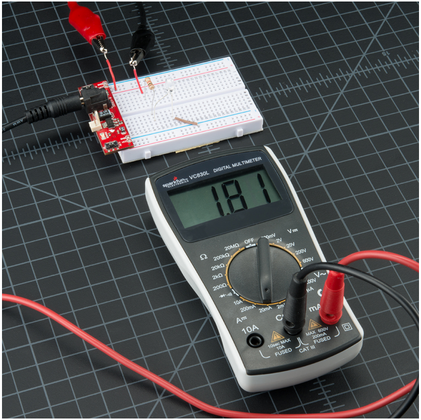
Power is the rate of doing work or **the rate of using energy**. (W = J/S)



Power = Voltage x Current

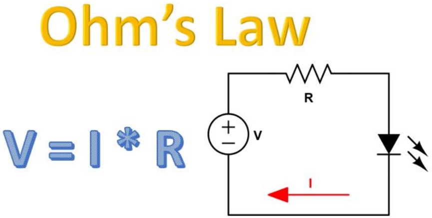
Energy is the **amount of power** produced or consumed **over a given time**. J = W x s

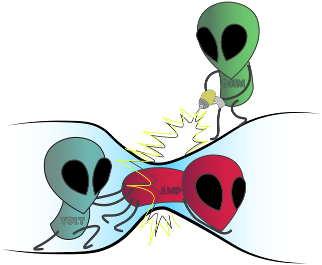
Measuring Voltage, Current, and Resistance



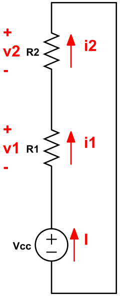
Ohm's Law

Georg Ohm (16 March 1789 – 6 July 1854) was a German physicist and mathematician. As a school teacher, Ohm began his research with the new electrochemical cell, invented by Italian scientist Alessandro Volta. Ohm found that there is a direct proportionality between the potential difference (voltage) applied across a conductor and the resultant electric current. This relationship is known as Ohm's law:





A word about circuit notation



Subscripts will be used to denote quanties (voltage, currect, etc) for different elements:

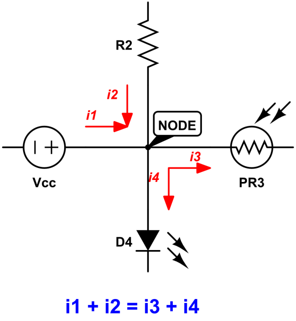
- i1 or i_1 is the current through Resistor 1 (R_1)
- i2 or i_2 is the current through Resistor 2 (R_2)
- v2 or v_2 is the votage across Resistor 2 (R_2)
- I is the current delivered by the power supply
- V_{cc} (common collector [a] voltage) is the notation will will use for $3.3V$ from the Particle

[a] Common Collector is a term for certain parts of transistor circuits. We will learn about Transistors in Lesson 11

Kirchhoff's First Law

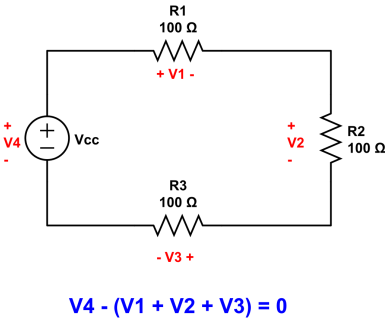
Gustav Robert Kirchhoff (12 March 1824 – 17 October 1887) was a German physicist who contributed to the fundamental understanding of electrical circuits. His first law:

> In an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node



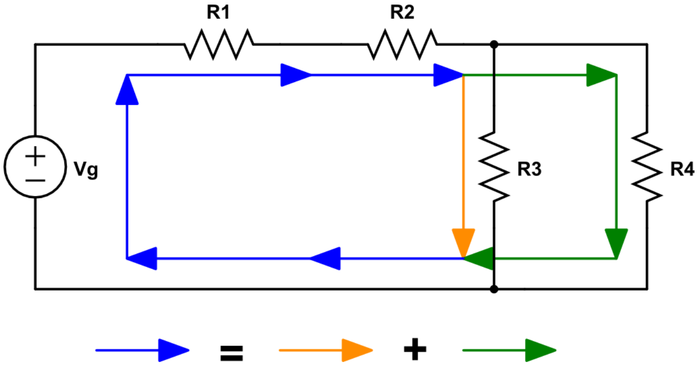
Kirchhoff's Second Law

The directed sum of the potential differences (voltages) around any closed loop is zero.



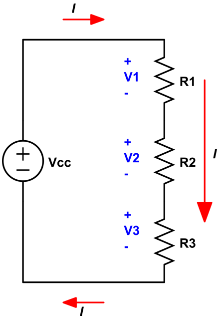
Kirchhoff's Second Law

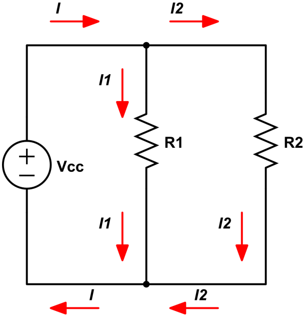
Resistors in Series and Parallel



How many nodes? How many loops?

