

# Quantum Electronics and Circuits

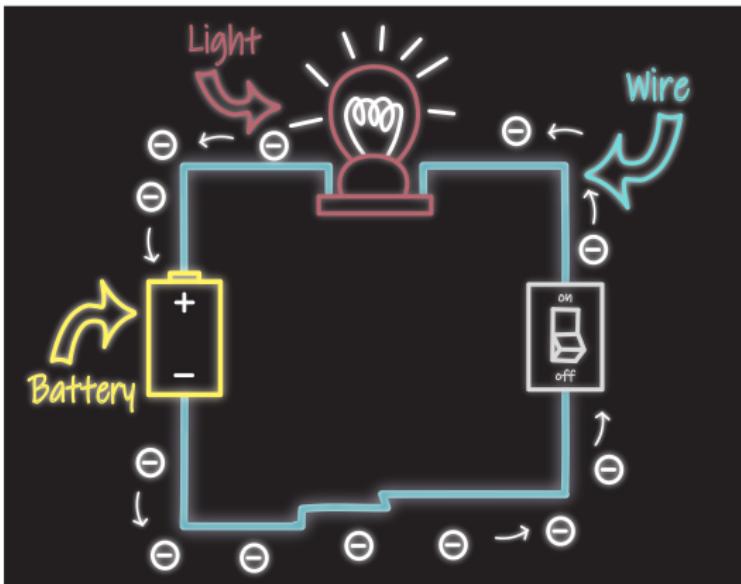
Brian Rashap

November 2025

# Electrical Components and Circuits

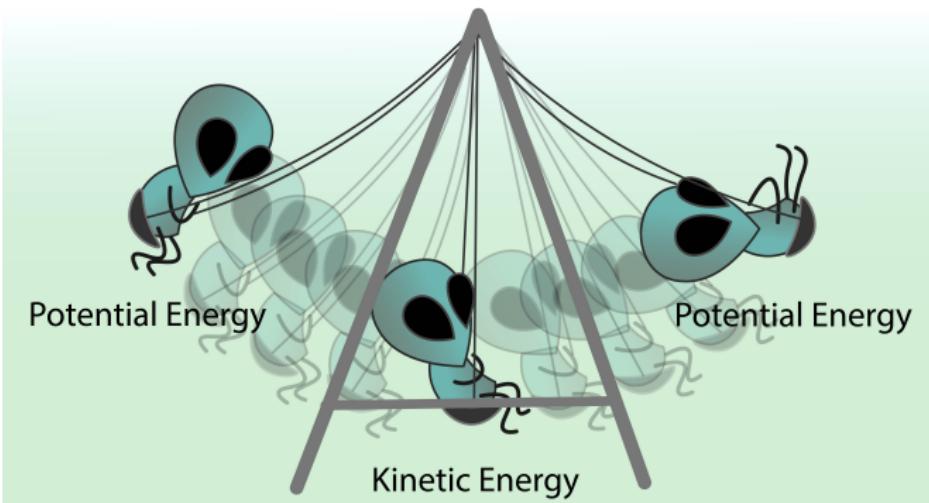


# Resistive Circuits





# Energy



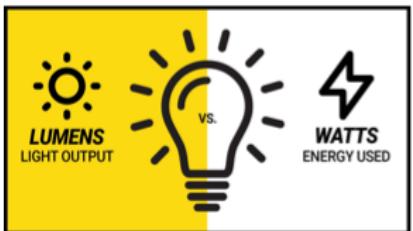
- Kinetic Energy - energy of motion
- Potential Energy - energy stored in an object



# Electrical Circuit Terms

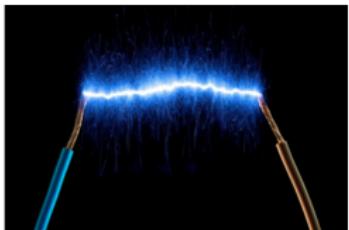


Voltage is **electric potential energy per unit charge** ( $V = J/C$ )

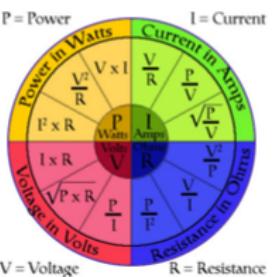


Power is the rate of doing work or **the rate of using energy**. ( $W = J/S$ )

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



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



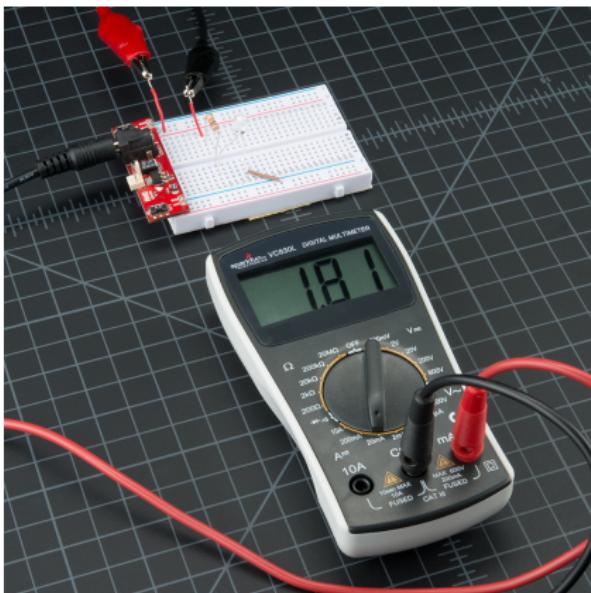
$$\text{Power} = \text{Voltage} \times \text{Current}$$



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



# Measuring Voltage, Current, and Resistance



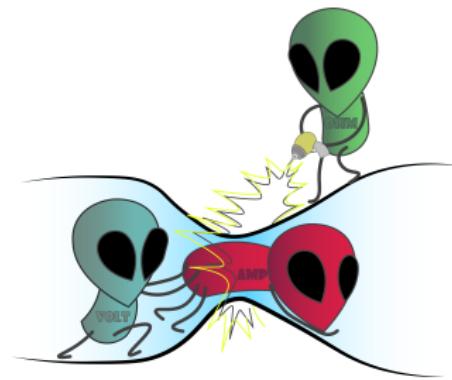
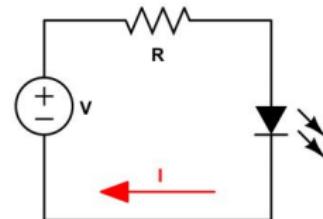


# Ohm's Law

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:

## Ohm's Law

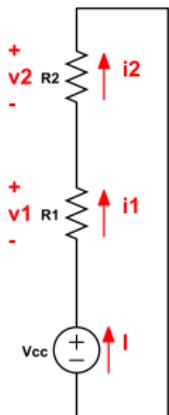
$$V = I * R$$





# A word about circuit notation

Subscripts will be used to denote quantities (voltage, current, etc) for different elements:



- $i_1$  or  $i_1$  is the current through Resistor 1 ( $R_1$ )
- $i_2$  or  $i_2$  is the current through Resistor 2 ( $R_2$ )
- $v_1$  or  $v_1$  is the voltage across Resistor 1 ( $R_1$ )
- $I$  is the current delivered by the power supply
- $V_{cc}$  (common collector <sup>a</sup> voltage) is the notation we will use for 3.3V from the Particle

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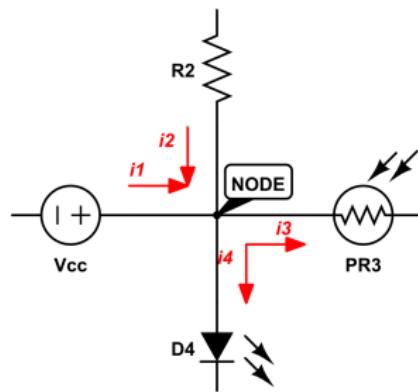
<sup>a</sup>Common Collector is a term for certain parts of transistor circuits. We will learn about Transistors in Lesson 11



