Fall 2023-24

ANALOG ELECTRONICS IN ROBOTICS

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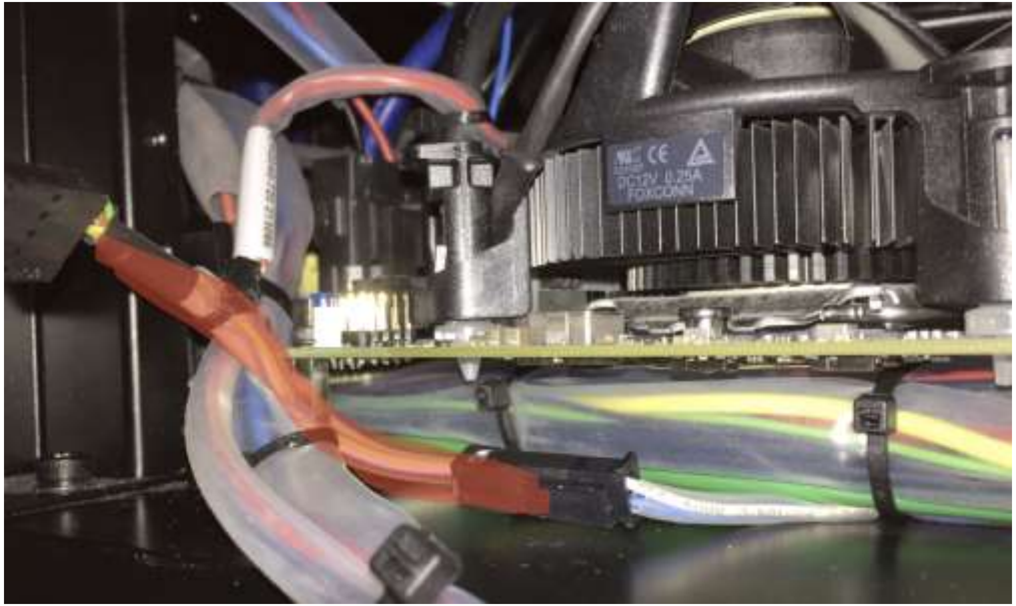
What will you learn today?

- Analog Electronics: what is it and why does it matter?
  - High level overview…
  - …with some practical considerations sprinkled in
- Common Electrical Circuit Elements
  - Conductors/Current
  - Voltage/Voltage source
  - Resistors
  - Capacitors
  - Inductors
- Analog Electronic Circuits
- Analyzing series and parallel networks
- Only DC (and quasi-DC): no frequency analysys!

Why?



Why?

Why? Workcell robot/automation integration

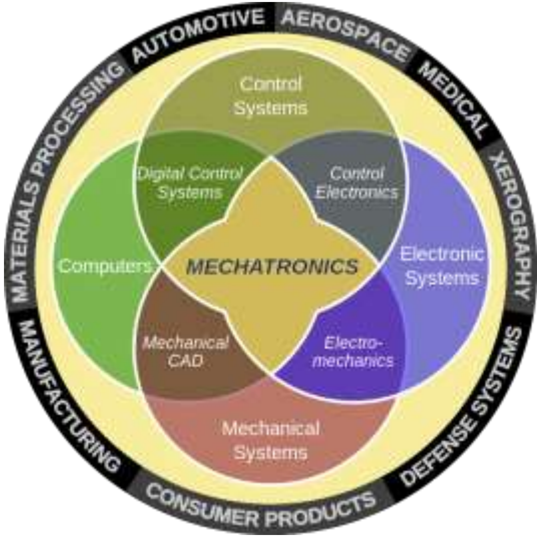
What are analog electronic circuits for?

- Two main purposes:
  - Providing power to elements
  - Transmitting signals
    - Sensor signals
    - [Motor] Commands
- In general, they may have other applications
  - Signal processing! (amplification, filtering…)
  - We are not looking at that today

Providing power: Electricity creates motion

- Batteries (DC) or a tether (AC or DC) will power your robot.
  - How do we get the necessary power to our computers, sensors, and motors?
  - How much total power do we need?
  - How do our computers interact with our sensors and motors?
  - How do I not fry the expensive components on my robot?
  - How do I not injure or kill me while building my robot?
  - How do I make sure my robot doesn't kill or injure others?
- These questions must be answered every time we use sensor data for a computer to determine where to send power to make something move.

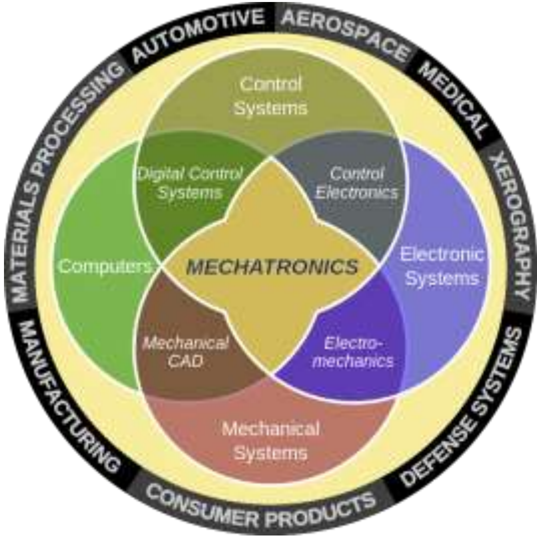
Transmitting signals: Supporting Mechatronics