Resistors in Series and Parallel

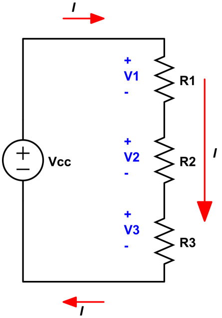




$$R_{eq} = R_1 + R_2 + R_3$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

Resistors in Series



Node Law: $I = I_1 = I_2 = I_3$

Loop Law:
$V_{cc} - (V_1 + V_2 + V_3) = 0$

Rearranging the Loop Law:

$$V_{cc} = V_1 + V_2 + V_3 \tag{1}$$

Using Ohm's Law:

$$V_{cc} = IR_1 + IR_2 + IR_3 \tag{2}$$

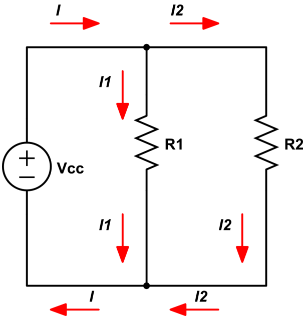
Using the Distributive Property:

$$V_{cc} = I(R_1 + R_2 + R_3) \tag{3}$$

Gives the Equivalent Resistance:

$$\boxed{R_{eq} = R_1 + R_2 + R_3} \tag{4}$$

Resistors in Parallel



Node Law: $I = I_1 + I_2$

Loop Law: $V_{cc} = V_1 = V_2$

$$I = I_1 + I_2 \tag{5}$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} \tag{6}$$

$$I = \frac{V_{cc}}{R_1} + \frac{V_{cc}}{R_2} \tag{7}$$

$$\frac{V_{cc}}{R_{eq}} = V_{cc}(\frac{1}{R_1} + \frac{1}{R_2}) \tag{8}$$

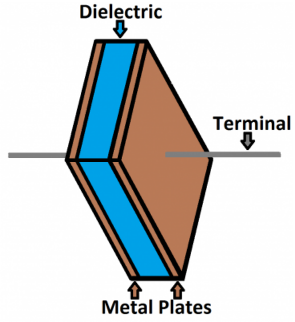
$$\boxed{\frac{1}{R_{eq}} = (\frac{1}{R_1} + \frac{1}{R_2})} \tag{9}$$

Capacitance and Filters

Capacitors

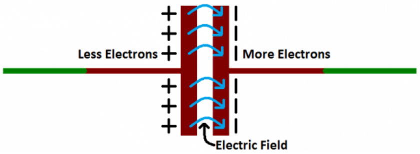
A capacitor is created out of two metal plates and an insulating material called a dielectric. The metal plates are placed very close to each other, in parallel, but the dielectric sits between them to make sure they don't touch.

- The dielectric can be made out of all sorts of insulating materials; paper, glass, rubber, ceramic, plastic, or anything that will impede the flow of current.
- The plates are made of a conductive material; aluminum, tantalum, silver, or other metals.



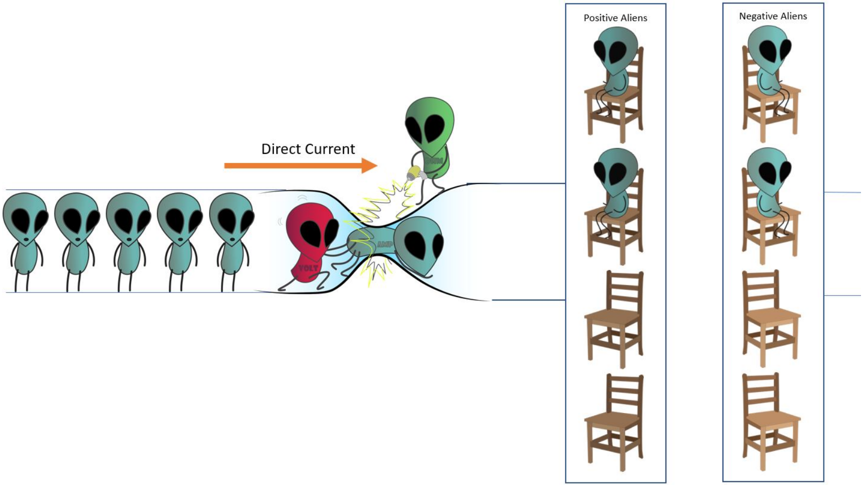
Capacitors

When current flows into a capacitor, the charges get "stuck" on the plates because they cannot get past the insulating dielectric. Electrons build up on one of the plates, and it becomes overall negatively charged. The large amount of negative charges pushes away like charges on the other plate, making it positively charged.

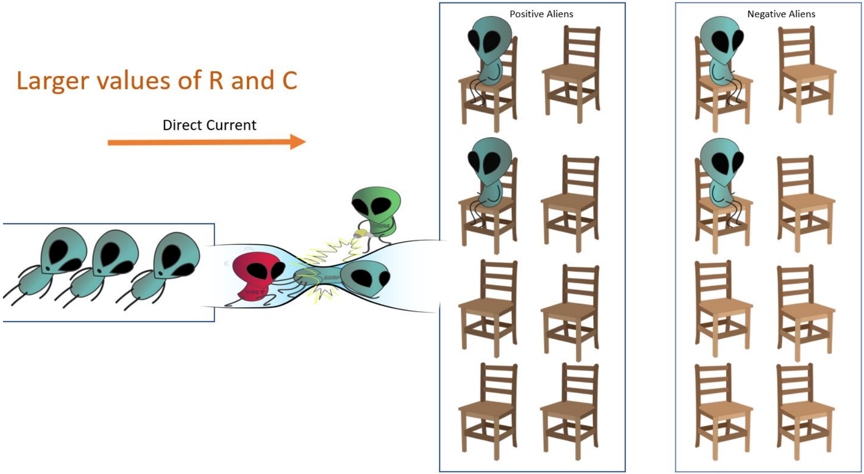


The stationary charges on these plates create an electric field, which influences electric potential energy and voltage. When charges group together on a capacitor like this, the capacitor is storing electric energy just as a battery might store chemical energy.

