PHY405-L02

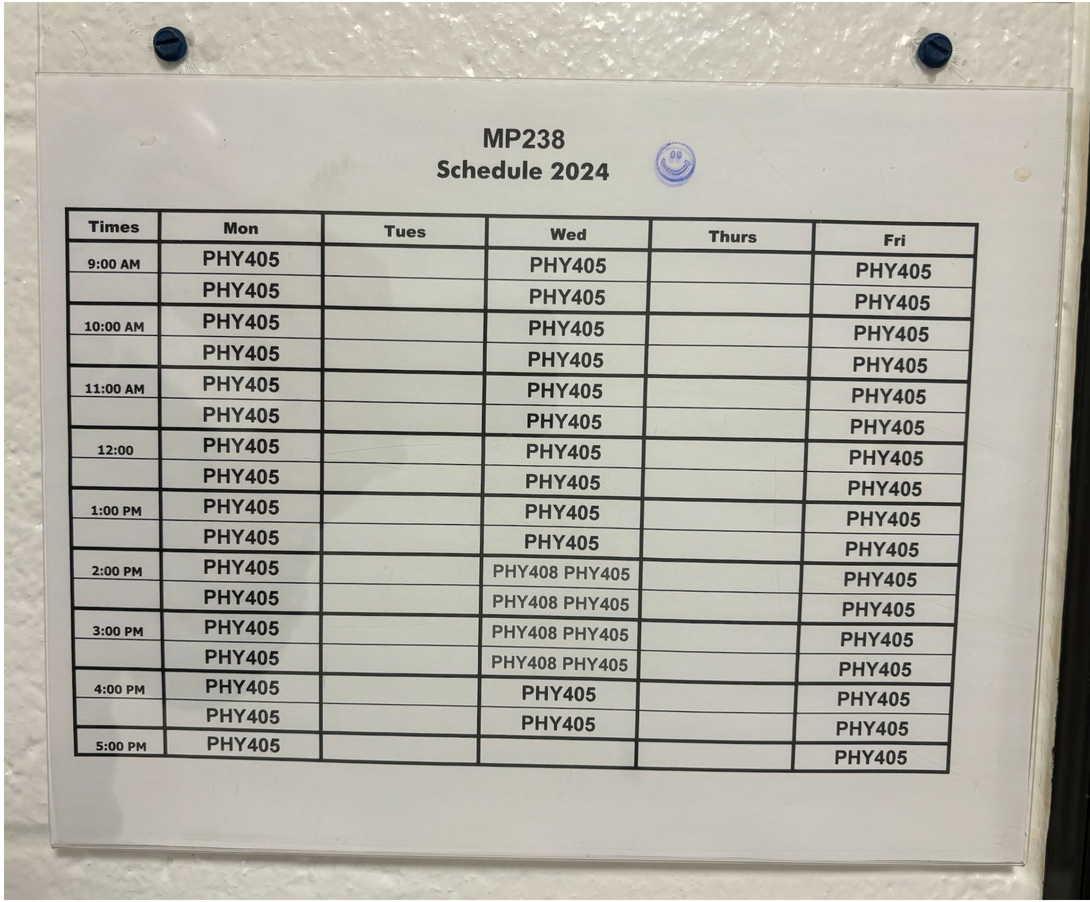
Basics Physics of Resistors, Capacitors, and Inductors

Labs

- Lab S due by noon Friday/Monday, depending on your PRA session
- Lab 1 posted
- In-person lab starts this Friday/next Monday

Free lab hours

- Lab sessions on M/F 2-5
- Free lab during other hours on MWF
- PHY 408 gets priority on Wed. afternoon
- New: if needed, TR 9-3 can be used ***IF*** the room is not occupied
    - Other classes take priority
    - Need to be out of the lab by 3 PM



MP238
Schedule 2024

Times	Mon	Tues	Wed	Thurs	Fri
9:00 AM	PHY405		PHY405		PHY405
	PHY405		PHY405		PHY405
10:00 AM	PHY405		PHY405		PHY405
	PHY405		PHY405		PHY405
11:00 AM	PHY405		PHY405		PHY405
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12:00	PHY405		PHY405		PHY405
	PHY405		PHY405		PHY405
1:00 PM	PHY405		PHY405		PHY405
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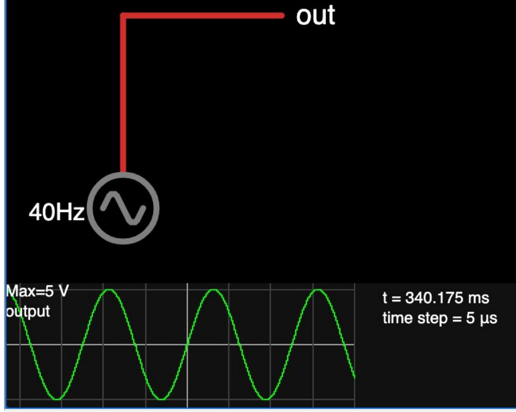
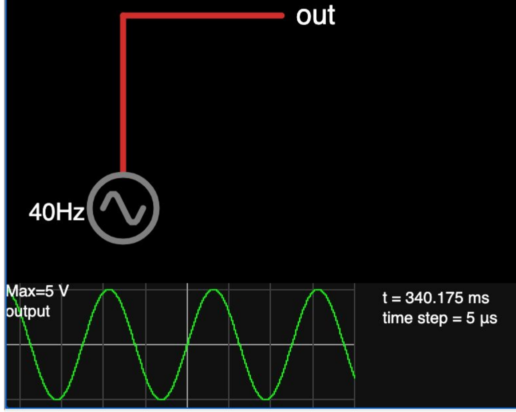
2:00 PM	PHY405		PHY408 PHY405		PHY405
	PHY405		PHY408 PHY405		PHY405
3:00 PM	PHY405		PHY408 PHY405		PHY405
	PHY405		PHY408 PHY405		PHY405
4:00 PM	PHY405		PHY405		PHY405
	PHY405		PHY405		PHY405
5:00 PM	PHY405				PHY405

Ground vs No ground?