# 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

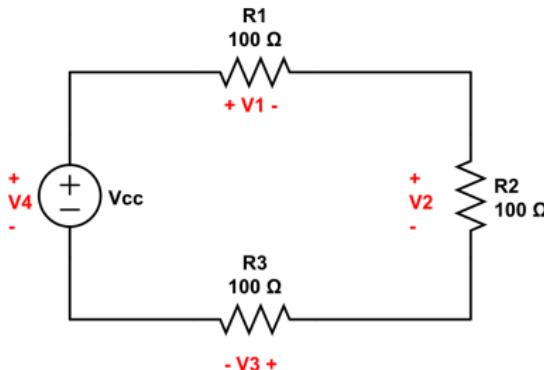


$$i_1 + i_2 = i_3 + i_4$$



# Kirchhoff's Second Law

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



$$V4 - (V1 + V2 + V3) = 0$$

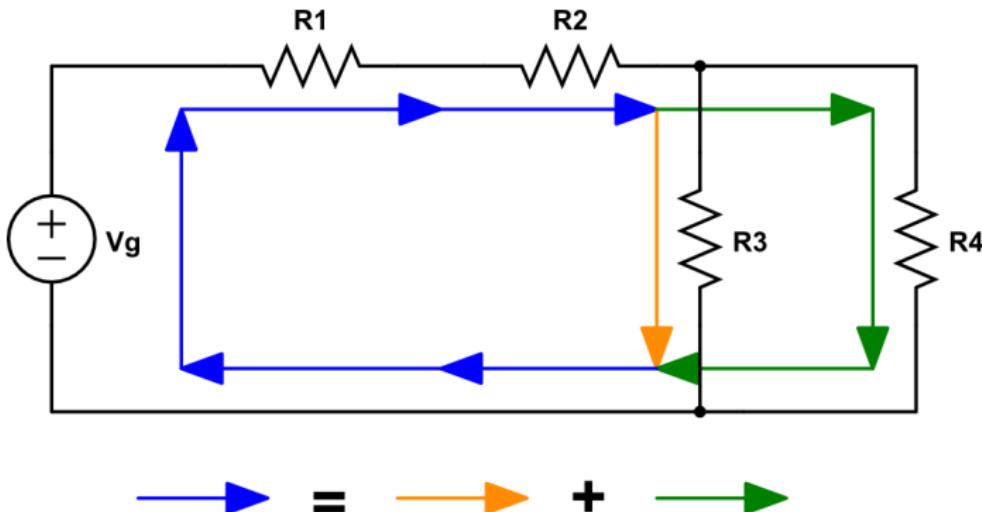


# Kirchhoff's Second Law





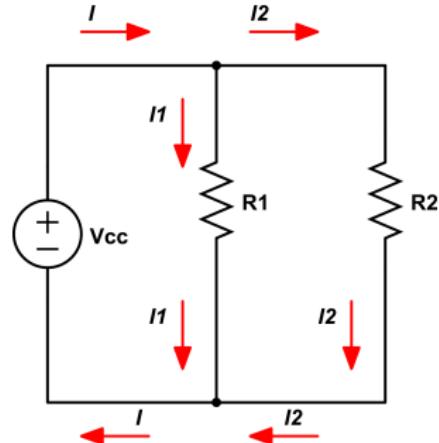
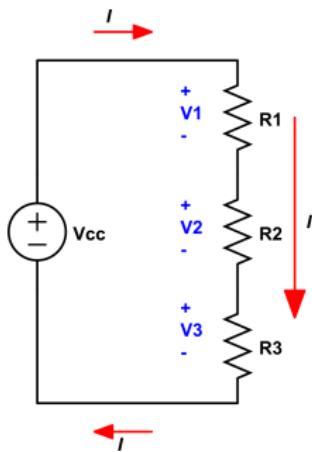
# Resistors in Series and Parallel



How many nodes? How many loops?



# Resistors in Series and Parallel

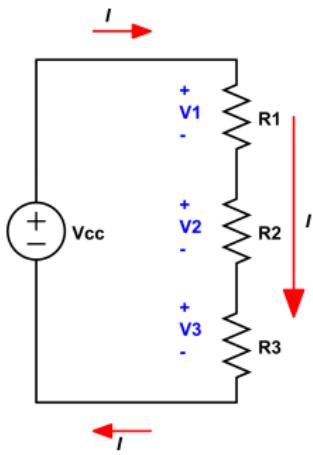


$$R_{eq} = R_1 + R_2 + R_3$$

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



# 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:

$$V_{cc} = V_1 + V_2 + V_3 \quad (1)$$

Using Ohm's Law:

$$V_{cc} = IR_1 + IR_2 + IR_3 \quad (2)$$

Using the Distributive Property:

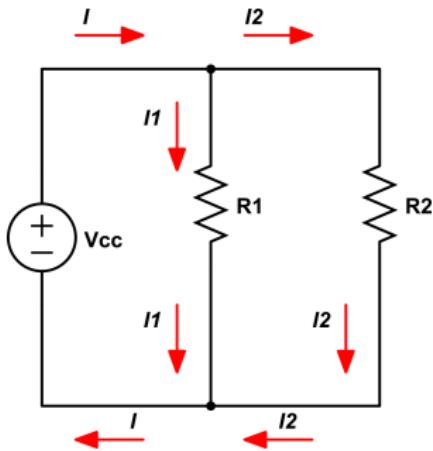
$$V_{cc} = I(R_1 + R_2 + R_3) \quad (3)$$

Gives the Equivalent Resistance:

$$R_{eq} = R_1 + R_2 + R_3 \quad (4)$$



# Resistors in Parallel



$$I = I_1 + I_2 \quad (5)$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} \quad (6)$$

$$I = \frac{V_{cc}}{R_1} + \frac{V_{cc}}{R_2} \quad (7)$$

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

Node Law:  $I = I_1 + I_2$

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

$$\frac{1}{R_{eq}} = \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (9)$$

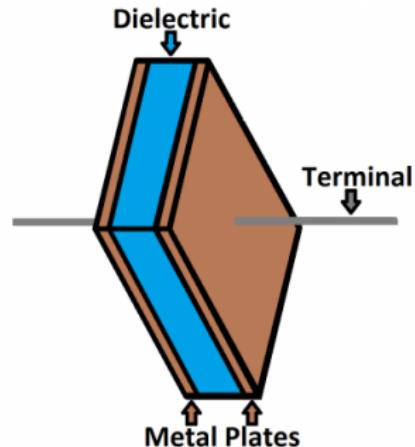
# Capacitance and Filters



# 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.

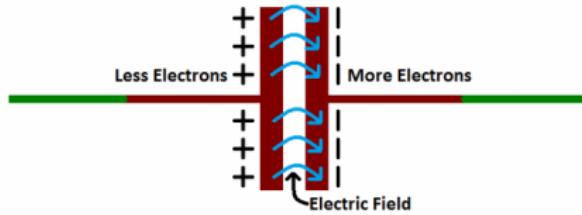
- The dielectric can be made out of all sorts of insulating materials; paper, glass, rubber, ceramic, plastic, or anything that will impede the flow of current.
- The plates are made of a conductive material; aluminum, tantalum, silver, or other metals.





# Capacitors

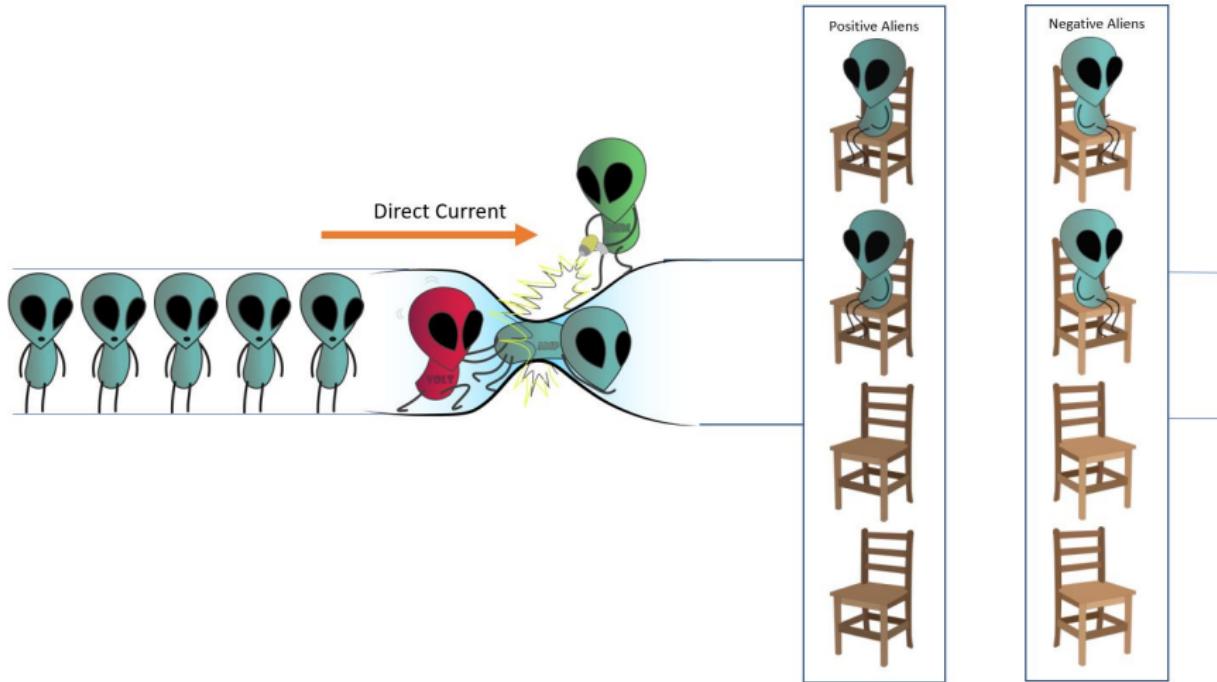
When current flows into a capacitor, the charges get "stuck" on the plates because they cannot get past the insulating dielectric. Electrons build up on one of the plates, and it becomes overall negatively charged. The large amount of negative charges pushes away like charges on the other plate, making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

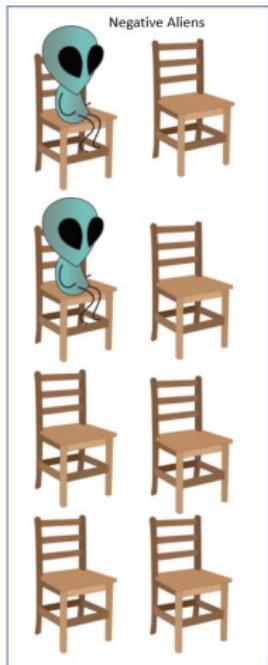
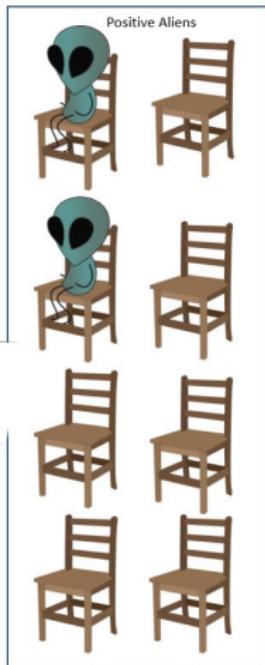
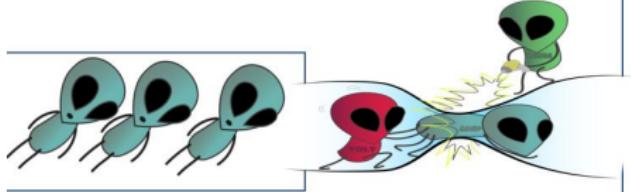