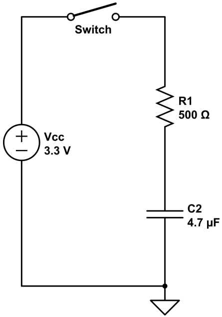
Capacitors in Circuits



Capacitors in Circuits



RC Time Constant



$$V_c(t) = V_c(0) * e^{\frac{t}{-\tau}}$$

Capacitance is defined as:

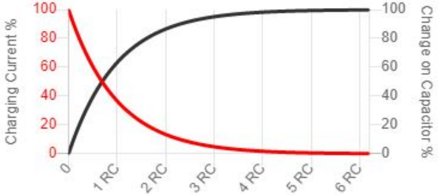
$$C = \frac{Q}{V}\left(\frac{Coulombs}{Volt}\right)$$

The current through a capacitor is:

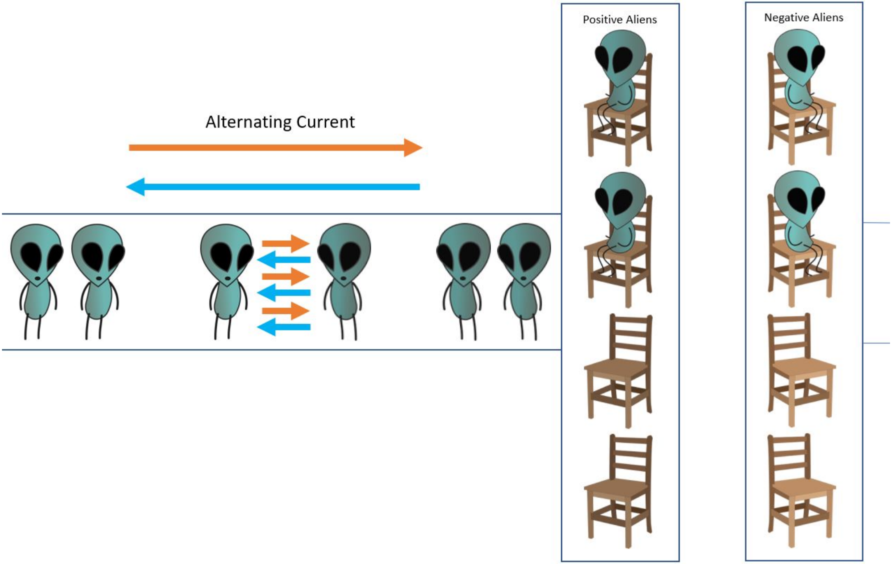
$$I = C\frac{\Delta V}{\Delta t}$$

And, therefore, the capacitor charges with a time constant (τ):

$$\tau = RC$$

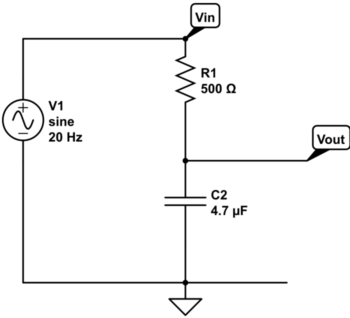


Alternating Current



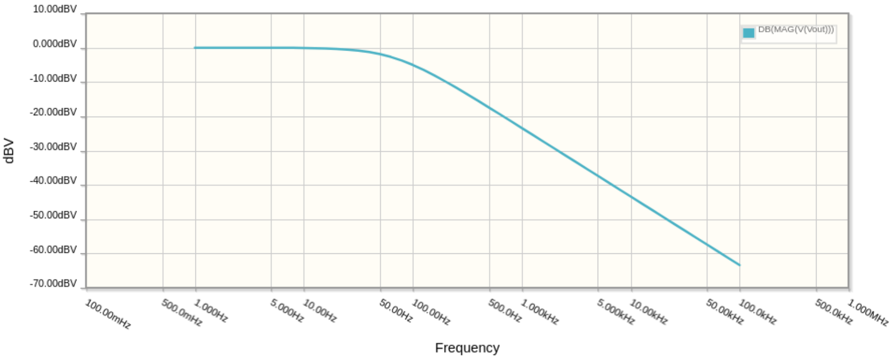
Low Pass Filter - cutoff frequency f_c

- At low frequencies, there is plenty of time for the capacitor to charge up to practically the same voltage as the input voltage.
- At high frequencies, the capacitor only has time to charge up a small amount before the input switches direction. The output goes up and down only a small fraction of the amount the input goes up and down. At double the frequency, there's only time for it to charge up half the amount.



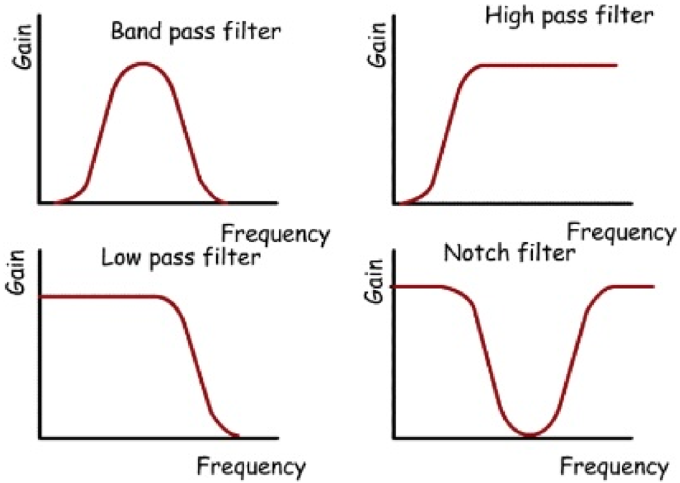
$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$

Low Pass Filter Response



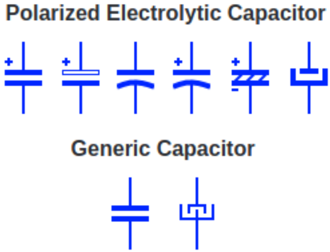
$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(500)(4.7x10^{-6})} = 67.5678Hz$$

Other types of filters



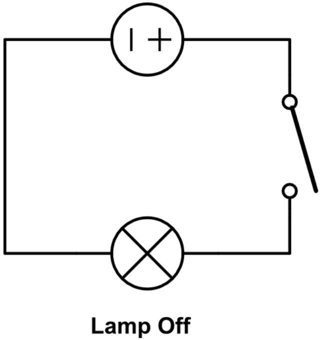
Capacitors - does it matter how they are placed

- Some types of capacitors (electrolytic and tantalum) are polarized (they have + and - terminals). This is due to how the dielectric film has been deposited. The reverse polarity leads to degradation of the dielectric.
- Other capacitors (ceramic and film) do not have a polarity and can be installed in either direction.