- Defined
  - The Integration of Computers, Electronics, and Mechanical Systems
- Where?
  - Robotics, Automation, Actuators (motors/gears/sensors), Automobiles, etc.
  - Anywhere motion is controlled by **electronics (the topic of today)**
- Why do we study mechatronics?
  - All the questions above must be answered before a system is deployed.
  - The disciplines are so tightly coupled in the modern world that **ALL roboticists need a working knowledge of the design space where disciplines intersect**

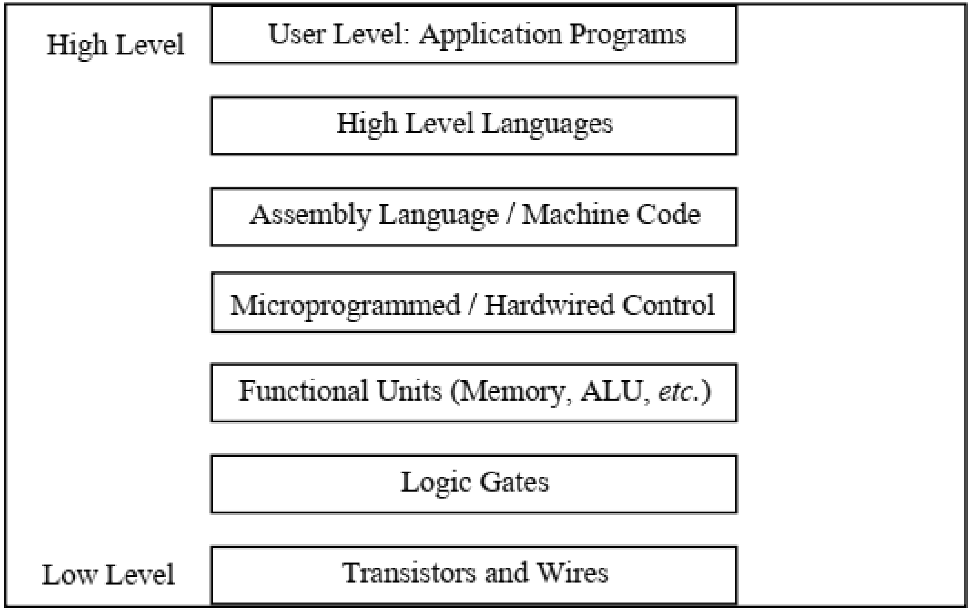
Common Topics in Mechatronics Courses

- **Electronic Circuits & Components**
- Semiconductor Electronics
- **System Response**
- Analog Signal Processing using OpAmps
- **Digital Signals & Logic**
- Microcontroller Programming & Interfacing
- Data Acquisition
- Sensors
- **Actuators (motors/gears)**
- **Component control methods (Bang-bang, PID, etc.)**
- **System control architectures (state machines)**



Levels of Machines

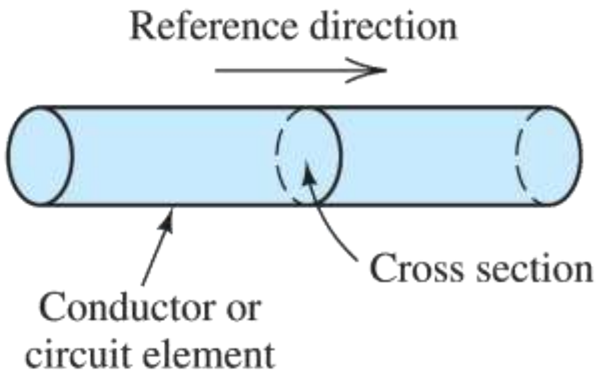
- We are going to be looking now at the (almost) lowest level
- The exact number of levels is debatable



What is electricity?

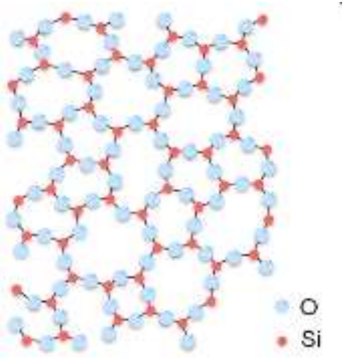
- A collection of phenomena that results from the ***flow*** of electric charge.
- The **charge** of one electron: 1.602 x 10^{-19} Coulombs
- **Current:** amount of charge, q, passing through a ***conductor*** each second (s)
  - *1 **Ampere** (A) (or Amp) = 1 Coulomb/Second*

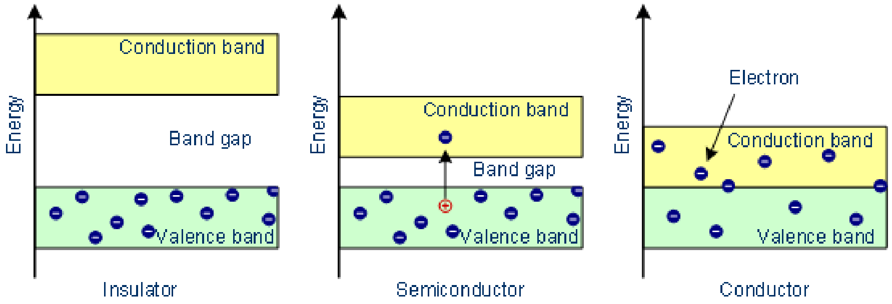
$$i(t) = \frac{dq(t)}{dt} \approx \frac{\Delta q}{\Delta t}$$

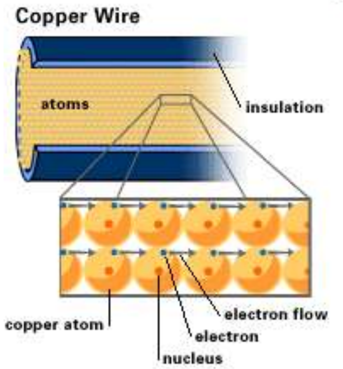


How well does electricity flow?