# Capacitors in Circuits

Larger values of R and C

Direct Current





# RC Time Constant

Capacitance is defined as:

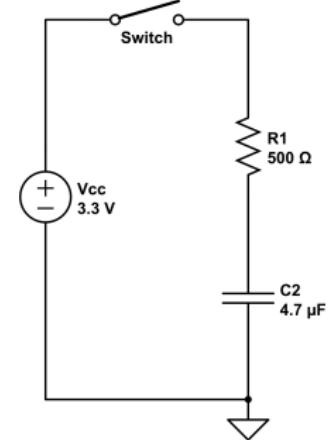
$$C = \frac{Q}{V} \left( \frac{\text{Coulombs}}{\text{Volt}} \right)$$

The current through a capacitor is:

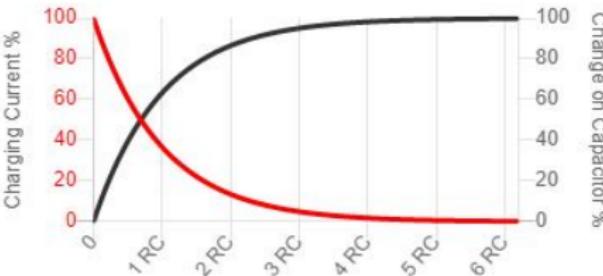
$$I = C \frac{\Delta V}{\Delta t}$$

And, therefore, the capacitor charges with a time constant ( $\tau$ ):

$$\tau = RC$$

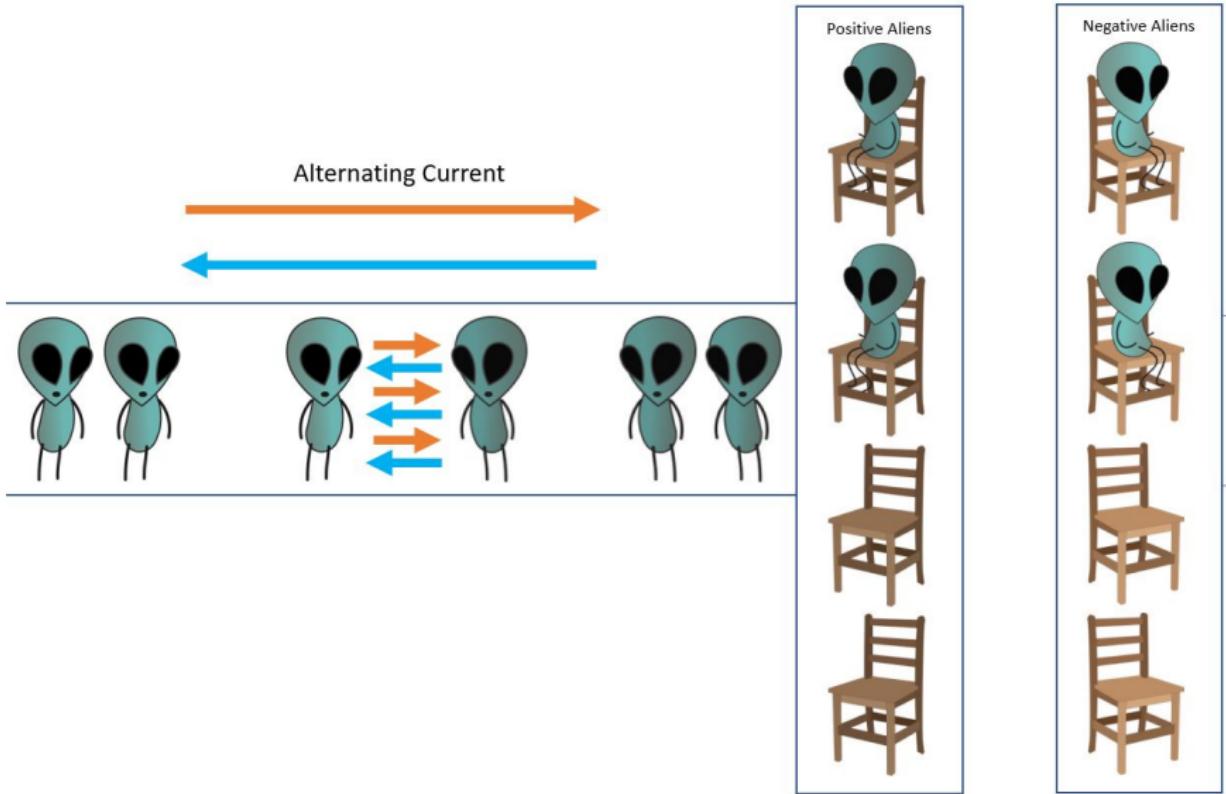


$$V_c(t) = V_c(0) * e^{-\frac{t}{\tau}}$$





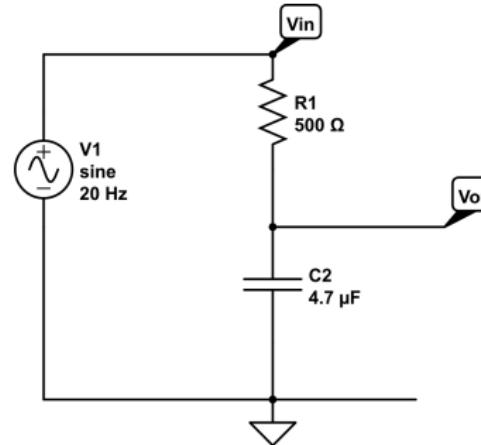
# Alternating Current





# Low Pass Filter - cutoff frequency $f_c$

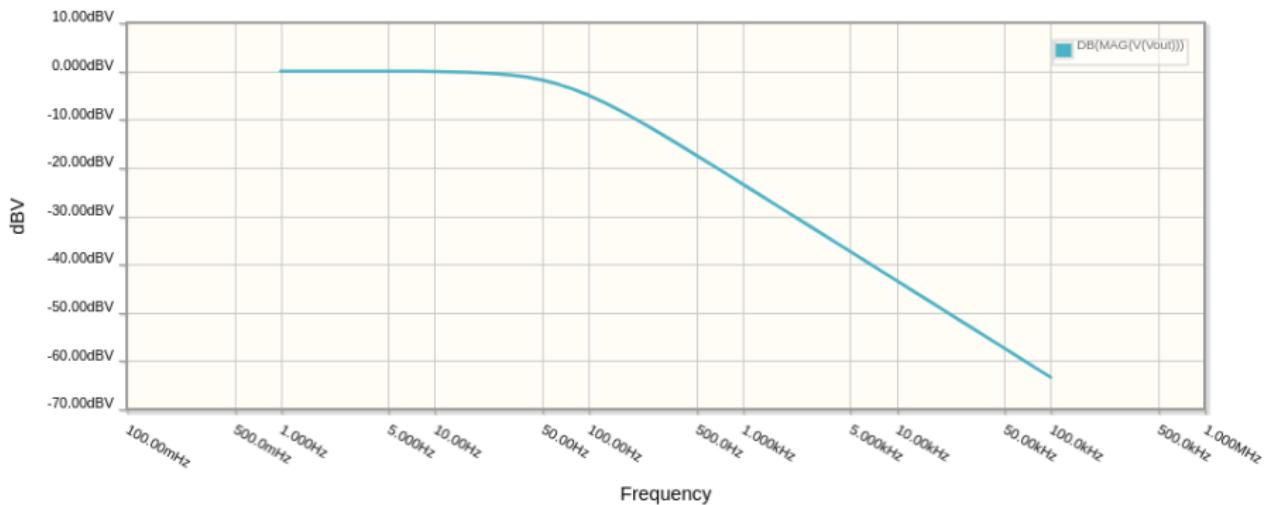
- At low frequencies, there is plenty of time for the capacitor to charge up to practically the same voltage as the input voltage.
- At high frequencies, the capacitor only has time to charge up a small amount before the input switches direction. The output goes up and down only a small fraction of the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



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



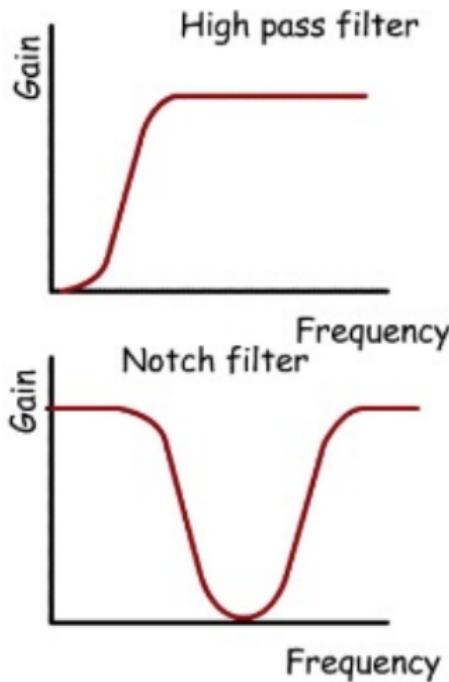
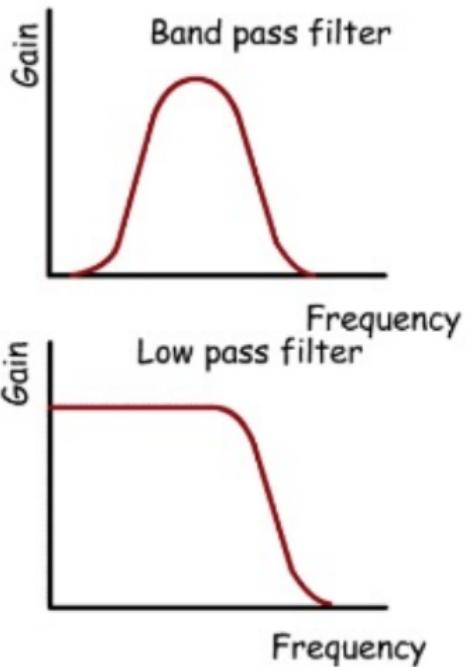
# Low Pass Filter Response



$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(500)(4.7 \times 10^{-6})} = 67.5678 \text{ Hz}$$



# Other types of filters

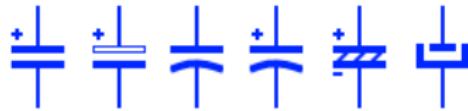




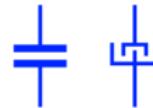
# Capacitors - does it matter how they are placed

- 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.