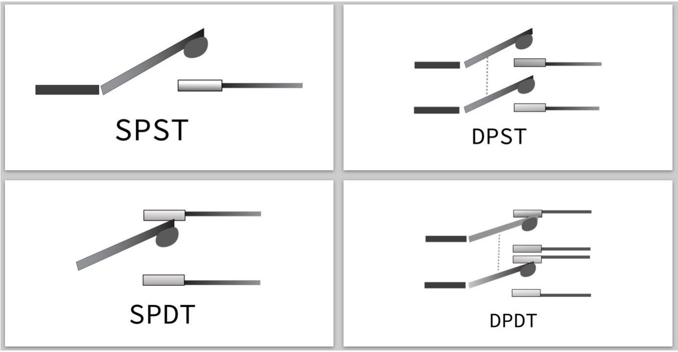


Switches, Inductance, and Relays

Switches

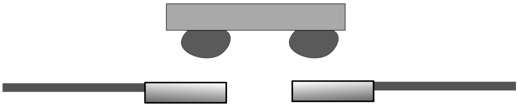


Poles and Throws



- Poles indicates the number of circuits that one switch can control for one operation of the switch.
- Throws indicates the number of contact points.

A Button - SPST



SPST

double break

Maxwell's Equations

- Gauss's Law

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

- Gauss's Law for Magnetism

$$\nabla \cdot B = 0$$

- Faraday's Law

$$\nabla \times E = -\frac{\delta B}{\delta t}$$

- Ampere-Maxwell Law

$$\nabla \times B = \mu_0 J + \mu_0 \epsilon_0 \frac{\delta E}{\delta t}$$

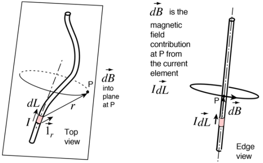
Maxwell's Equations - What They Mean

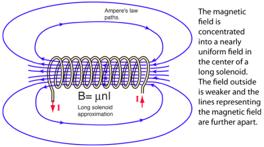
- Gauss's Law: Electric charges are "sources" or "sinks" for electric fields
- Gauss's Law for Magnetism: There are no magnetic monopoles
- Faraday's Law: A changing magnetic field induces current
- Ampere-Maxwell Law: Moving charges and changing electric fields both create circulating magnetic fields.

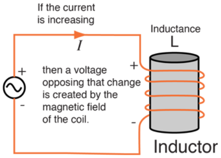
Permittivity and Permeability:

- Permittivity of free space: $\epsilon_0 = 8.85 \times 10^{-12}$ (F/m)
- Permeability of free space: $\mu_0 = 4\pi \times 10^{-7}$ (H/m)

Inductors

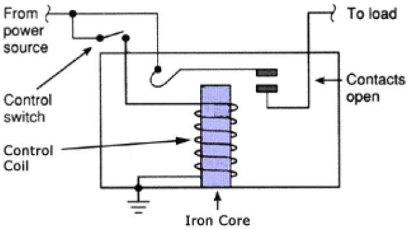






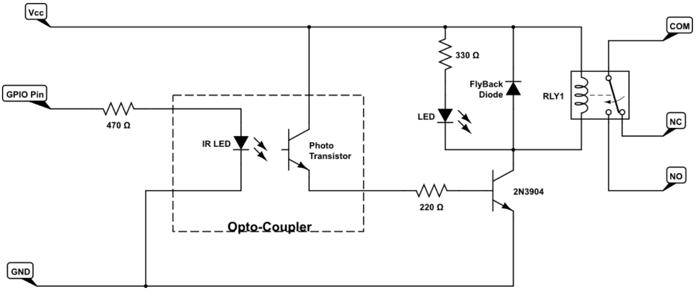
- Current flowing in a wire produces a magnetic field (B) around the wire (from Ampere's Law).
- Wire wrapped into a coil produces a magnetic field that resembles a bar magnet through the center of the coil.
- Also, in a coil, this magnetic field produces an effect known as Inductance (L) that opposes changes in electric current.

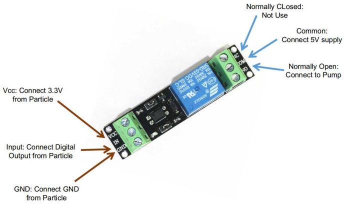
Relays



- When the control terminal has current, the coil around the iron core creates a magnetic field
- The magnetized core attracts a cantilevered arm closing the circuit to the load
- When current is stopped, the core is no longer magnetized and a spring opens the contact.

Optocoupled Relay



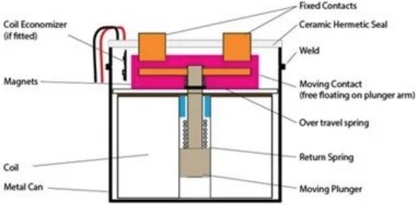


- Optocoupler isolates the relay load (which could be up to 240V) from the controller electronics.