- It depends…



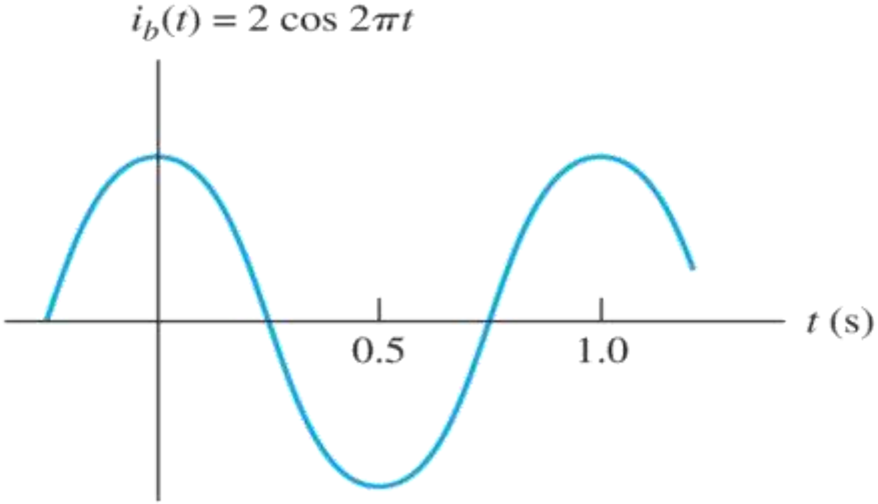




- **Conductors**: charge flows easily
  - Electrons jump easily from the outer layers of one atom to the next
  - Copper, Gold, Aluminum, Silver, etc.
- **Insulators**: do not conduct
  - very hard for electrons in the outer layer to leave atom (high attractive forces)
  - Porcelain, Plastic, Rubber, Glass, etc.
- **Semiconductors**: materials with conductivity between conductors and insulators
  - Silicon, Phosphorous, Arsenic, Germanium, etc.

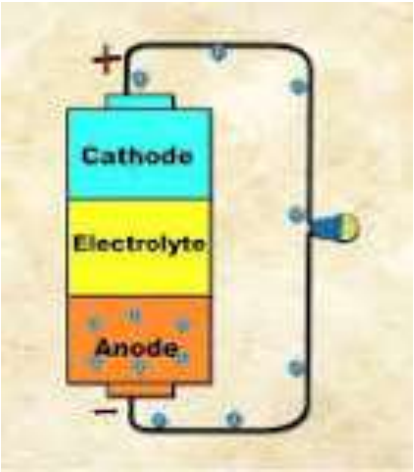
Two common types of current

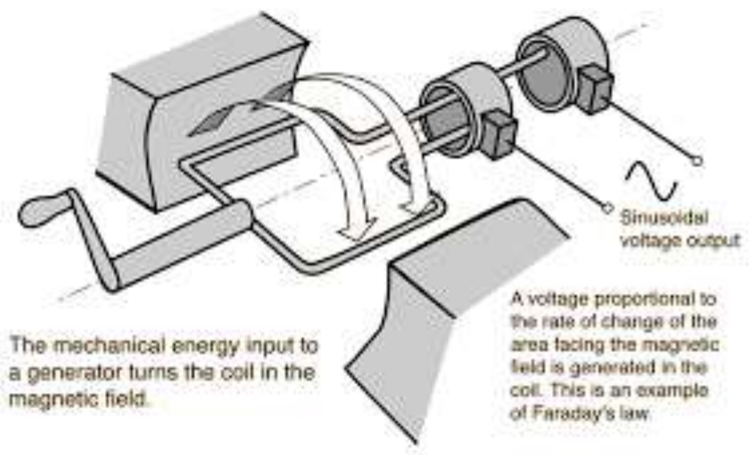
- Direct Current (DC)
  - Constant flow
- Alternating Current (AC)
  - Regularly varies with time



What makes electricity flow?

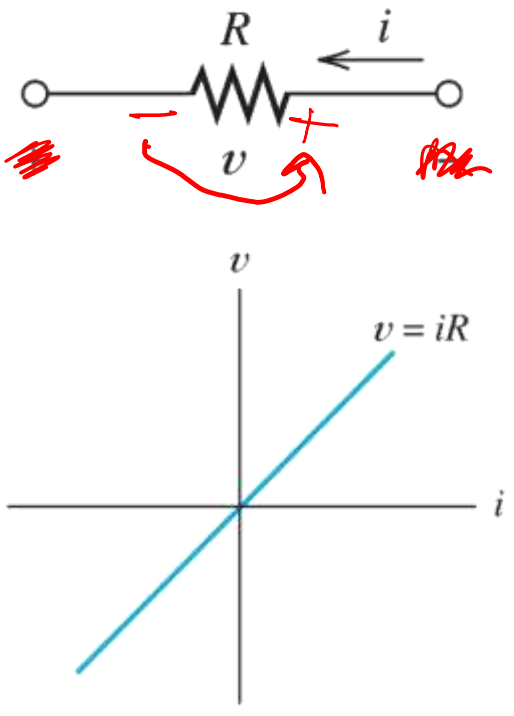
- **Voltage** (aka electric pressure): difference in electric potential between two points.
  - Can be the difference between the cathode and anode in a battery, or
  - It can leverage the principles of electromagnetism, etc.
  - Measured in energy/unit charge, joules/coulomb = Volt





What slows down that current?