Polarized Electrolytic Capacitor



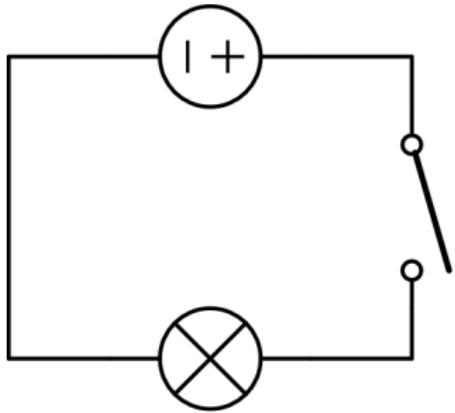
Generic Capacitor



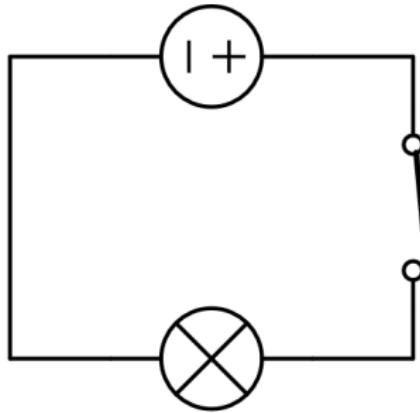
# Switches, Inductance, and Relays



# Switches



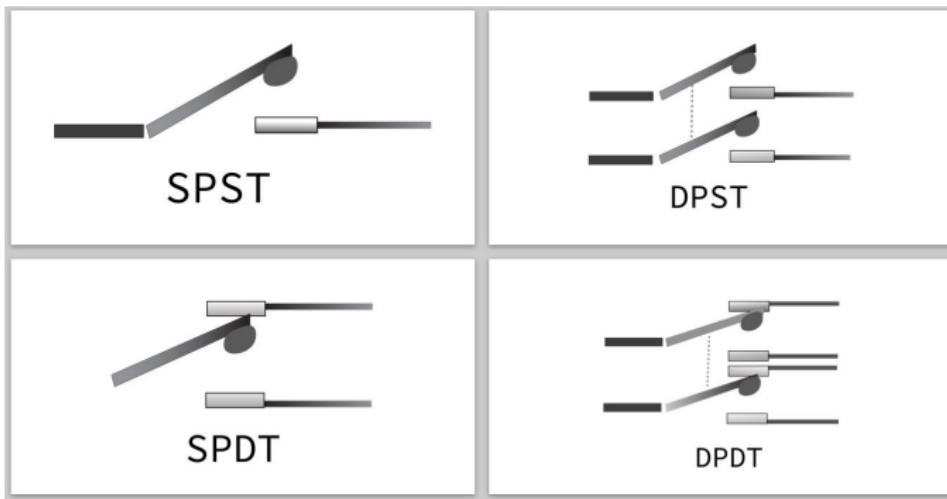
Lamp Off



Lamp On



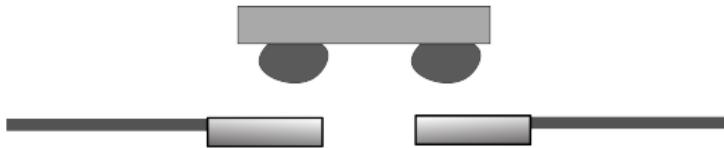
# Poles and Throws



- 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

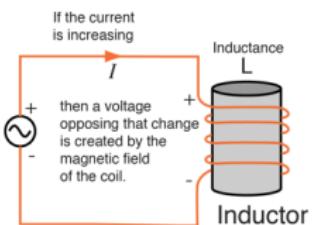
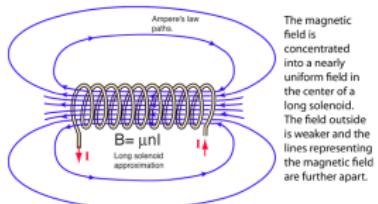
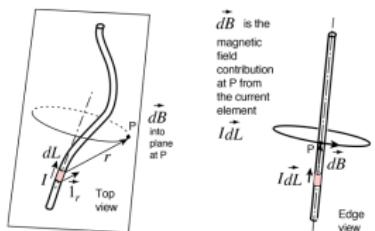
- Gauss's Law: Electric charges are "sources" or "sinks" for electric fields
- Gauss's Law for Magnetism: There are no magnetic monopoles
- Faraday's Law: A changing magnetic field induces current
- Ampere-Maxwell Law: Moving charges and changing electric fields both create circulating magnetic fields.

## 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)



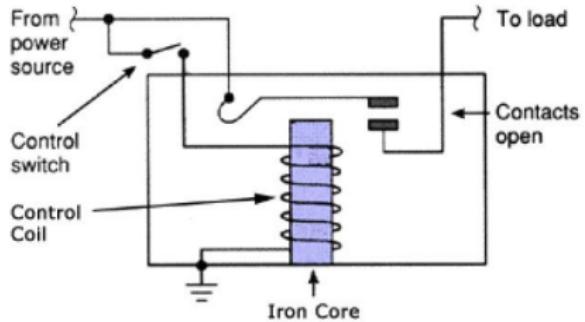
# Inductors



- 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.



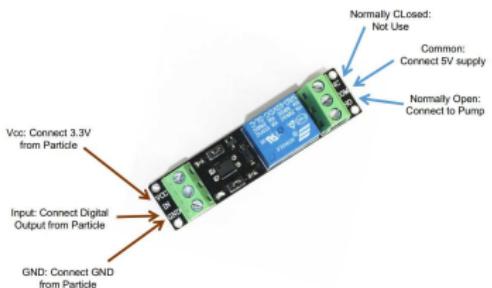
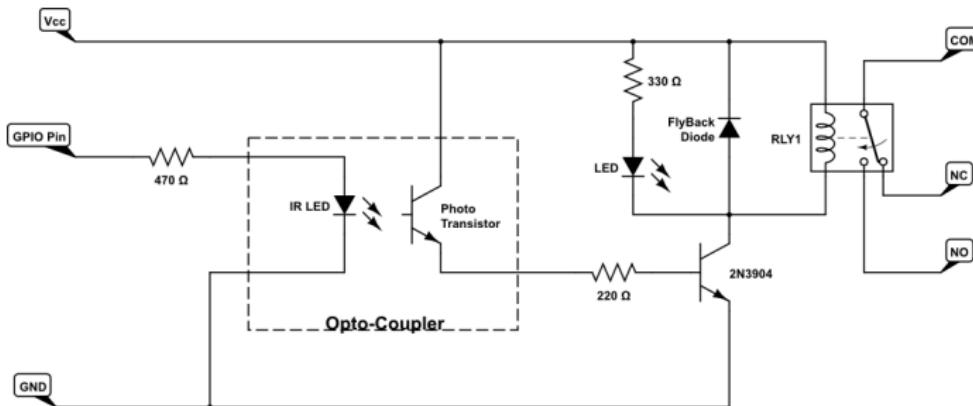
# Relays



- 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.