The 35144 Relay in the Vacuum Systems

Double Pole, Double Throw Relay

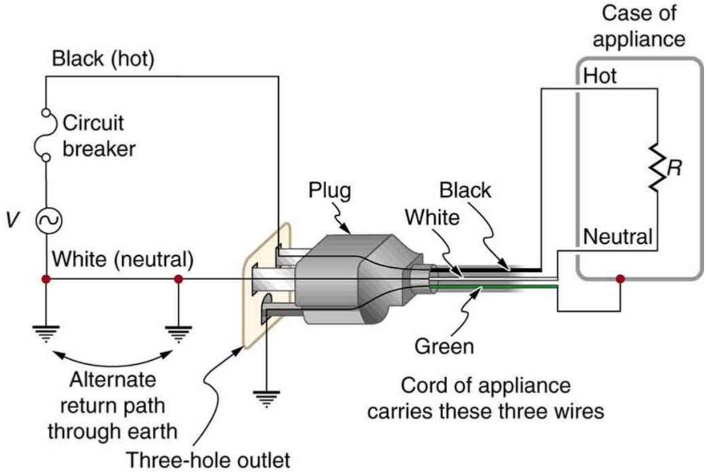
Contactor



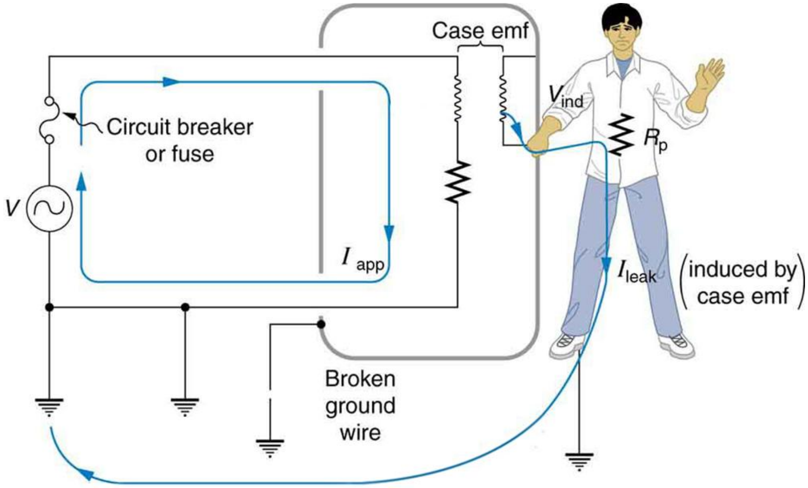
Difference between contactor and other relays

- Higher current, voltage, and power ratings
- Often join 2 poles without a common circuit between them
- Built in arc suppression, allowing them to handle high currents, such as motor starting inrush currents
  - Gas filled Contactors
  - Magnetic Blowout Contactors