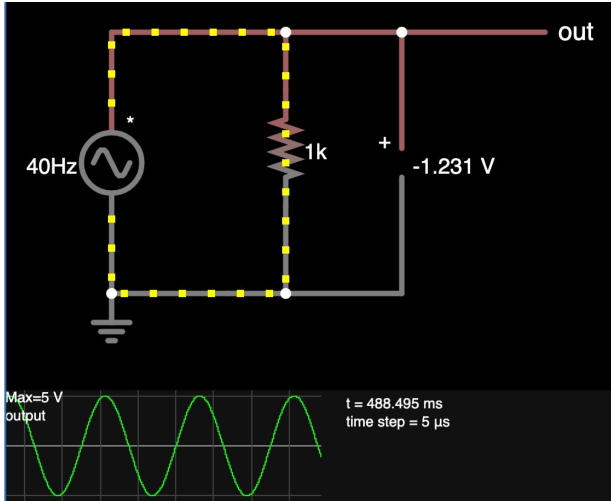


- In falstad there's a "one-terminal (AC) voltage source" option
- This breaks physics law… Or… How to understand it?
- This is modeling a "single ended voltage source", where the reference voltage is assumed "Ground"

Ground vs No ground?

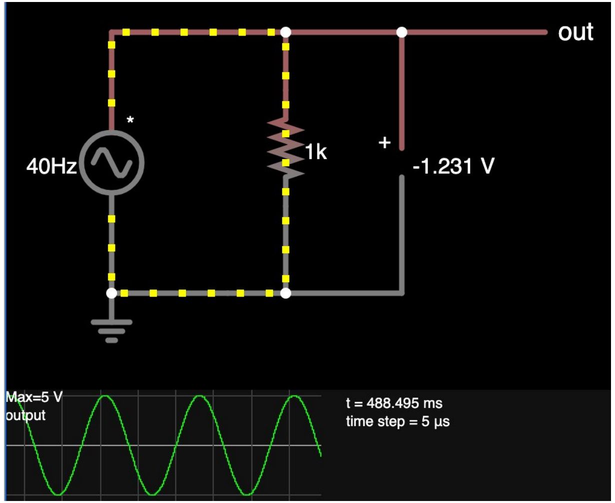


- In falstad there's a "one-terminal (AC) voltage source" option
- This breaks physics law… Or… How to understand it?
- This is modeling a "single ended voltage source", where the reference voltage is assumed "Ground"
- Often causes confusions, so… Explicit connections are encouraged in this course



Idealized source and idealized measurements

- AC Voltage source and Voltmeter here are both idealized
  - The internal resistance of Voltage source is 0
  - The impedance of Voltmeter is infinity
- In reality, neither is true
- Thus, important to model non-idealized components, if you want your simulation to look realistic



Some physics…

- Charge Q (1 Coulomb = $6.24 \times 10^{18} e$)
  - source of electric fields
  - Coulomb's Law: $$E = \frac{Q}{4\pi\epsilon_0 x^2}$$
- Voltage V = U/Q (1 Volt = 1 Joule/Coulomb)
  - Potential energy difference: $$dU_E = QdV$$
- Capacitance C = Q/V (1 Farad = 1 Joule/Volt^2)
  - Energy stored in electric field: $$U_E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \int \frac{1}{2}\epsilon E^2$$
- Current I = dQ/dt (1 Ampere = 1 Coulomb / second)
  - charge movement
  - source of magnetic fields

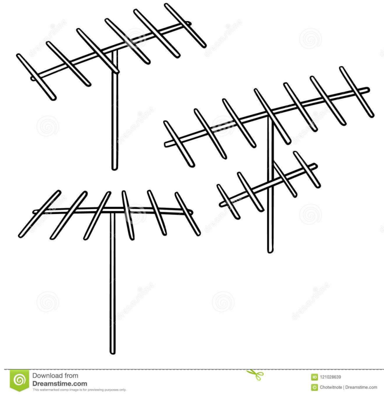
Some more physics

- Inductance L = *V* / (dI / dt) (1 Henry = 1 Joule / Ampere^2)
  - Energy stored in magnetic field: $U_B = \frac{1}{2}LI^2 = \int \frac{1}{2\mu}B^2$
- Resistance R = V/I (1 Ohm = 1 Watt / Ampere^2)
  - Loss of electric energy by a current (Joule's Law)

$$P_{Joule} = dU/dt = IV = I^2R = V^2/R$$

    - energy can be converted to heat (e.g. in a resistor) or do useful work
- Relates current through and voltage across a component
  - **I = V / R (Ohm's Law)**
    - Only true for a limited range of materials, voltages, and currents.

Signal might not be bound to your circuit



- Energy can also be dissipated by radiation :
  - $$P_{rad} = \frac{1}{4\pi\epsilon_0}\frac{2}{3c^3}I^2$$
- Energy losses usually negligible unless circuit is designed to radiate, e.g. via antenna
- Zero for stable DC currents, but not when switching on and off.
- Can cause unwanted communication (noise) between circuits.
- For high frequency signal (> ~100 kHz), signal might jump across wires a bit, through stray capacitor, radiation, etc.

Impedance

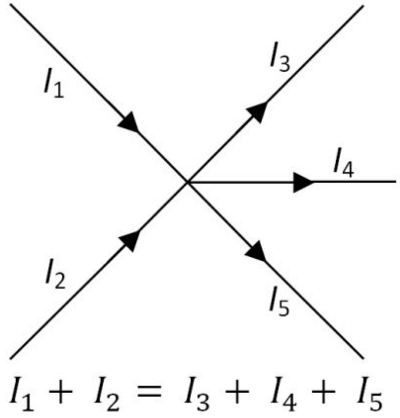
- $$Z = \frac{\text{Voltage}}{\text{Current}} = \frac{V}{I}$$
- For a sinusoidal current applied to a linear circuit

$$Z = \frac{|V|e^{j(\omega t + \phi_V)}}{|I|e^{j(\omega t + \phi_I)}} = |Z|e^{j\phi_Z}$$

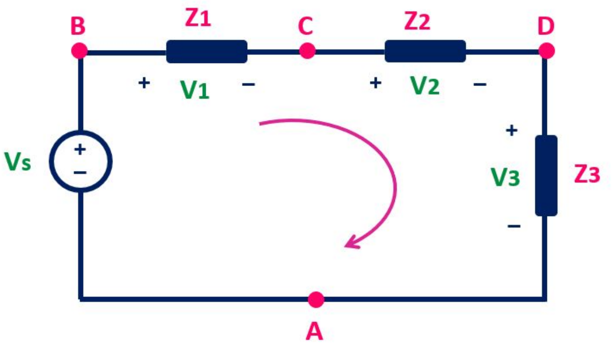
- ϕ_Z is the phase of the current relative to the applied voltage
- Eg. A resistor has an impedance of **R**, with zero phase
- For a more complicated component or network, Z can be complex, or frequency dependent…

To reduce confusion, in electrical engineering, **j** is used for $\sqrt{-1}$, since i is sometimes used for electrical current.