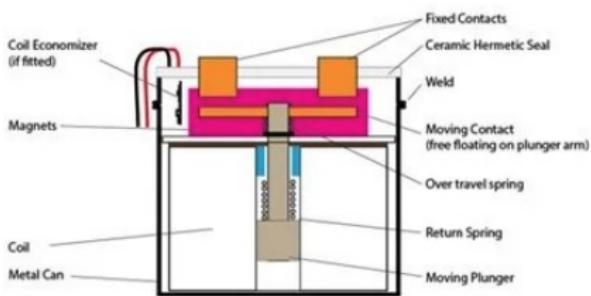
# The 35144 Relay in the Vacuum Systems

Double Pole, Double Throw Relay





# Contactor

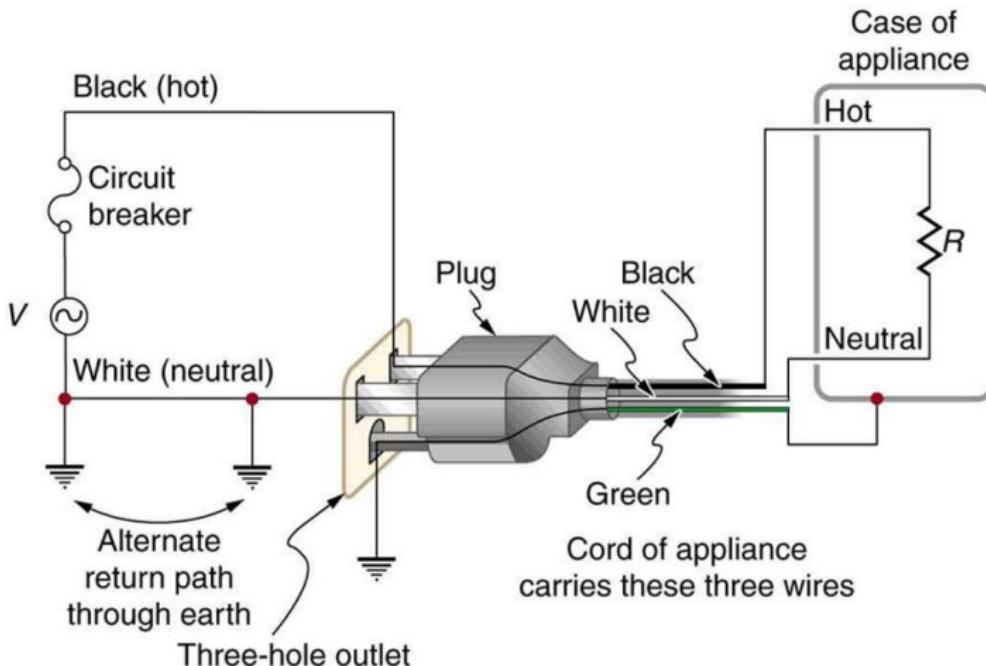


Difference between contactor and other relays

- 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

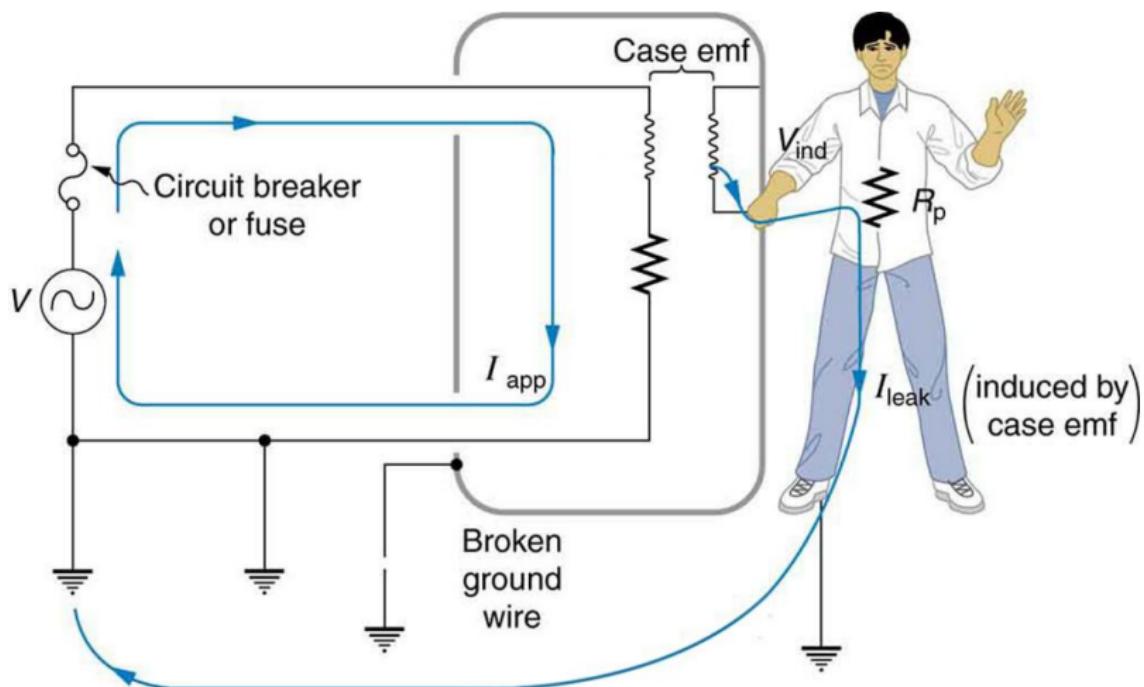


# Electrical Safety - Three Wires



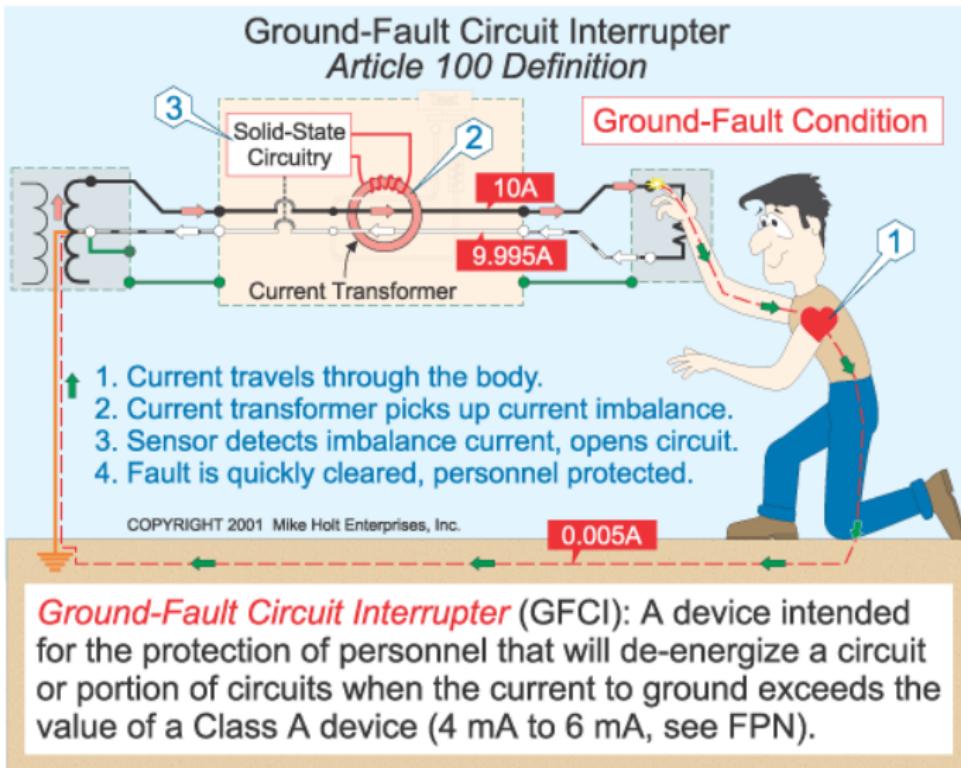


# Electrical Safety - Electric Shock





# Electrical Safety - GFCI

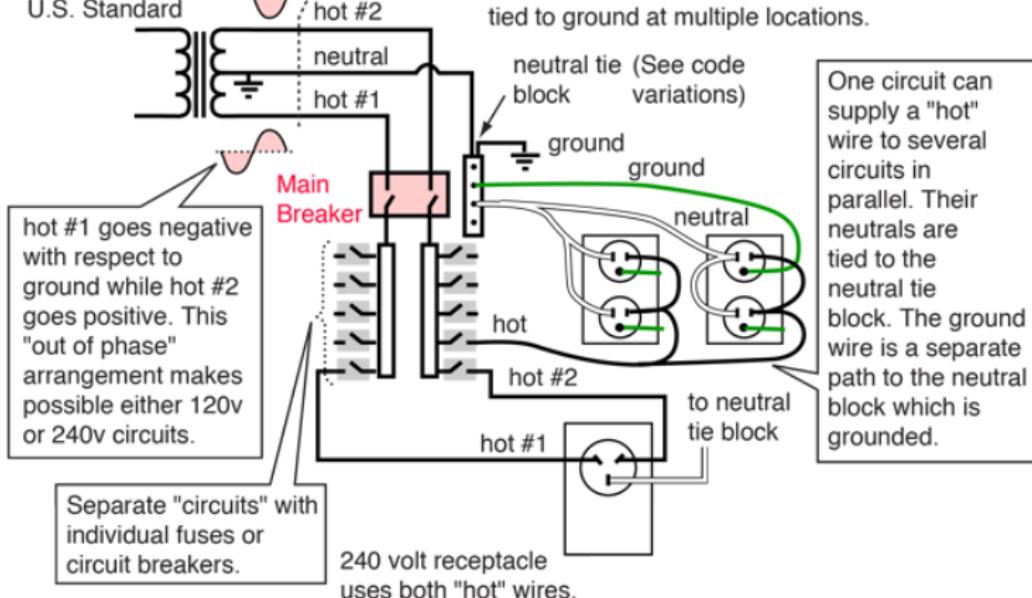




# Electrical Safety - 240V

120 volts rms  
60 Hz is the  
U.S. Standard

Three wires to house: two high voltage or "hot" wires  
and a "neutral" return wire which is  
tied to ground at multiple locations.



One circuit can supply a "hot" wire to several circuits in parallel. Their neutrals are tied to the neutral tie block. The ground wire is a separate path to the neutral block which is grounded.