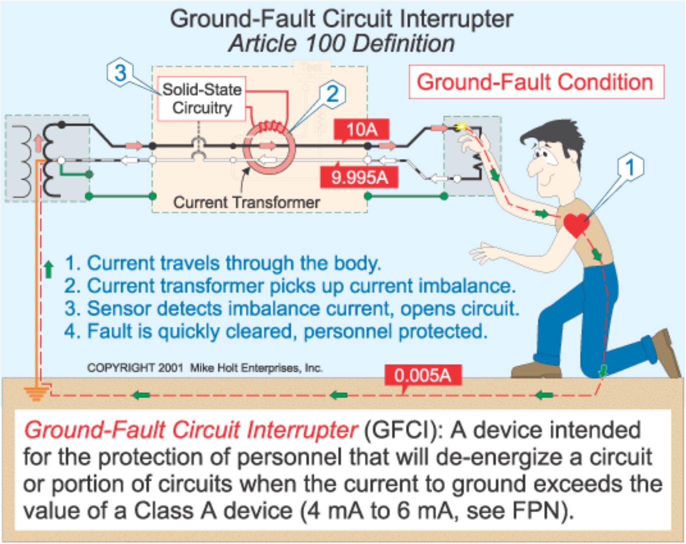
Electrical Safety - Three Wires



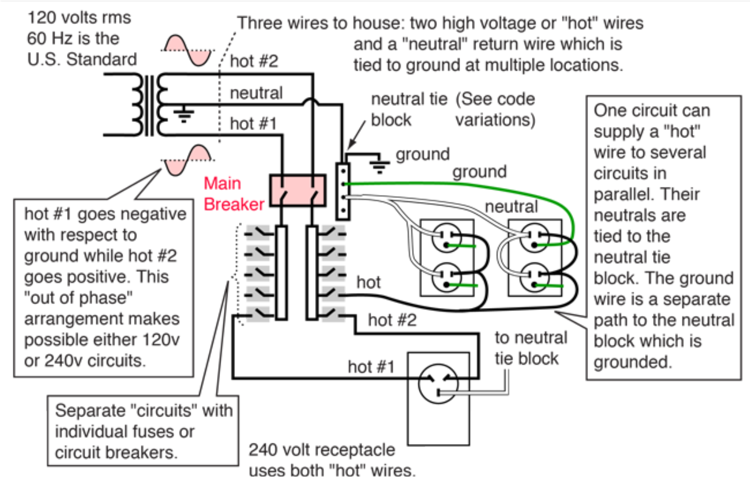
Electrical Safety - Electric Shock



Electrical Safety - GFCI

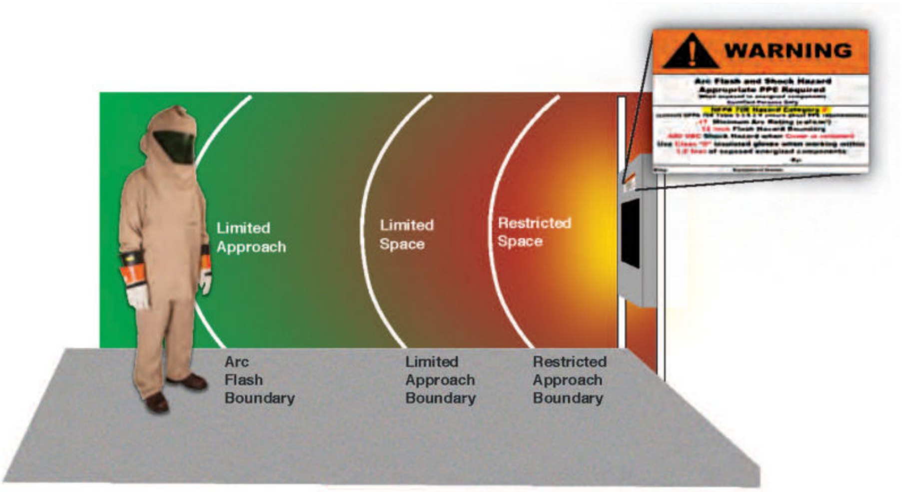


Electrical Safety - 240V



Arc Flash

Arc Flash

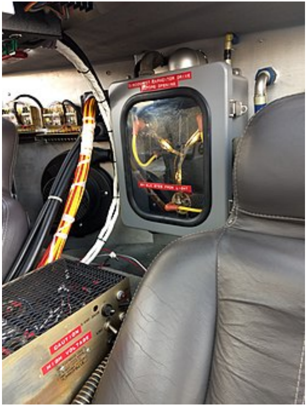

WARNING
Arc Flash and Shock Hazard
Appropriate PPE Required
Limited Approach
Limited Space
Restricted Space
Arc Flash Boundary
Limited Approach Boundary
Restricted Approach Boundary

Three Point Check

1. Verify the test tool works properly when the function switch is placed to "voltage" by testing for voltage on a known energized source, or by using an electronic proving unit, and observing the correct reading on the meter face.
2. Test the circuit to be verified by measuring phase-to-phase and phase-to-ground across all phases. Zero energy must be indicated.
3. Ensure the test tool still indicates voltage properly by placing the test probes, once again, on a known, energized source or the electronic proving unit.

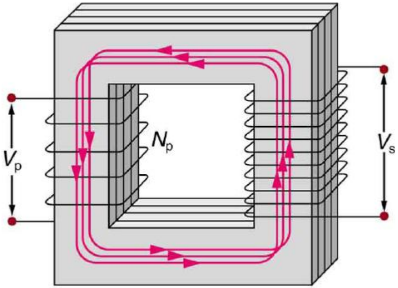
Transformers and Rectifiers

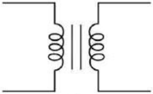
Magnetic Flux



Magnetic Flux (Φ) is the amount of magnetic field lines per unit area.

Transformer




Transformer symbol

From Faraday's Law:

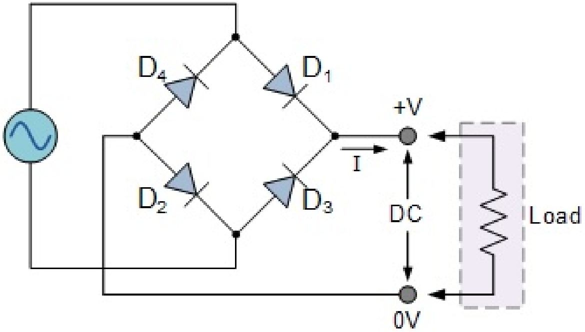
$$V = -N\frac{\Delta\Phi}{\Delta t}$$

Because the change in flux is the same on both sides of the transformer:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

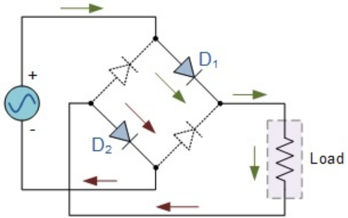
The voltage change is a result of the different number of windings

Full Wave Rectifier

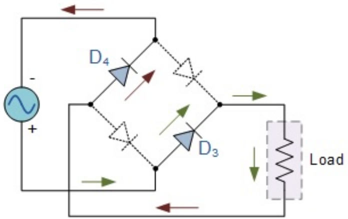


Full Wave Rectifier in Action

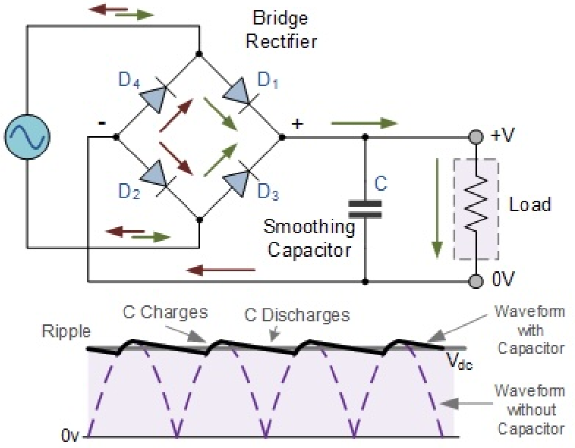
Positive Half Cycle



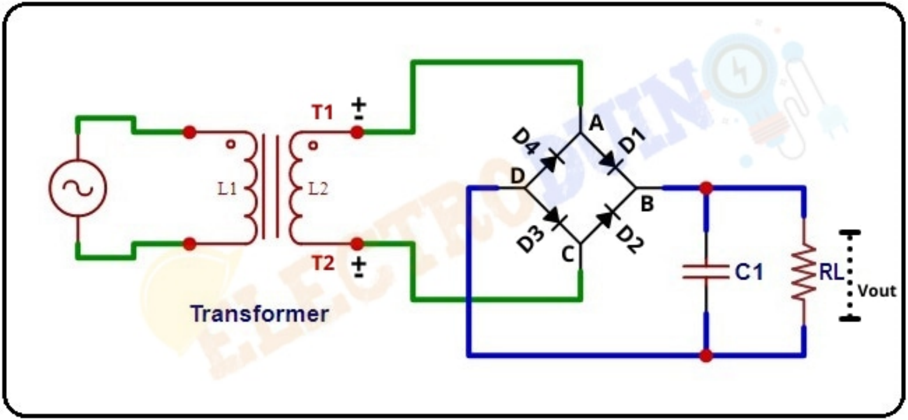
Negative Half Cycle



Full Wave Rectifier with Smoothing Capacitor



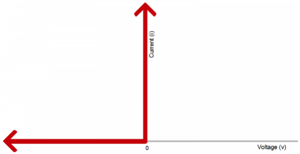
Putting it All Together

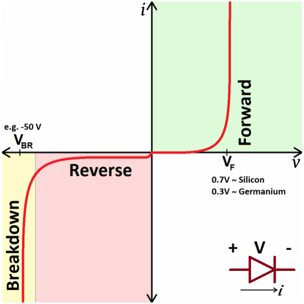


Diodes and Photodetectors

Diodes

The key function of a diode is to control the direction of current-flow. Current passing through a diode can only go in one direction, called the forward direction. Current trying to flow the reverse direction is blocked.