- **Resistance**: The opposition of current by the medium the current is pushed through.
- Measured in Ohm's (Ω)
- **Energy is lost as heat.**
- Resistance depends on
  - Type of material
  - Length of material
  - Cross-sectional area of material
  - Temperature
  - Quality of material
  - Etc.
- Voltage & Current related by resistance
  - Ohm's Law (**V = iR**)



(b) Ohm's law

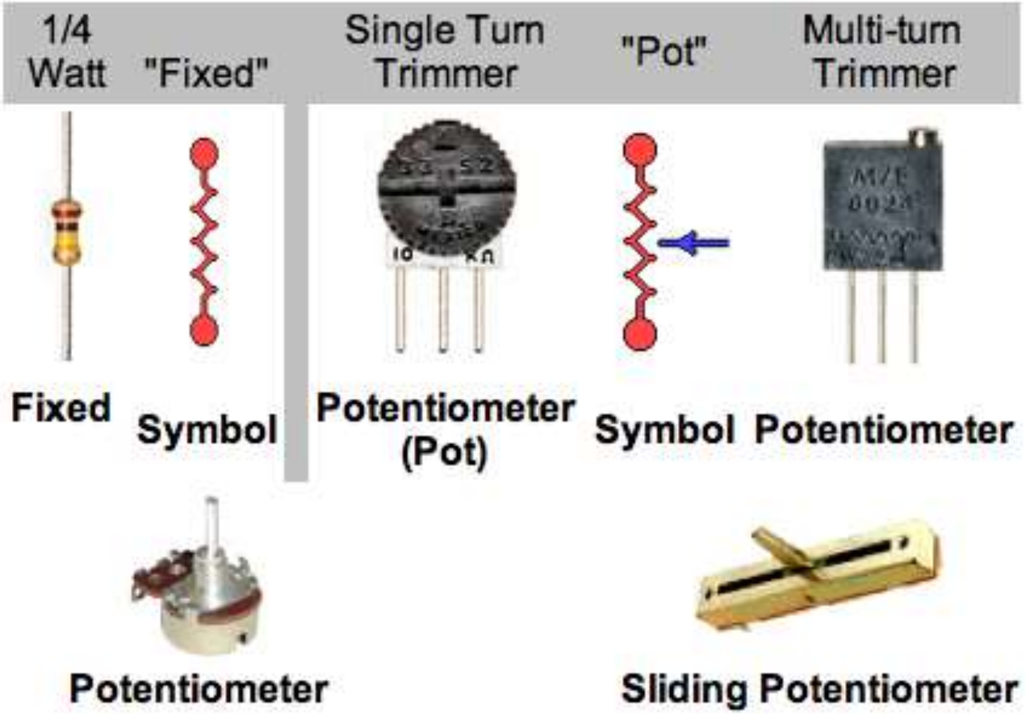
Materials and Resistance

- Resistance depends on
  - Material's innate **resistivity** ρ
  - Length of material
  - Cross-section of material
  - Temperature (significance varies)
  - Quality of material (purity)
  - Quality of connections