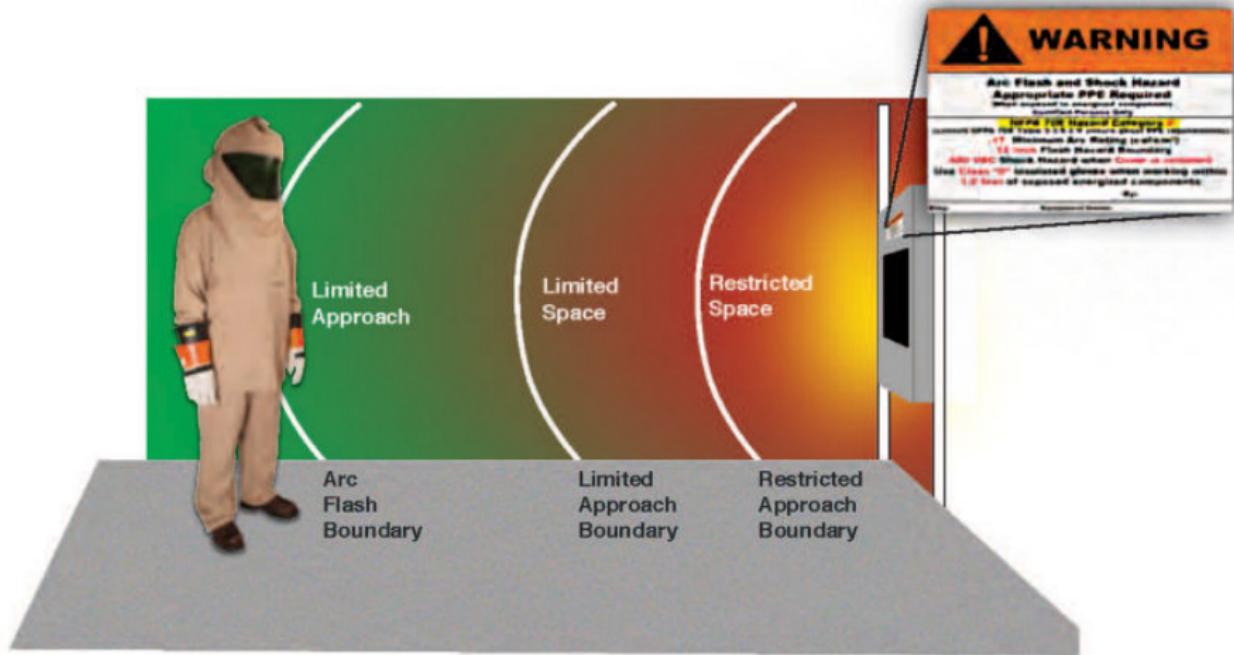


# Arc Flash





# Arc Flash





# Three Point Check



- ➊ 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.
- ➋ Test the circuit to be verified by measuring phase-to-phase and phase-to-ground across all phases. Zero energy must be indicated.
- ➌ 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



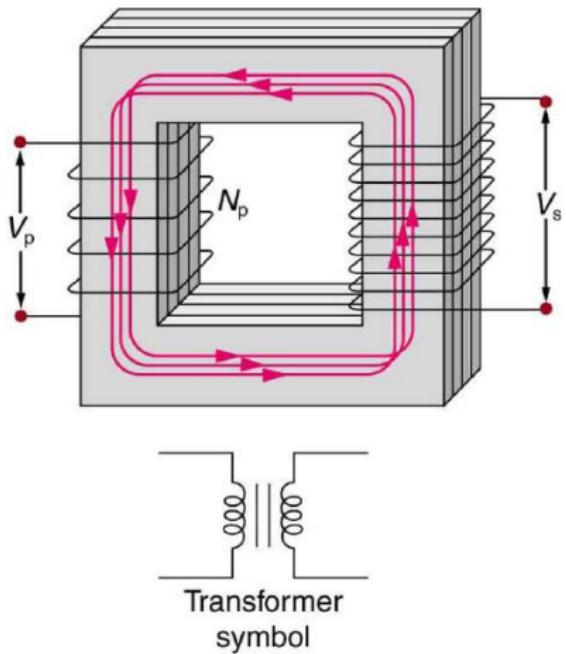
# Magnetic Flux



Magnetic Flux ( $\Phi$ ) is the amount of magnetic field lines per unit area.



# Transformer



From Faraday's Law:

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

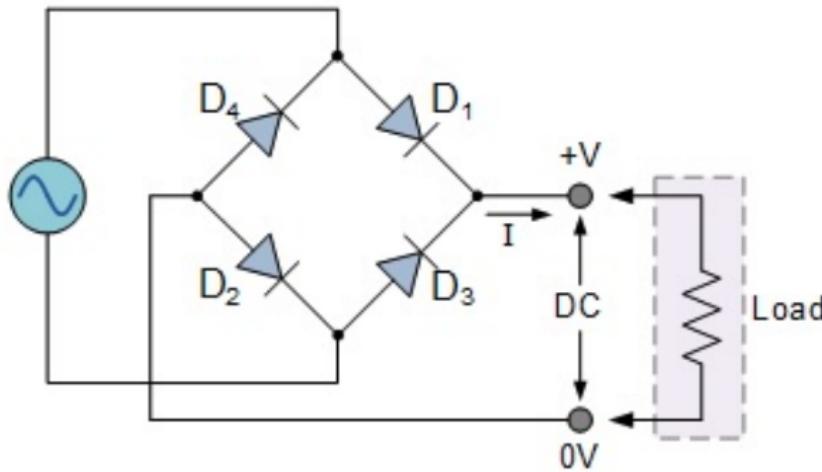
Because the change in flux is the same on both sides of the transformer:

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

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



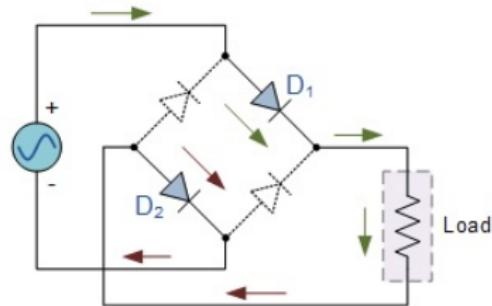
# Full Wave Rectifier



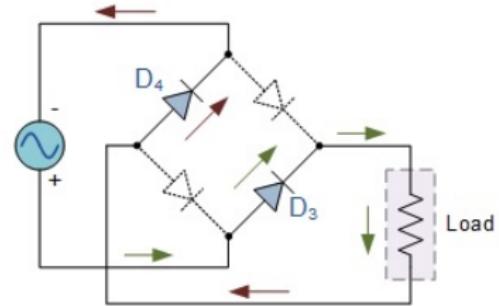


# Full Wave Rectifier in Action

Positive Half Cycle

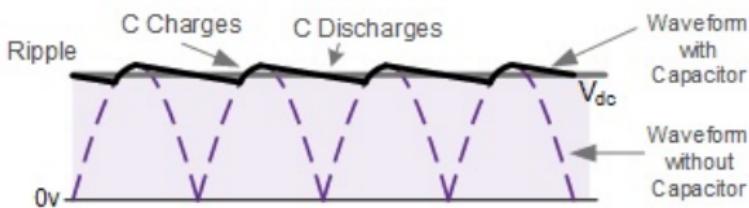
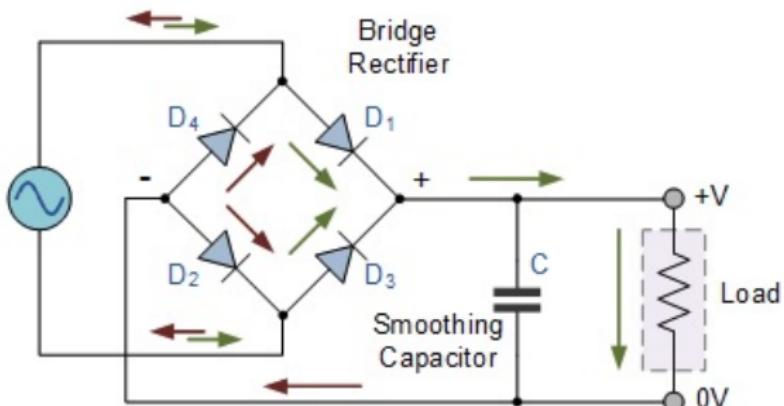


Negative Half Cycle



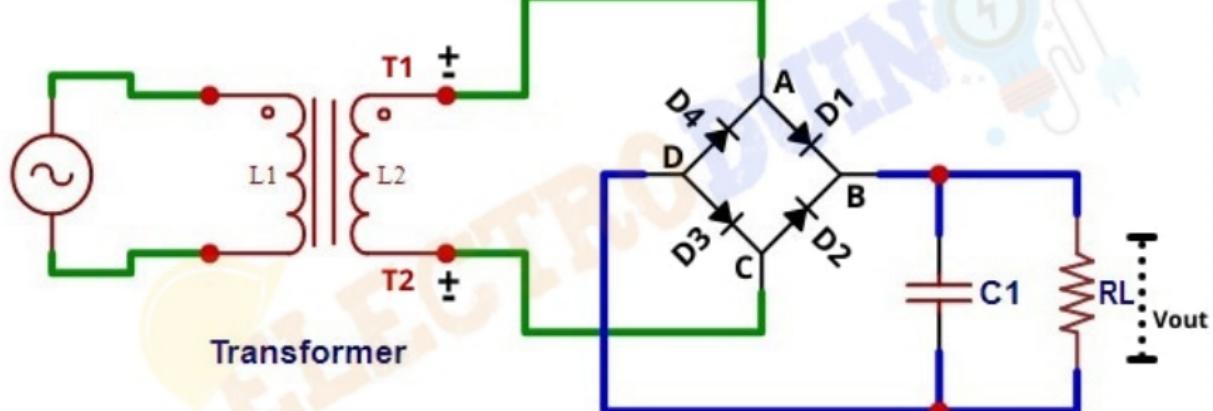


# Full Wave Rectifier with Smoothing Capacitor





# Putting it All Together

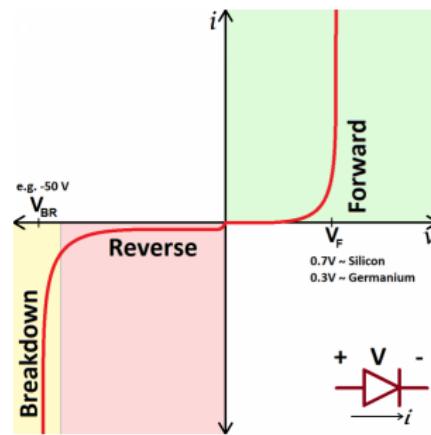


# Diodes and Photodetectors



# 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.

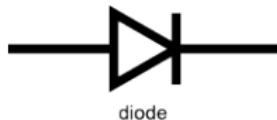


A non-ideal diode needs a small forward voltage ( $V_F$ ) to turn on and will fail (breakdown) with a large negative voltage ( $V_{BR}$ ).