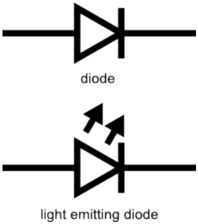




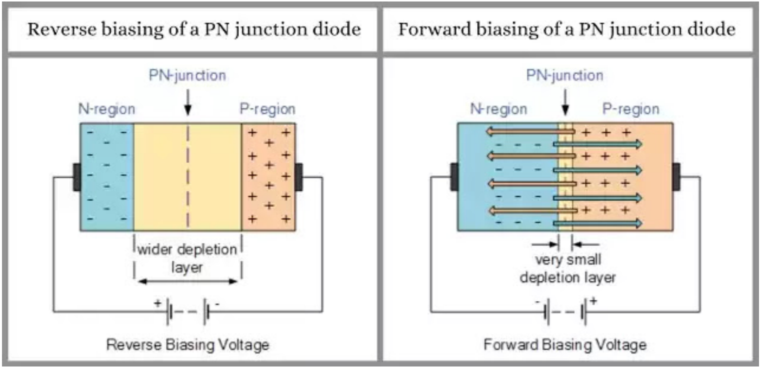
A non-ideal diode needs a small forward voltage (V_F) to turn on and will fail (breakdown) with a large negative voltage (V_{BR}).

Light Emitting Diodes

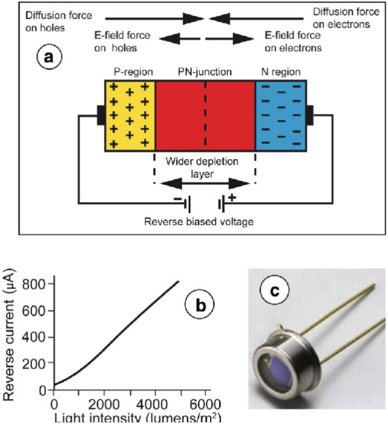
LEDs (that's "ell-ee-dees") are a particular type of diode that convert electrical energy into light.

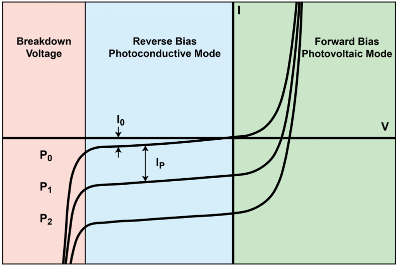


Diodes in Reverse and Forward Bias

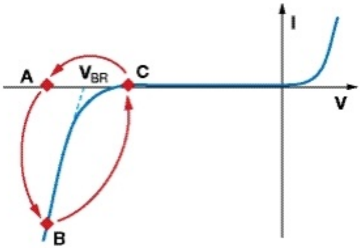


Photodiode


Diffusion force on holes
Diffusion force on electrons
E-field force on holes
E-field force on electrons
a
P-region
PN-junction
N region
Wider depletion layer
Reverse biased voltage
Reverse current (μA)
800
600
400
200
0
0
2000
4000
6000
Light intensity (lumens/m²)
b
c


Breakdown Voltage
Reverse Bias Photoconductive Mode
Forward Bias Photovoltaic Mode
I
V
I0
IP
P0
P1
P2

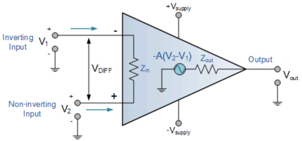
Avalanche Photodiode (APD)

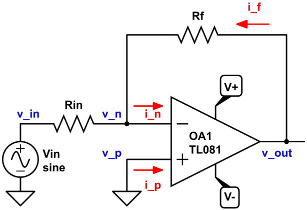


- Operates in reverse direction and biased slightly beyond the breakdown threshold voltage V_{BR} (Geiger Mode)
- An active quenching circuit limits the current through the APD in order to avoid destruction and lowers the bias voltage below V_{BR}
- There is a deadtime after quenching
- In addition to photo-generated events, Dark Counts can happen spontaneously

Operational Amplifiers

Ideal Op Amp





- Op Amp amplifies the difference in voltage between the two inputs
- Ideal OpAmp Assumptions
  - Amplification is infinite ($> 20k$)