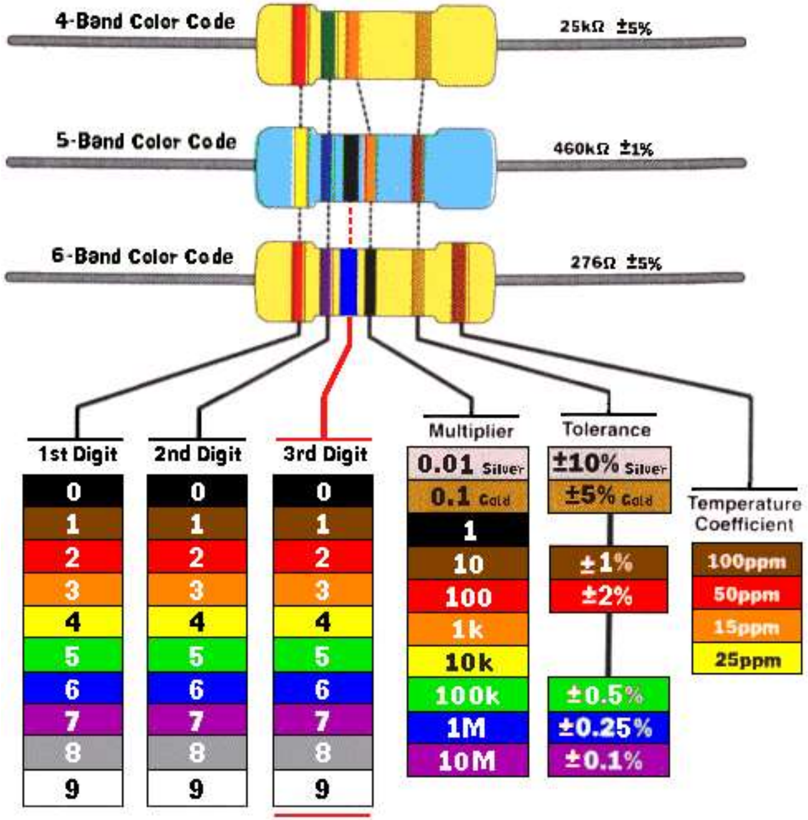
$$R = \frac{\rho l}{A}$$

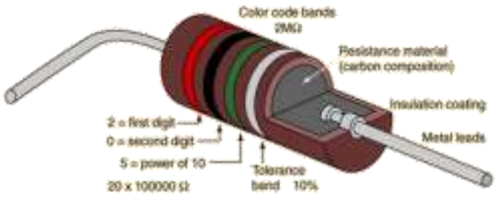
Material	Resistivity (Ωm)
Silver[1]	1.59×10^{-8}
Copper[1]	1.7×10^{-8}
Gold[1]	2.44×10^{-8}
Aluminium[1]	2.82×10^{-8}
Tungsten[1]	5.6×10^{-8}
Brass[2]	0.8×10^{-7}
Iron[1]	1.0×10^{-7}
Platinum[1]	1.1×10^{-7}
Lead[1]	2.2×10^{-7}
Manganin[3]	48.2×10^{-8}
Constantan[3]	4.9×10^{-7}
Mercury[3]	9.8×10^{-7}
Nichrome[1][4]	1.50×10^{-6}
Carbon[1][5]	3.5×10^{-5}
Germanium[1][5]	4.6×10^{-1}
Silicon[1][5]	6.40×10^{2}
Glass[1]	10^{10} to 10^{14}
Hard rubber[1]	approx. 10^{13}
Sulfur[1]	10^{15}
Paraffin	10^{17}
Quartz (fused)[1]	7.5×10^{17}
PET	10^{20}
Teflon	10^{22} to 10^{24}

Types of Resistors



Standard colored coding for fix resistors

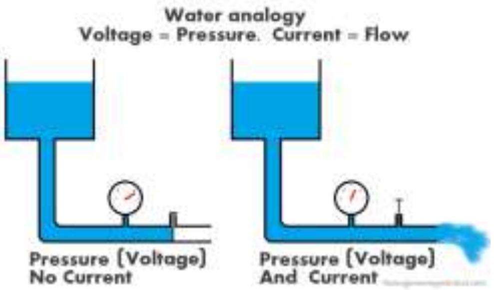


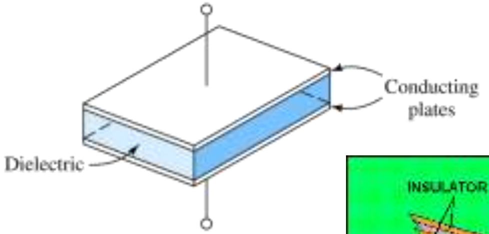


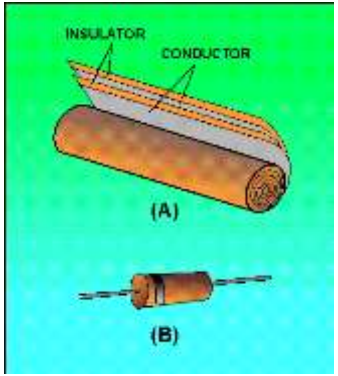
Need more examples? Google has this one covered.

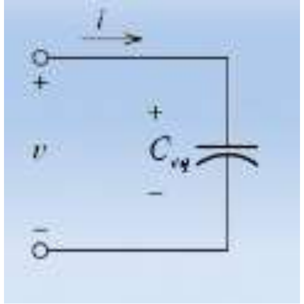
Capacitors

- Provide passive energy storage
  - Often store energy and later return it to the system
  - E.g. Provide burst of energy for flash in camera
  - **Often the biggest hazard in an electronic circuit**
  - Measured in **Farads** = Coulombs/Volt
  - In a DC circuit (or after some transient) → Open circuit! (i=0)