Kirchoff's Laws



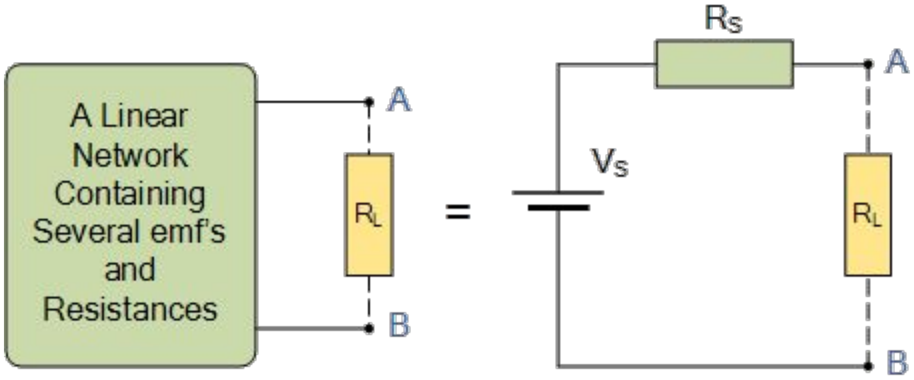
- In steady state:
- Electric charge is conserved
  - The sum of the currents into a point in a circuit equals the sum of the currents out.
- Energy is conserved
  - The sum of the voltage drops around any closed circuit is zero.



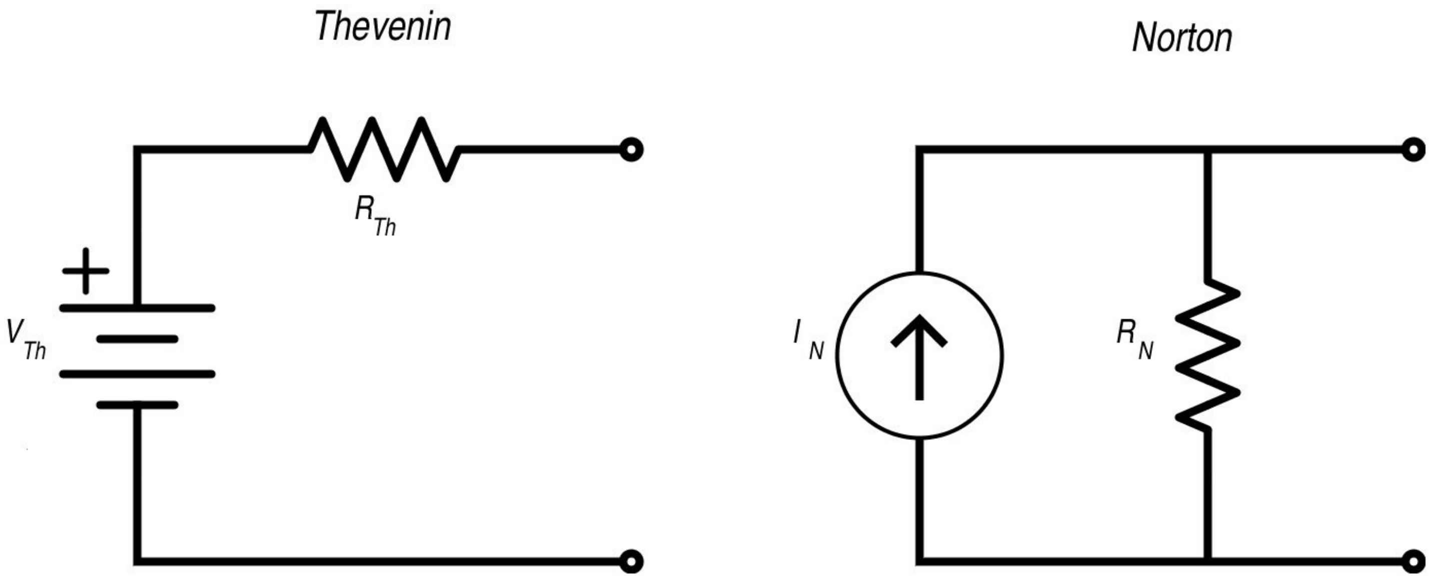
https://www.allaboutelectronics.org/kirchhoffs-voltage-law-kvl-explained/

Thevenin/Norton Theorems

- Any combination of ideal resistors and DC voltage sources with two terminals is equivalent to a single ideal resistor and ideal voltage source in series/parallel.
  - The Thevenin equivalent voltage V_{Th} is the open circuit voltage between the terminals.
  - The Thevenin equivalent resistance is $R_{Th} = V_{Th}/I_{SC}$, where I_{SC} is the current that flows between the terminals when they are short-circuited.



Thevenin/Norton Theorems

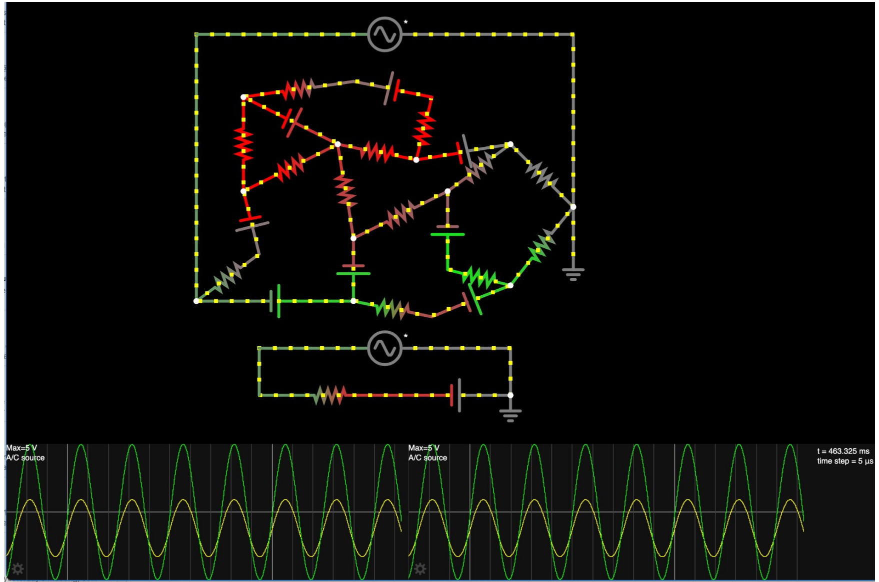


Thevenin/Norton Theorems -- with AC

- Any two terminal network of ideal linear impedances and voltage sources (all with the same frequency) is equivalent to a single ideal impedance, an DC (offset) voltage source, and an AC voltage source in series/parallel.