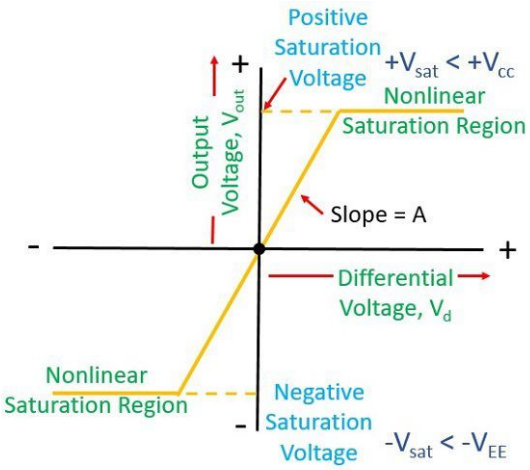
$$v_n = v_p$$

  - Input impedance is infinite

$$i_n = i_p = 0$$

  - Output impedance is zero

OpAmp in saturation



Op Amp Circuits

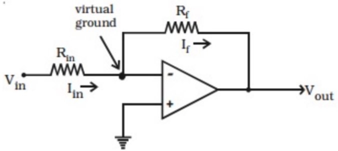


Fig Inverting amplifier

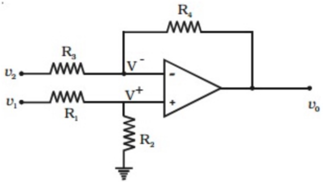


Fig Difference amplifier

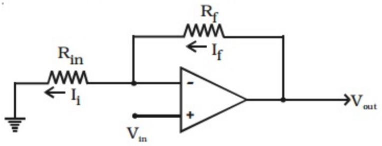


Fig Non-inverting amplifier

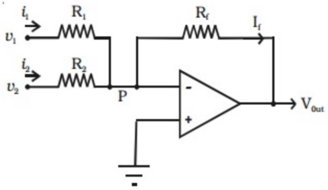
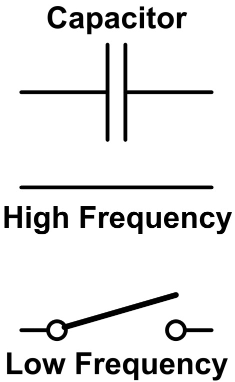


Fig Summing amplifier

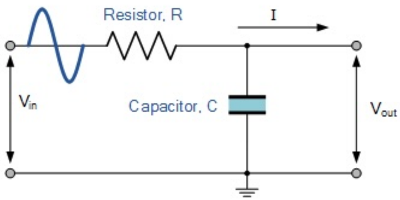
Capacitors Revisited

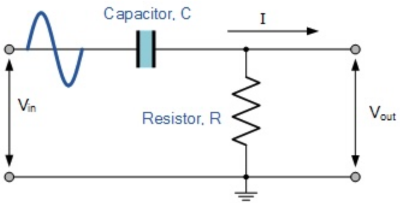


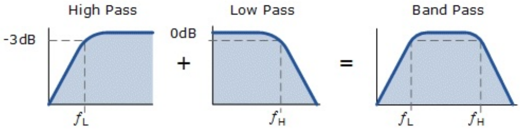
Capacitor acts like:

- High Frequency: Short
- Low Frequency: Open

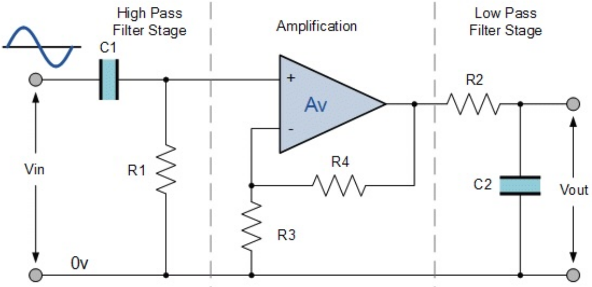
Passive Filters

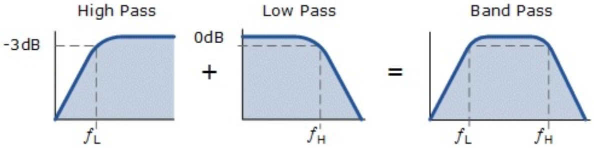




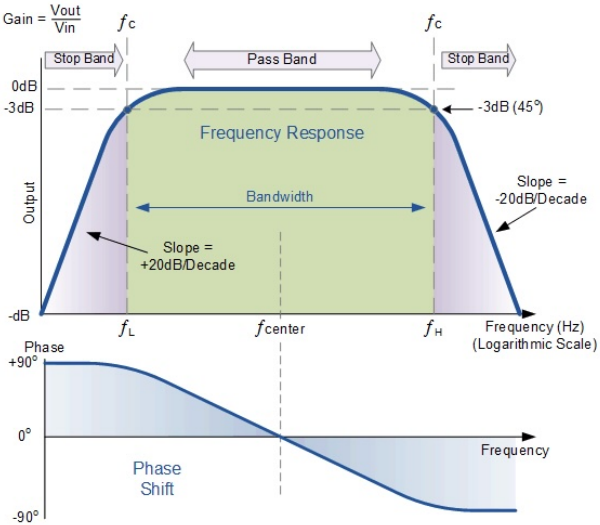


Active Bandpass Filter

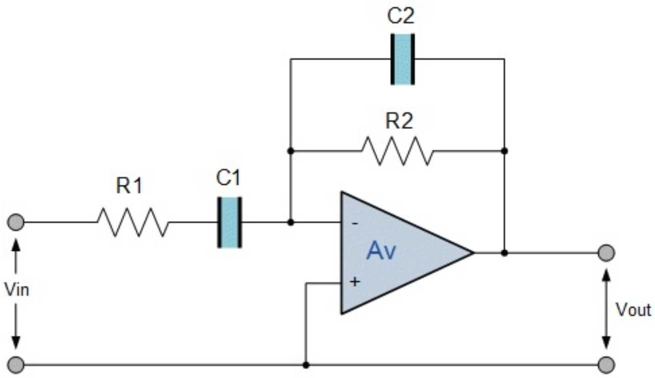




Active Bandpass Response

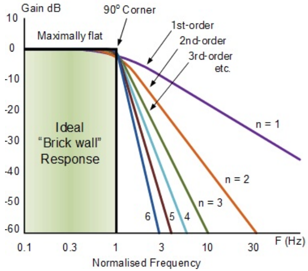


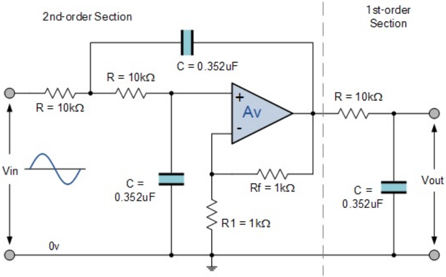
Inverting Active Bandpass Filter



$$f_L = \frac{1}{2\pi R_1 C_1} \qquad f_H = \frac{1}{2\pi R_2 C_2}$$

Higher Order Butterworth (Lowpass) Filters





First described in 1930 by the British engineer and physicist Stephen Butterworth in his paper entitled "On the Theory of Filter Amplifiers".