# Light Emitting Diodes

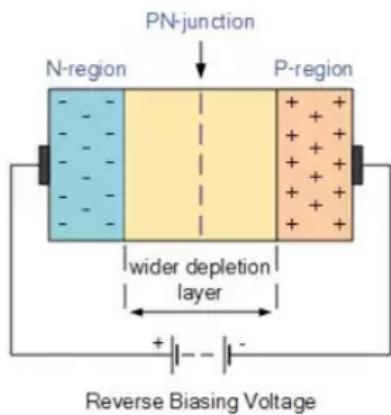
LEDs (that's "ell-ee-dees") are a particular type of diode that convert electrical energy into light.



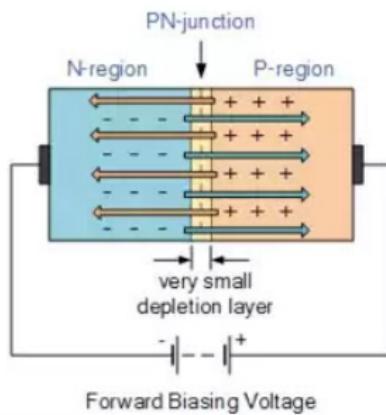


# Diodes in Reverse and Forward Bias

Reverse biasing of a PN junction diode

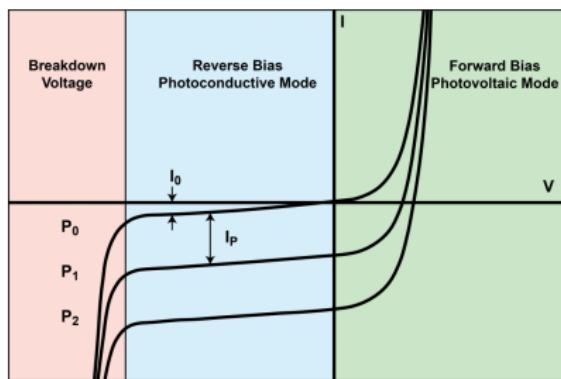
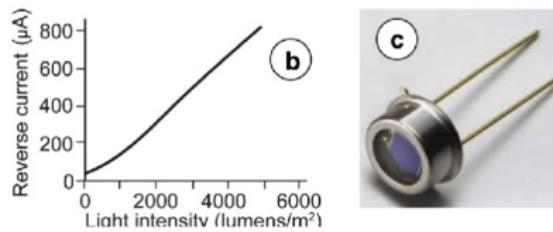
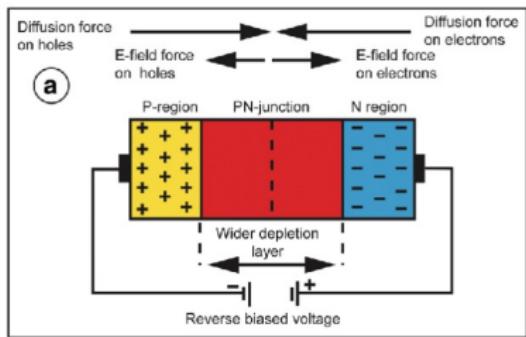


Forward biasing of a PN junction diode





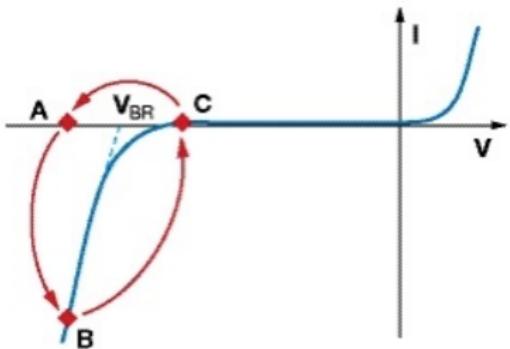
# Photodiode





# Avalanche Photodiode (APD)

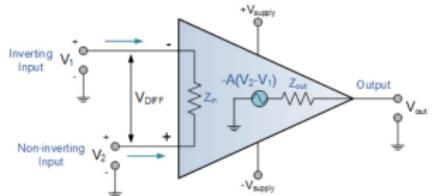
- Operates in reverse direction and biased slightly beyond the breakdown threshold voltage  $V_{BR}$  (Geiger Mode)
- An active quenching circuit limits the current through the APD in order to avoid destruction and lowers the bias voltage below  $V_{BR}$
- There is a deadtime after quenching
- In addition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



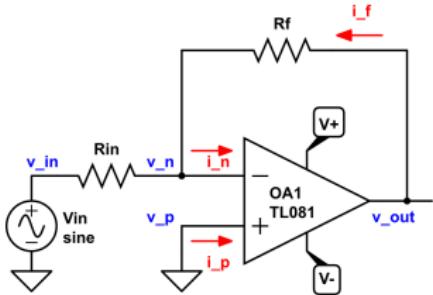
# Operational Amplifiers



# Ideal Op Amp



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

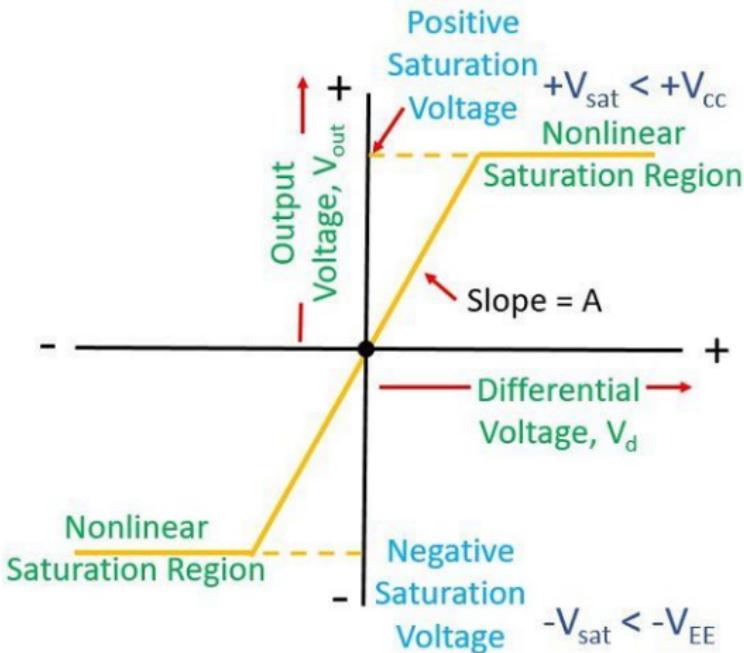


$$v_n = v_p$$

- Input impedance is infinite
- $i_n = i_p = 0$
- Output impedance is zero

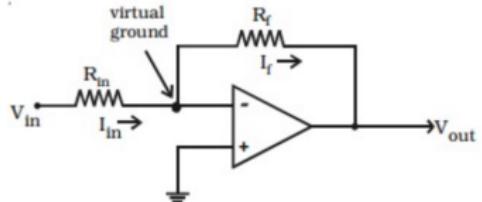


# OpAmp in saturation

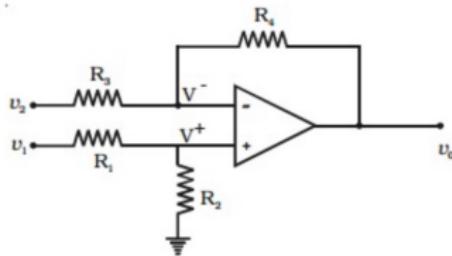




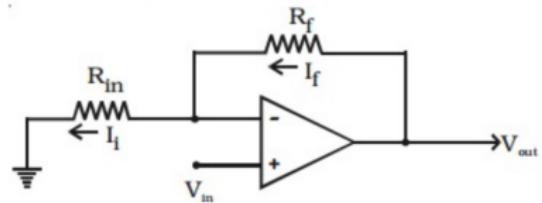
# Op Amp Circuits



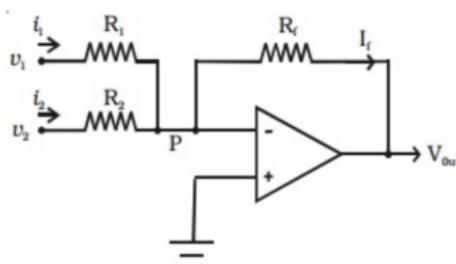
*Fig*      *Inverting amplifier*



*Fig*      *Difference amplifier*



*Fig*      *Non-inverting amplifier*

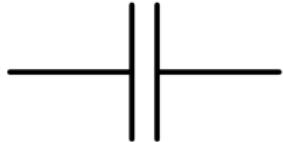


*Fig*      *Summing amplifier*



# Capacitors Revisited

**Capacitor**



**High Frequency**



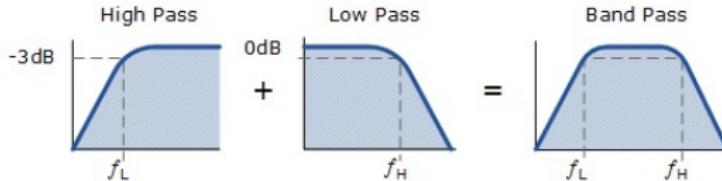
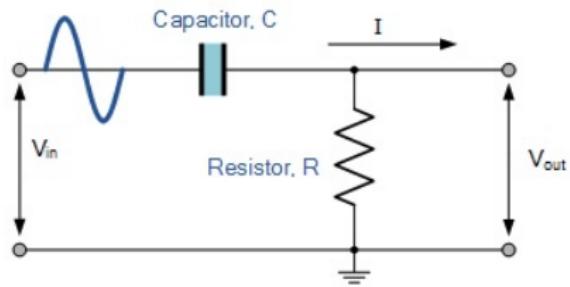
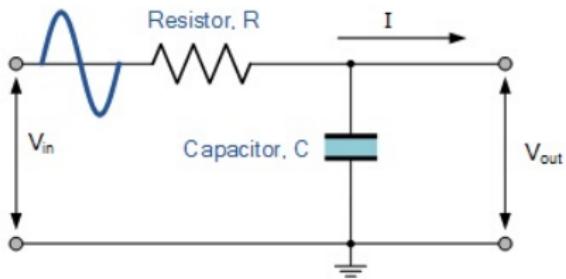
**Low Frequency**