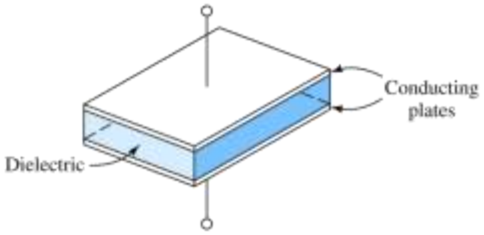


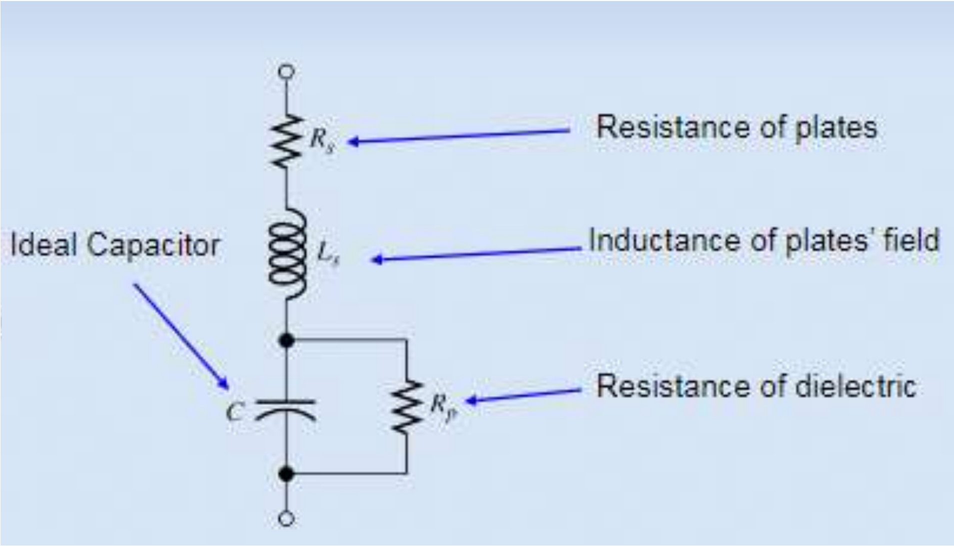




$$i = C\frac{dv}{dt}$$

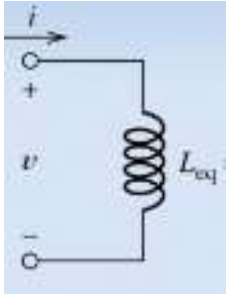
REAL Capacitors





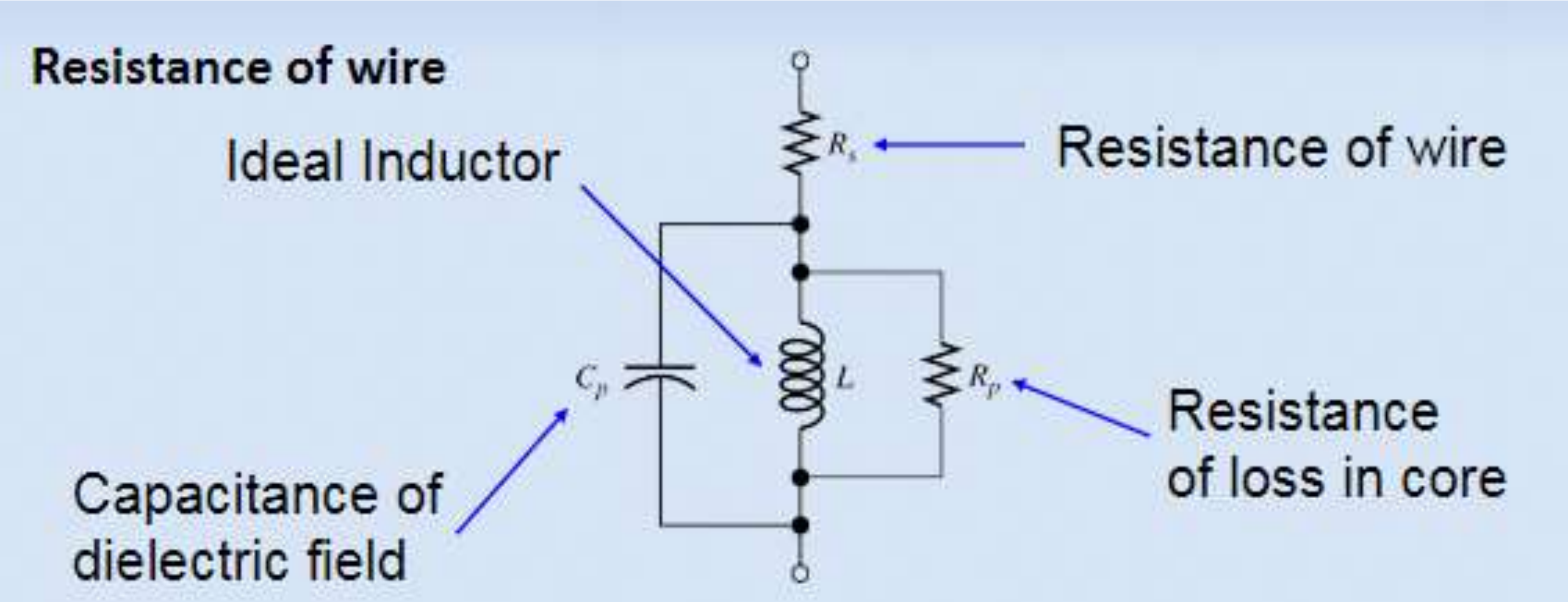
Inductors

- Passive energy storage in the form of magnetic energy when electricity is applied to it.
- Commonly found in transformers or motors.
- Henries (H) = Volt seconds / Ampere
- In a DC circuit (or after a transient) → short circuit! (V=0)