Thevenin/Norton Theorems

- See the Falstad examples:
  - Circuits → Basics → Thevenin's Theorem
  - Circuits → Basics → Norton's Theorem



Notes: Ideal power supply vs Realistic power supply

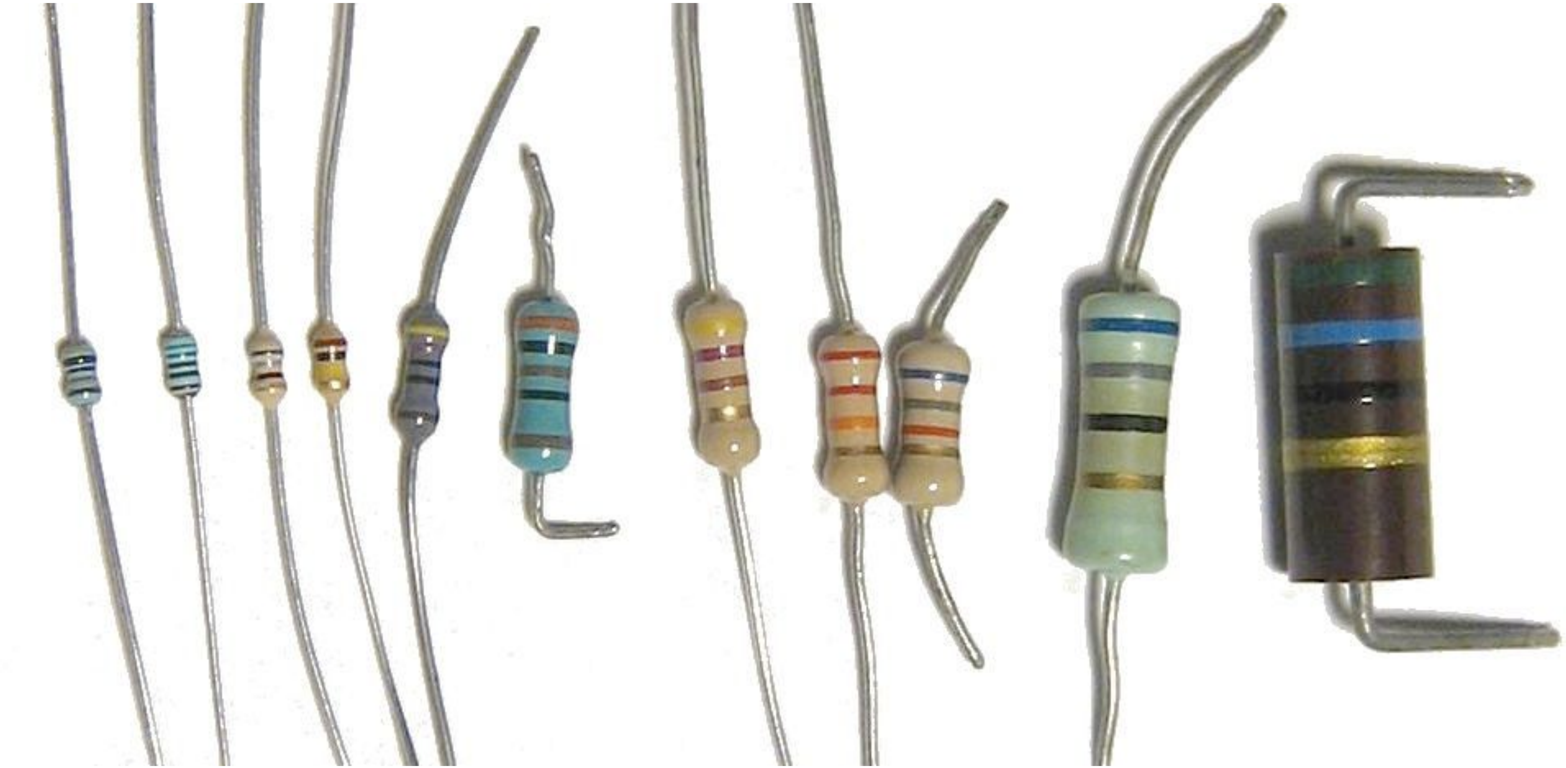
- A **ideal voltage or current source** has no capacitance or inductance and maintains a fixed voltage or current between its two terminals, independent of the load resistance R_{load}.
  - an ideal voltage source has zero resistance.
  - and ideal current source has infinite resistance
- If a real voltage source has too small of a load resistance
  - the voltage drops if the source cannot provide enough power.
  - the source **may fry** if too much power is required and it does not have an internal fuse, sacrificial resistor, or other power-limiting control
- If a real current source has too large of a load resistance
  - the current drops if the source cannot provide enough power

Components

Resistors, capacitors, and inductors are known as passive components because their (ideal) impedance does not change with voltage.

- Every real component or circuit has a (possibly nonlinear) resistance, capacitance, and inductance.