Capacitor acts like:

- High Frequency: Short
- Low Frequency: Open

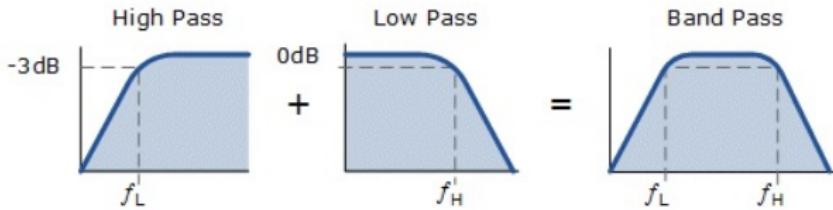
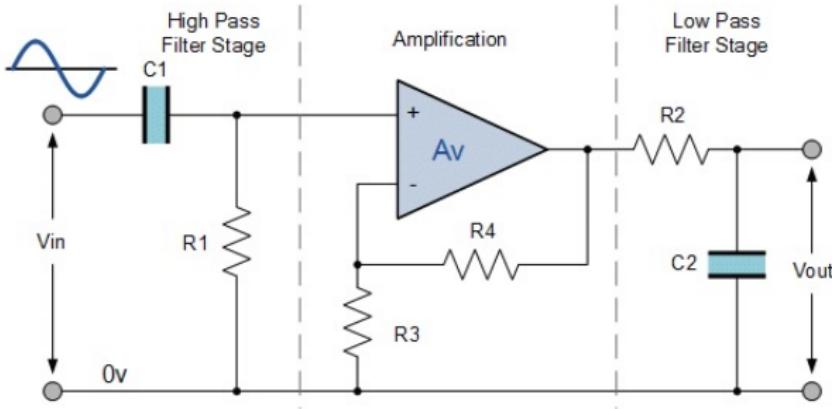


# Passive Filters



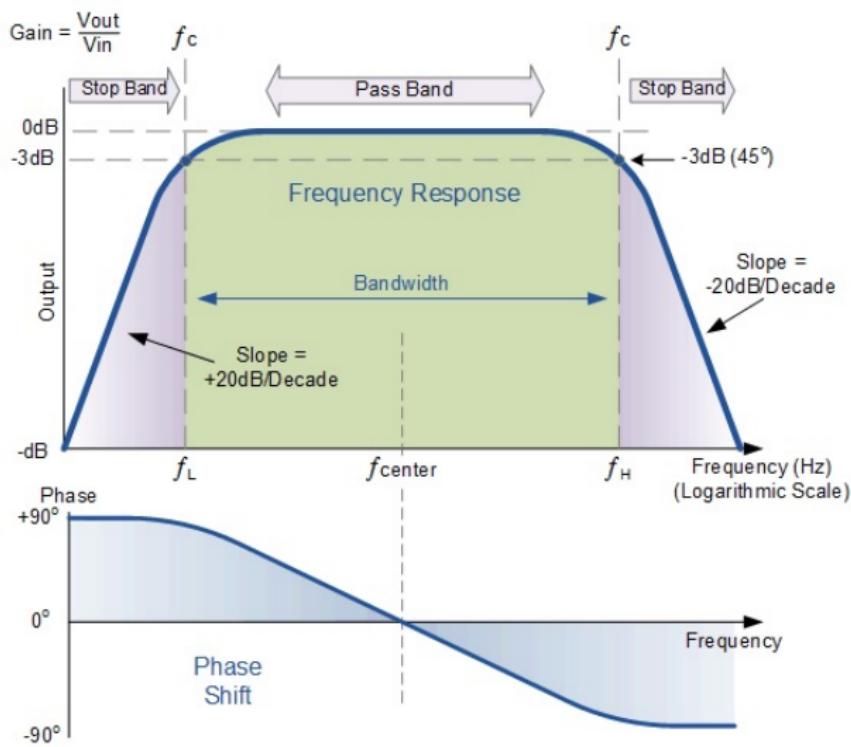


# Active Bandpass Filter



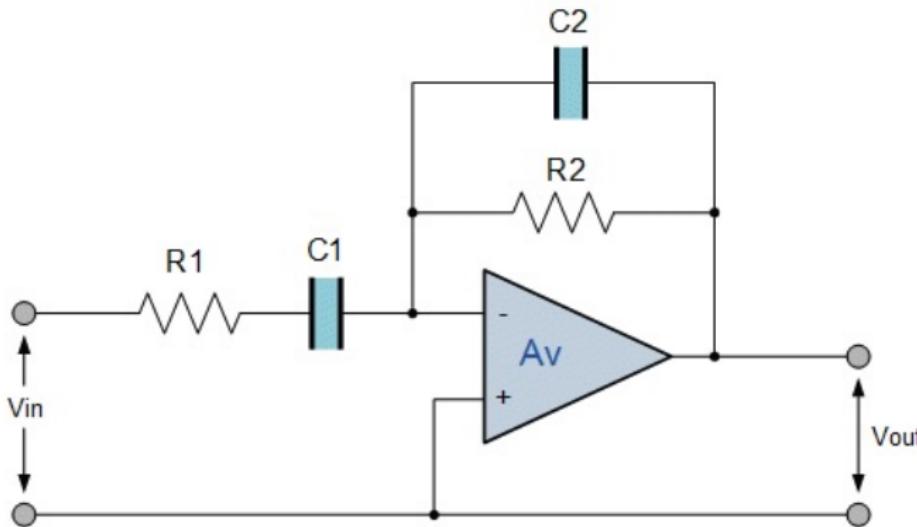


# Active Bandpass Response





# Inverting Active Bandpass Filter

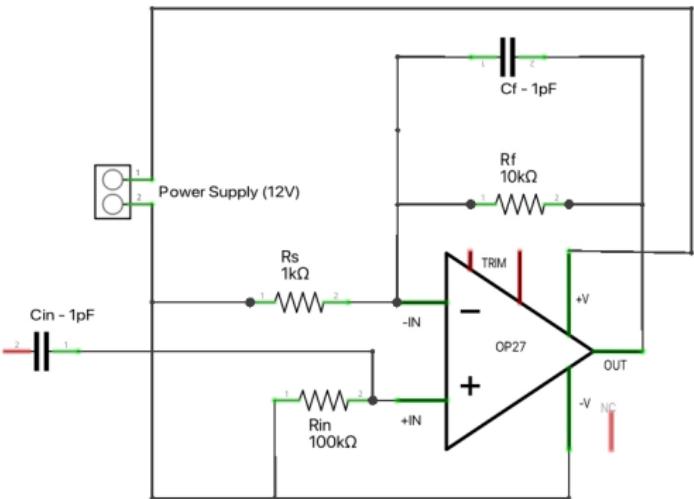
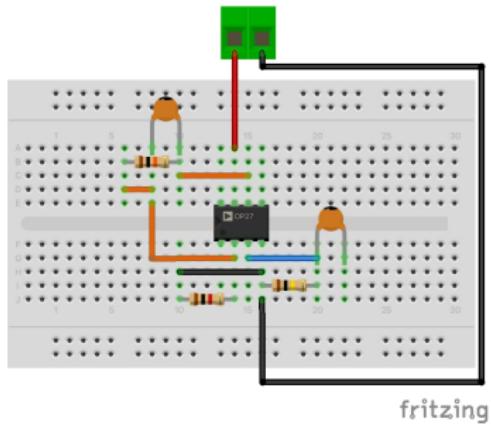


$$f_L = \frac{1}{2\pi R_1 C_1}$$

$$f_H = \frac{1}{2\pi R_2 C_2}$$



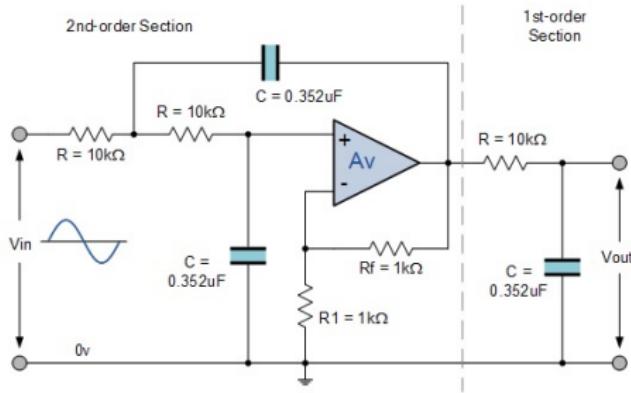
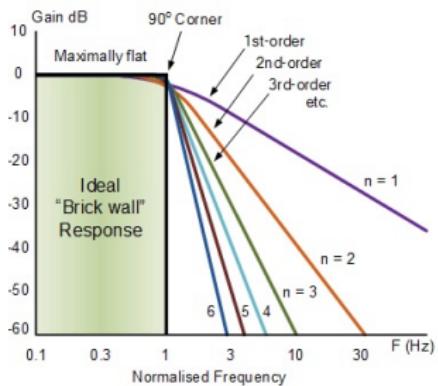
# Non-inverting Bandpass filter



fritzing



# 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".