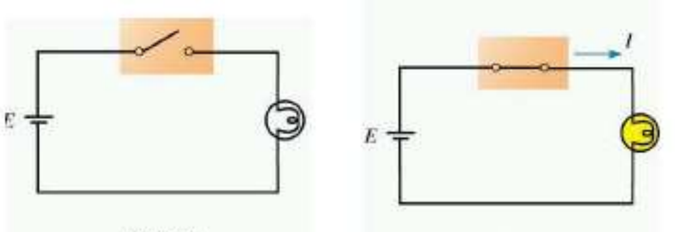


$$v_L(t) = L\frac{di}{dt}$$

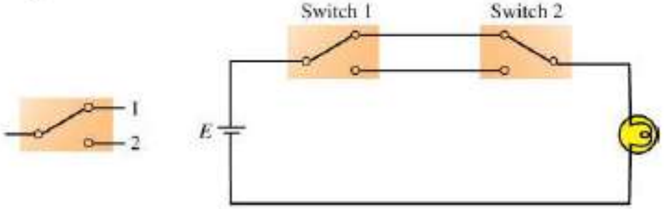
REAL Inductors



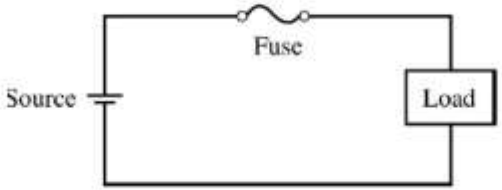
Switches and Fuses



(a) Open (b) Closed

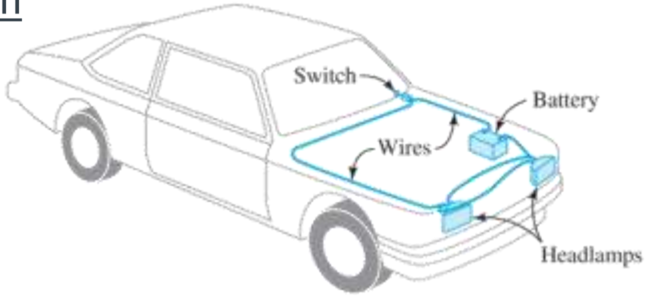


(a) SPDT switch (b) Two-way switch control of a light



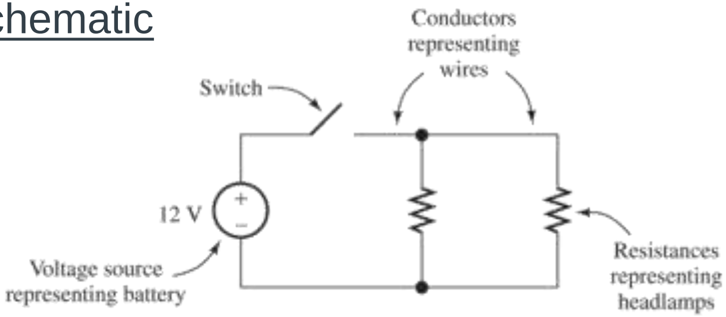
The Basic Electric Analog Circuit

System



(a) Physical configuration

Schematic

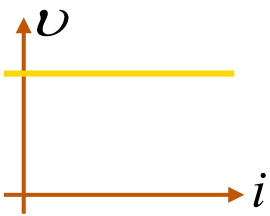


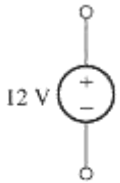
(b) Circuit diagram

- A simple circuit contains…
  - A **Source** of energy
    - Battery
  - Interconnecting **conductors**
    - Insulated copper wire
  - A **Switch**
    - Er….. the switch
  - A **load** or loads
    - Headlamps

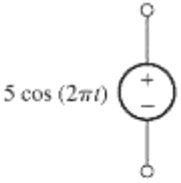
A note on sources

- Maintains (rather attempts to maintain) specified voltage or current
- Ideally independent of other power variable
- Voltage Source

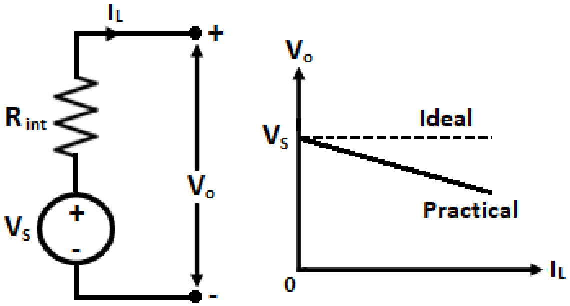




(a) Constant or dc voltage source



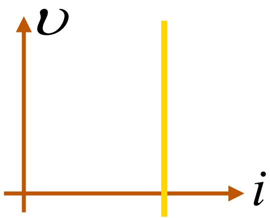
(b) Ac voltage source

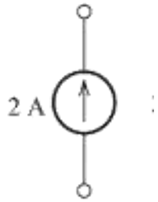


Practical Voltage Source and Its Graph

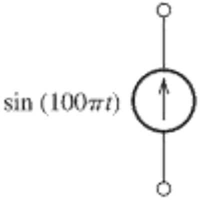
In well loaded circuits like robots, one must account for the internal resistance of the battery.