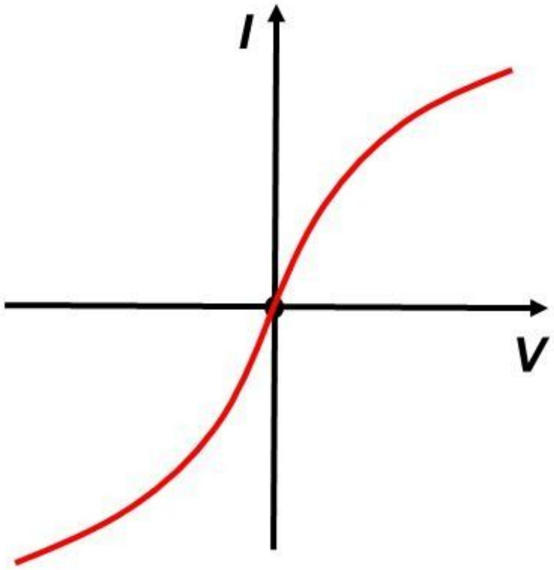
Resistors



Resistors

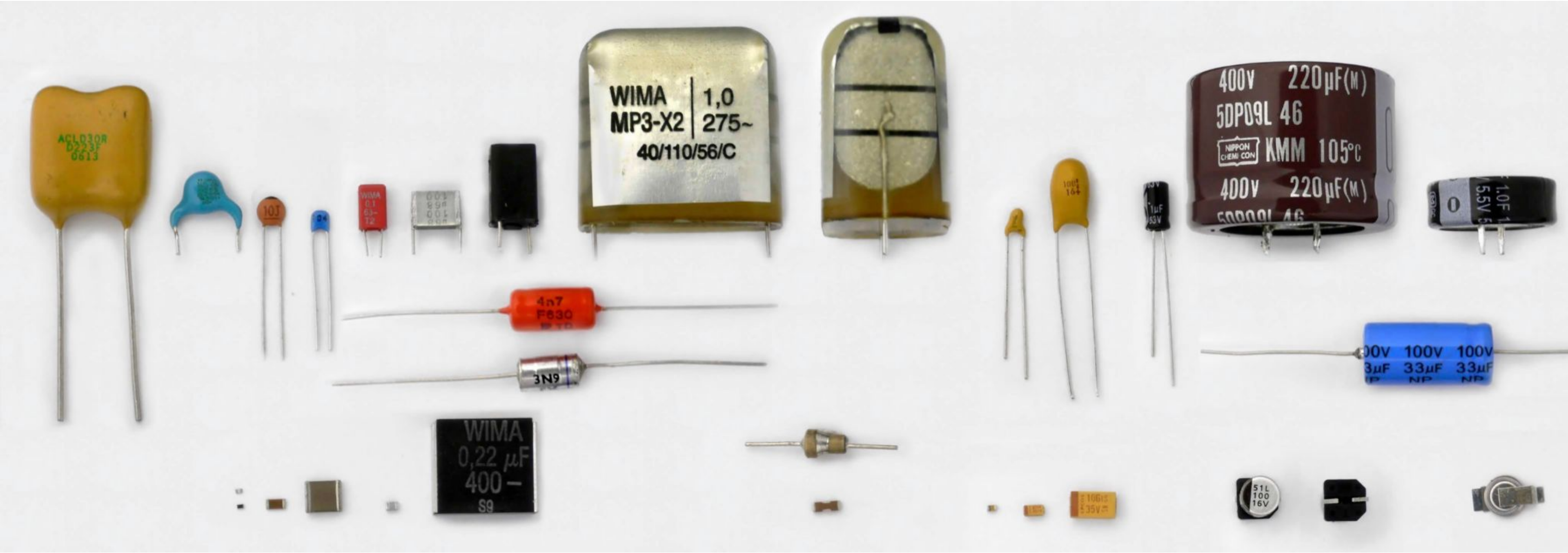
- Resistors work as they are constructed from materials that obey Ohm's Law over a useful range of voltages and currents.
  - No material obeys Ohm's Law under all conditions, e.g. they melt, explode, go quantum, ….
  - Resistivity of most materials depends on temperature, so if increasing current heats up a resistor, its resistance will change.
- Any load that dissipates energy in an electric circuit, counts as resistance, but it may be very non-linear.
  - e.g. the electric motor driving the wheels of an electric car,
  - Increasing the current to the car's motor increases the car's velocity v, but wind resistance increases as v^2
- The impedance of an ideal resistor is $Z = R$.

Non-linear component example
Light bulb

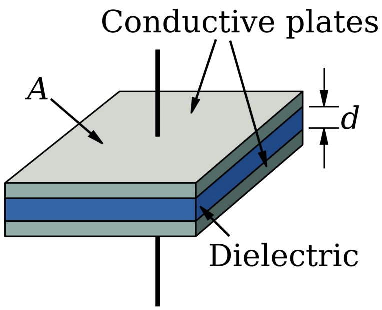


- The resistance of the light filament is a function of temperature
- Often use I-V curve to characterize electrical components
- The apparent I-V curve of a light bulb is not a linear function

Capacitors


WIMA
MP3-X2
1,0
275~
40/110/56/C
400v 220µF(M)
5DP09L 46
NIPPON CHEMI-CON
KMM 105°C
400v 220µF(M)
10J
4n7
F630
3N9
100V 33µF
WIMA
0,22 µF
400 –
S9
51L
100
16V

Capacitors



- Capacitors work by charge separation.
    - Eg. for parallel plate capacitor , $C = k\epsilon_0 A/d$
- The impedance of an ideal capacitor is

$$Z_C = \frac{1}{j\omega C}$$

- Since $V = IZ$, and $1/j = e^{-j\frac{\pi}{2}}$, the voltage across a capacitor **lags** the current by $\frac{\pi}{2} = 90^\circ$

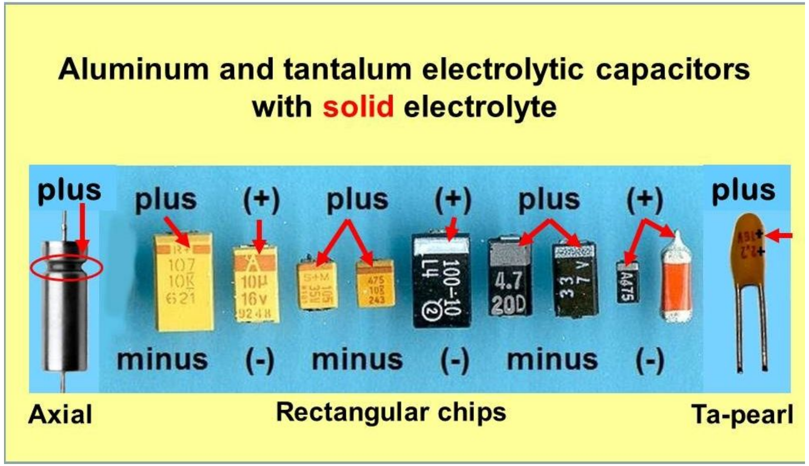
Electrolytic capacitors

- Small capacitors usually made of interleaved metallic layers separated by a ceramic dielectric.
  - No specific polarity for those
- Larger capacitors (e.g. ≥ 1μF) made from coiled metallic foil anode separated by an extremely thin surface oxide layer from a gel electrolytic cathode.
- They have a specific polarity, and can be recognized by their plastic coated tubular can package.
- Putting the wrong polarity voltage across an electrolytic capacitor might cause an explosion

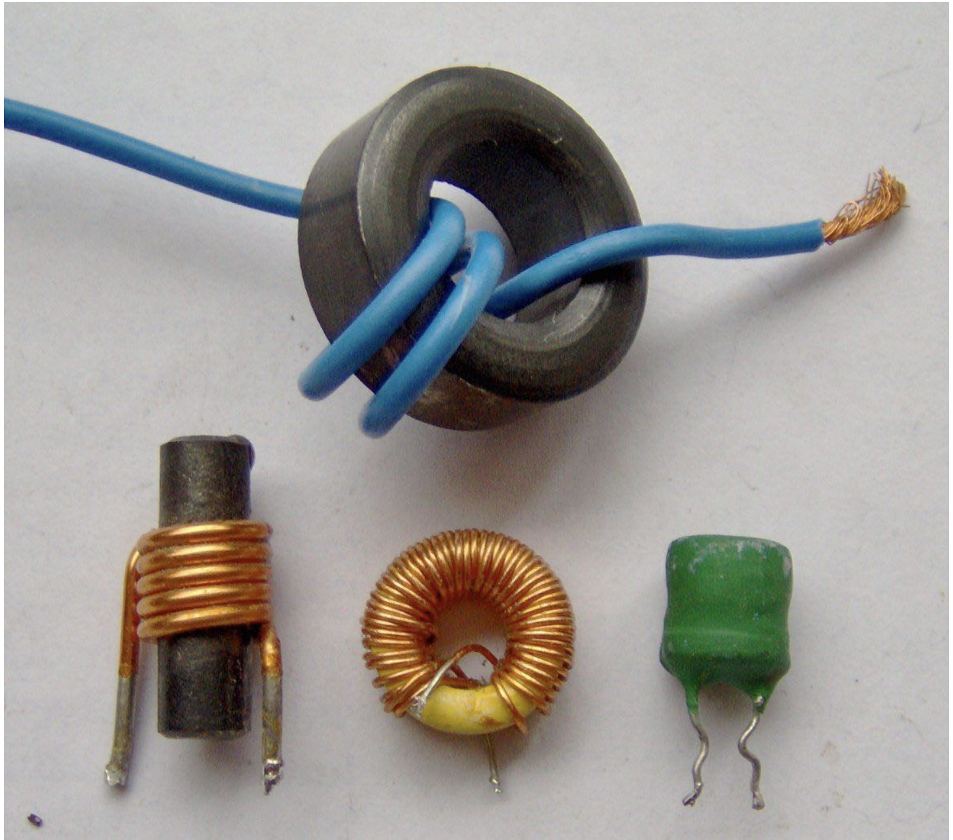
"An electrolytic capacitor that has exploded via the vent port on the top, showing the internal dielectric material." (source: Wikipedia)

Electrolytic capacitors -- polarity

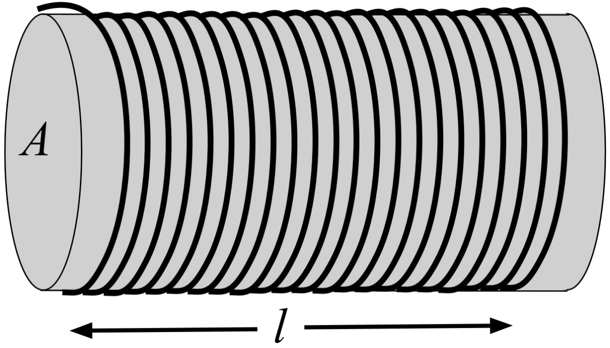
- Common electrolytic capacitor with polarity markings
- **Even better: Check specs sheet for every component!**



Inductors



Inductors



- The inductance of a N-turn solenoid of length l and cross-sectional area A, filled with a material of relative permeability μ_r, is

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

- The impedance of an ideal inductor is $Z_L = j\omega L$
- The voltage across an inductor leads the current by $\frac{\pi}{2} = 90^\circ$

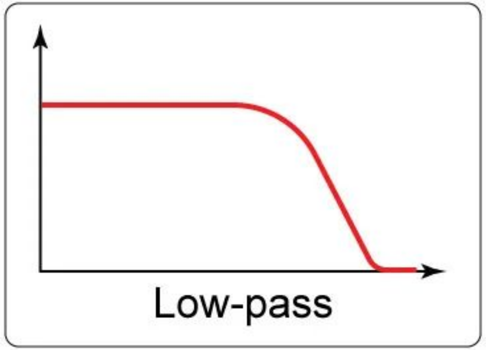
Filters

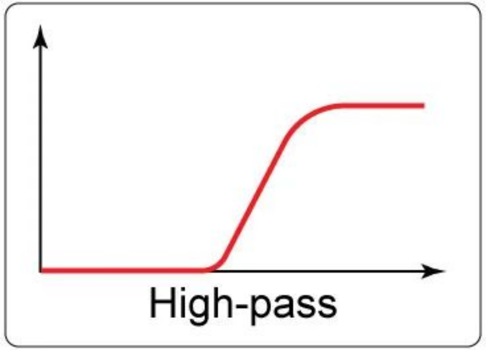
Electronic components can be used to build filter circuits that pass only a range of frequencies. Such filters are characterized by their steady-state transfer function :

$$H(\omega) = \frac{V_{output}(\omega)}{V_{input}(\omega)}$$

Where $\omega = 2\pi f$ is the radial frequency

Low pass and high pass filters

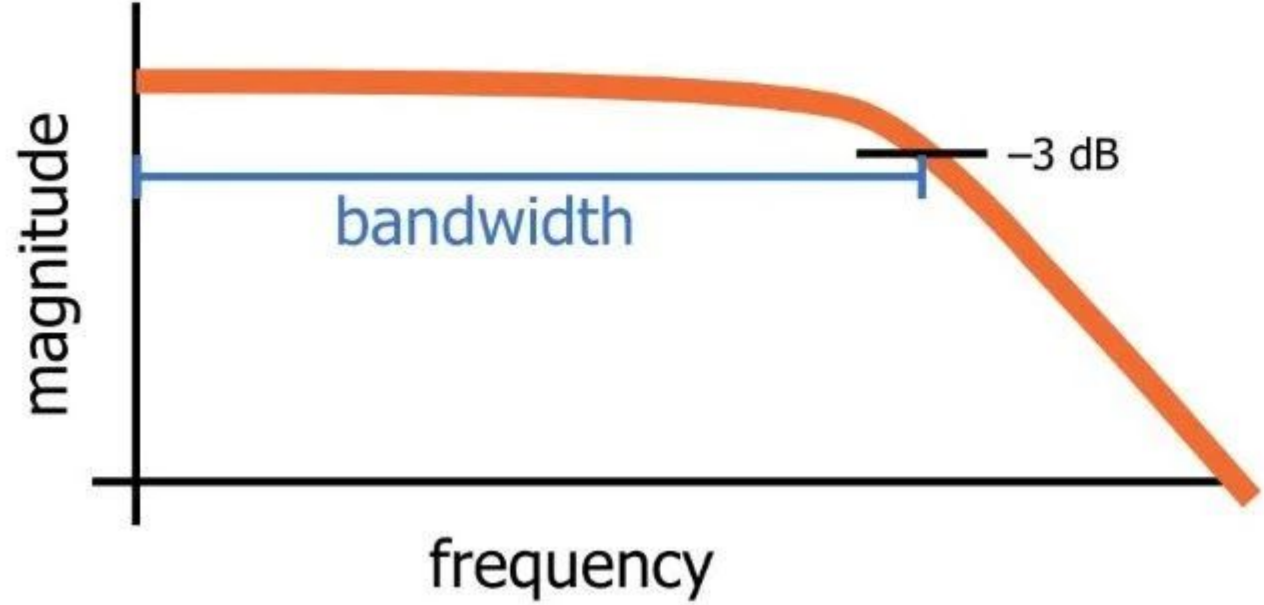




- Passive low-pass filters attenuate high frequency signals by
  - shorting them to ground through a capacitor, or
  - blocking them with an inductor in series.
- Passive high-pass filters attenuate low frequency signals by
  - shorting them to ground through a inductor, or
  - blocking them with an capacitor in series.

-3 dB

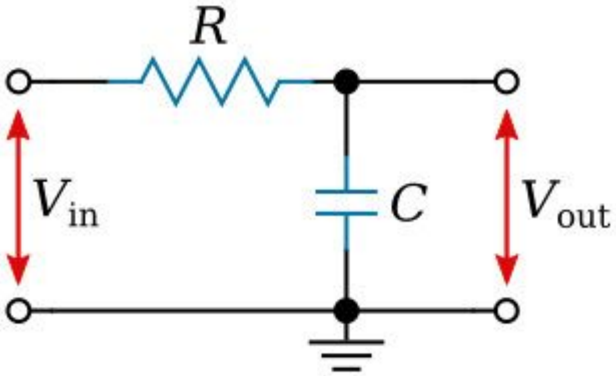
https://www.allaboutcircuits.com/technical-articles/low-pass-filter-tutorial-basics-passive-RC-filter/



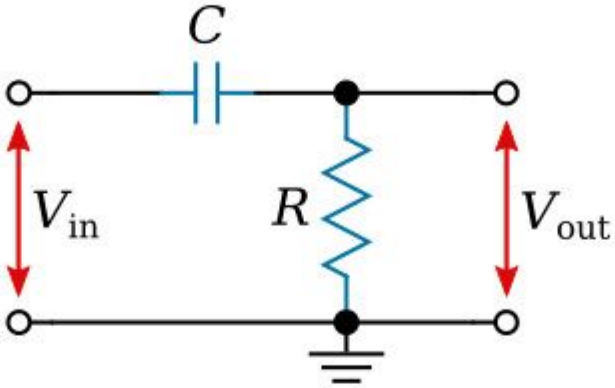
- “Cutoff frequency” usually refers to the –3 dB frequency
- The power decreases by 50% at this point
- Since $P \propto V^2$, voltage decreases by $1/\sqrt{2}$

RC Filters

RC Low Pass Filter



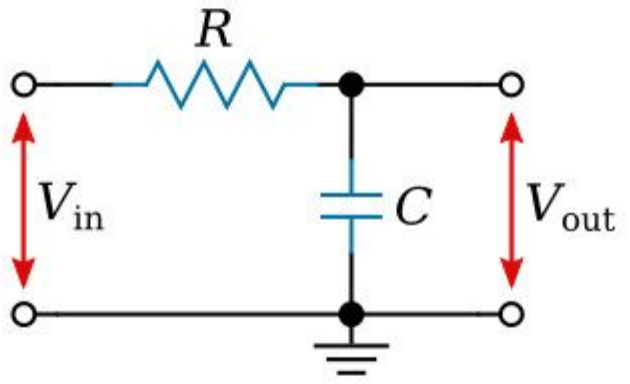
RC High Pass Filter



RC Filter -- Transfer function & cutoff frequency

- This circuit is a voltage divider

$$V_{\text{out}} = \frac{Z_C}{Z_R + Z_C} V_{\text{in}}$$



- With $Z_C = \frac{1}{j\omega C}$ and $Z_R = R$

$$V_{\text{out}} = \frac{1/j\omega C}{R + 1/j\omega C} V_{\text{in}}$$

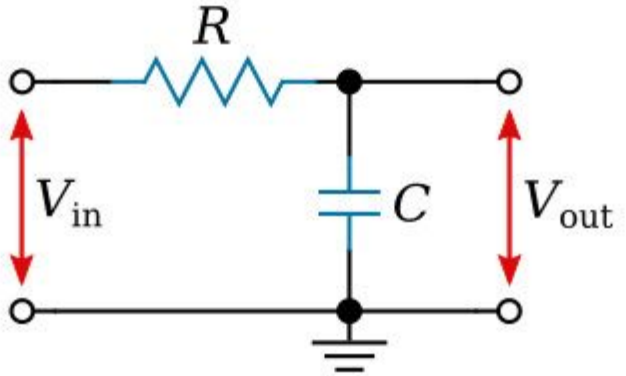
- Transfer function: $H(\omega) = \frac{V_{\text{out}}(\omega)}{V_{\text{in}}(\omega)} = \frac{1}{1 + j\omega RC}$

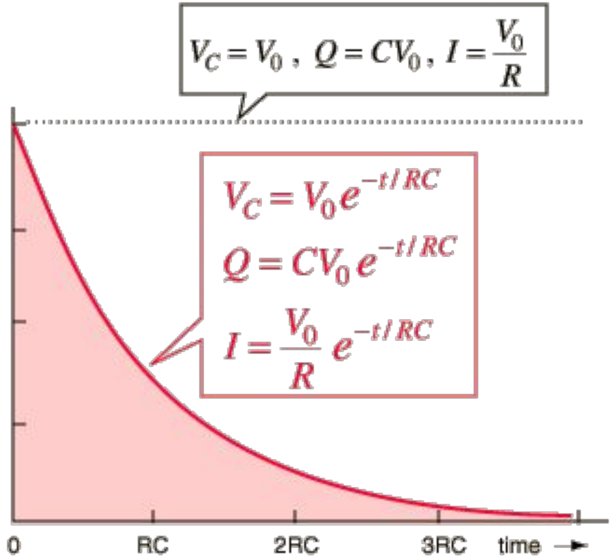
- Cutoff radial frequency: $|H(\omega)| = 1/\sqrt{2} \rightarrow \omega = \frac{1}{RC}$
- Cutoff frequency: $f = \frac{1}{2\pi RC}$

RC Filters - Time Constant

- If V_{in} is held at V for sufficiently long time then shorted. How does V_{out} change?
- Total charge Q= V*C will get discharged through the resistor
- Time constant

$$\tau_{\mathrm{RC}} = RC$$

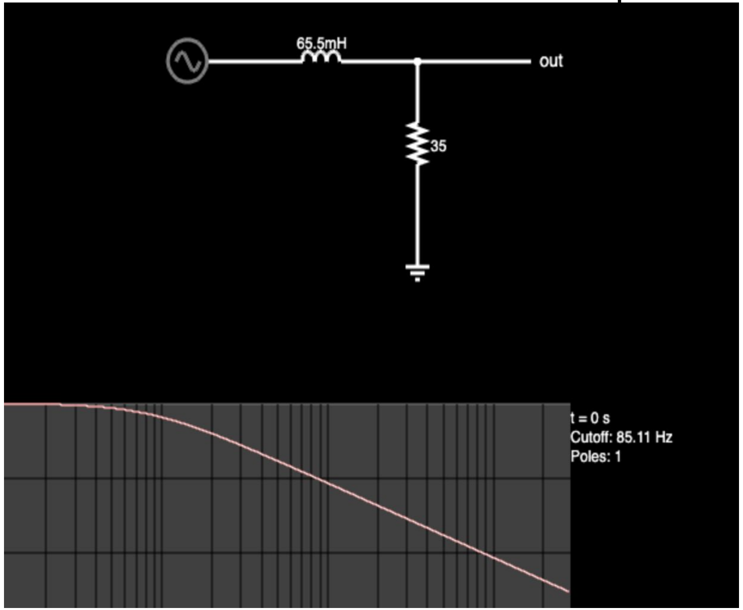




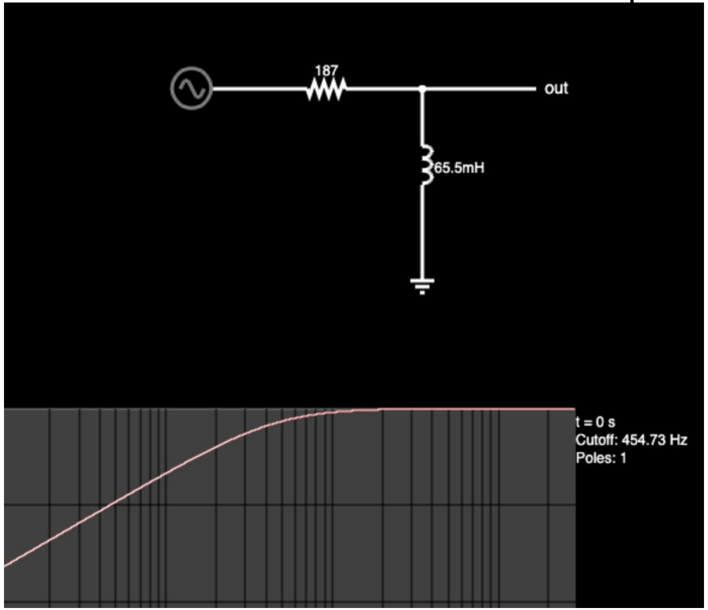
http://hyperphysics.phy-astr.gsu.edu/hbase/electric/capdis.html

RL Filters

http://www.falstad.com/circuit/e-filt-lopass-l.html



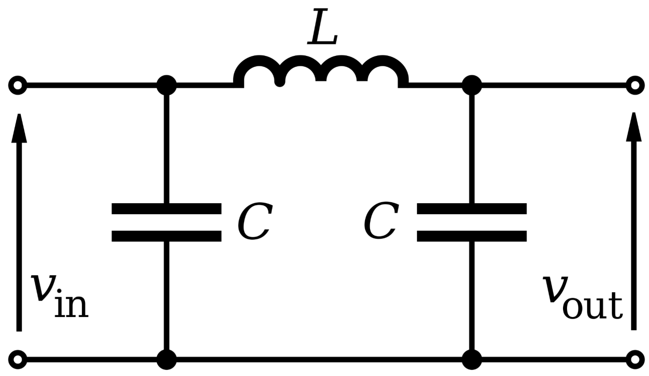
https://www.falstad.com/circuit/e-filt-hipass-l.html

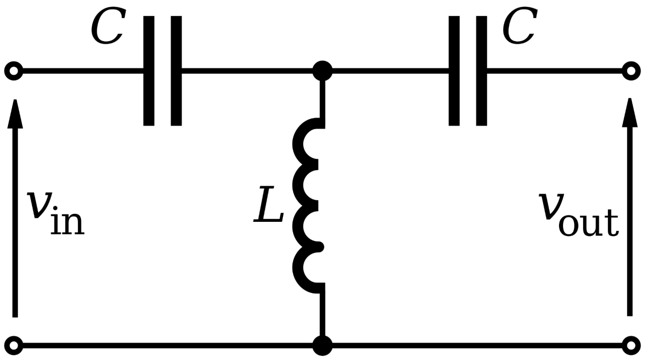


- Time constant: $\tau_{\mathrm{LR}} = L/R$
- Cutoff frequency: $f = \frac{1}{2\pi\tau_{\mathrm{LR}}} = \frac{R}{2\pi L}$

Higher order filters

- Can daisy chain filters to achieve better performance
- Examples: Pi filter, T filter, etc.





Lab 1

https://www.physics.utoronto.ca/apl/405/Lab_01.html

PHY405 LABS LECTURES RESOURCES

PHY405 Electronics, Lab 1

Last updated: Jan. 18, 2023

Adapted from Prof. David Bailey's website in 2022

Sign in

Please sign in every time you use the lab, including regular practice sessions and free-lab sessions.

Overview

An introduction to many basic course instruments and tools.

- Familiarization with operation and characteristics of electronic workstation equipment:
  - Soldering
  - Oscilloscope / Wave Generator, Multimeter, DC Power Supply
  - Simple real circuit on breadboard

Lab 1

- Read lab manual **before** you come to the lab
- Read equipment manuals **before** you come to the lab
- Design your circuit ahead of time
  - They are likely the ones you simulated last week
- Sign in
- Follow safety restrictions
- Soldering iron is hot. Wear safety goggles
- Bring your lab notebook
  - You work in pairs, but each needs to take your own note, and each submit your own lab report
- If something doesn't work, it's expected. Debug and get help

Please close the drawer/doors behind you…

Clean up after you are done

Yes, this is important enough to deserve it's own slide

Questions?