- Current Source



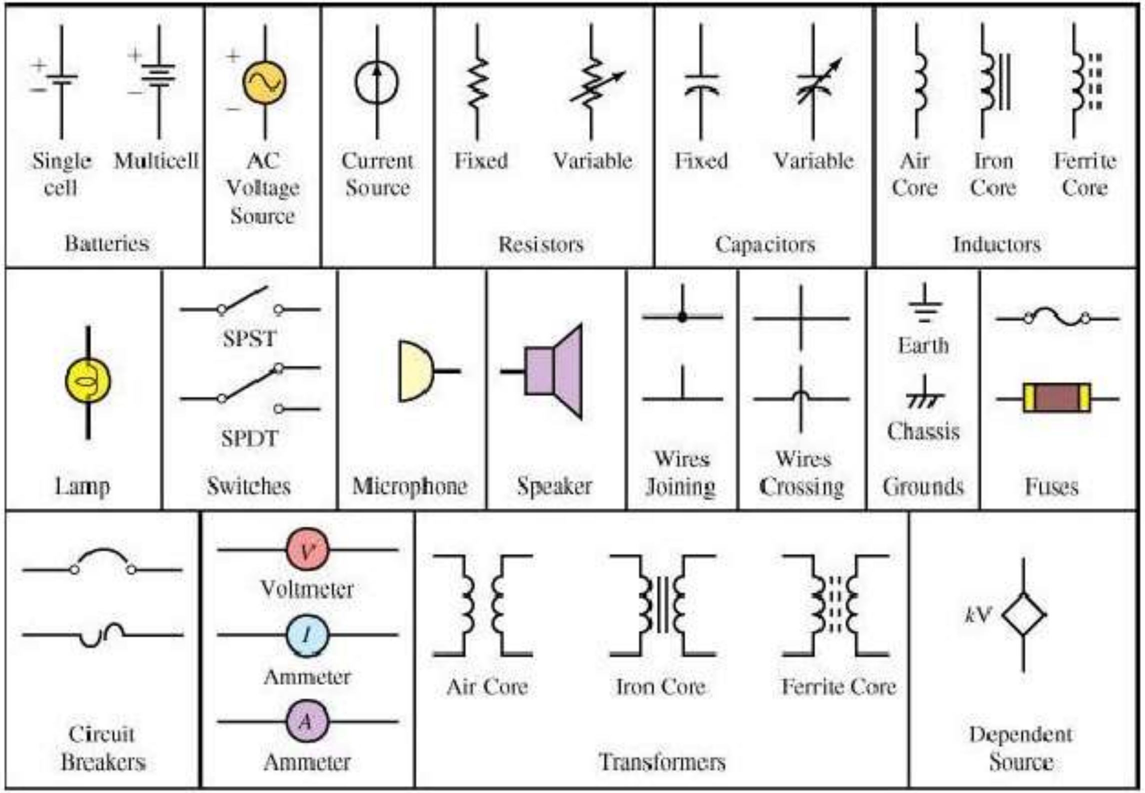


(a) Dc current source



(b) Ac current source

Common basic electric circuit components



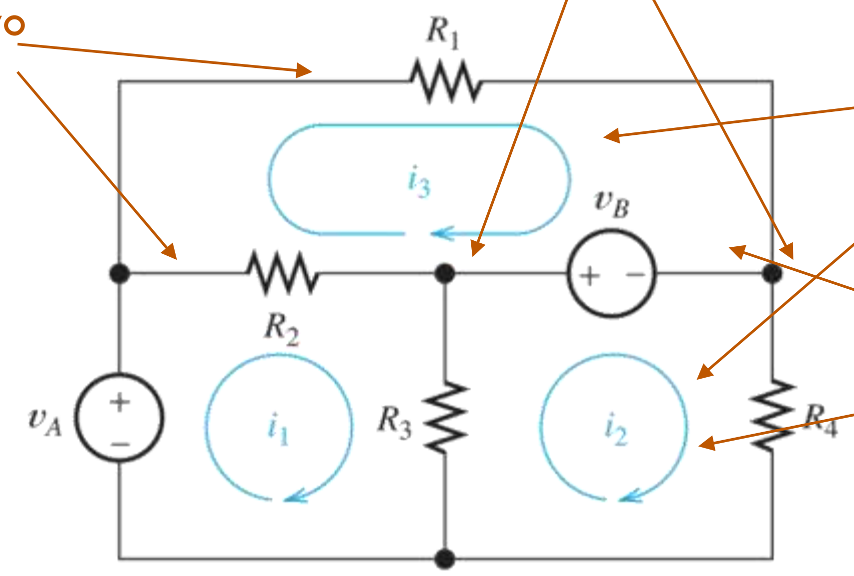
Analyzing circuits: nomenclature*

Nodes (Any point w/ at least two Branches)

Branches (Connects two Nodes)

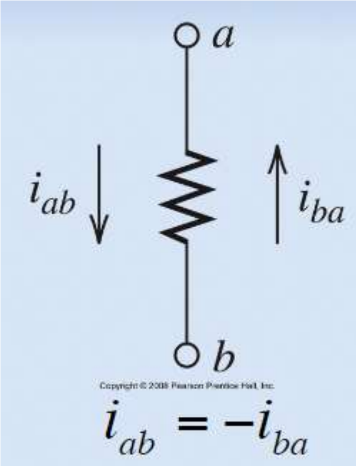
Meshes (Smallest Loop)

Loops (any closed path through a circuit where the same node is not traversed twice)

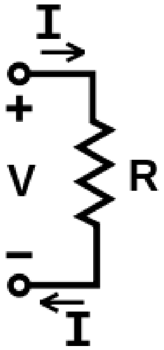


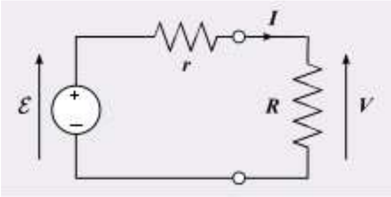
***every book, tutorial manual may use its own nomenclature don't assume anything is universal.**

On Signs of Current and Voltage



Double subscript notation

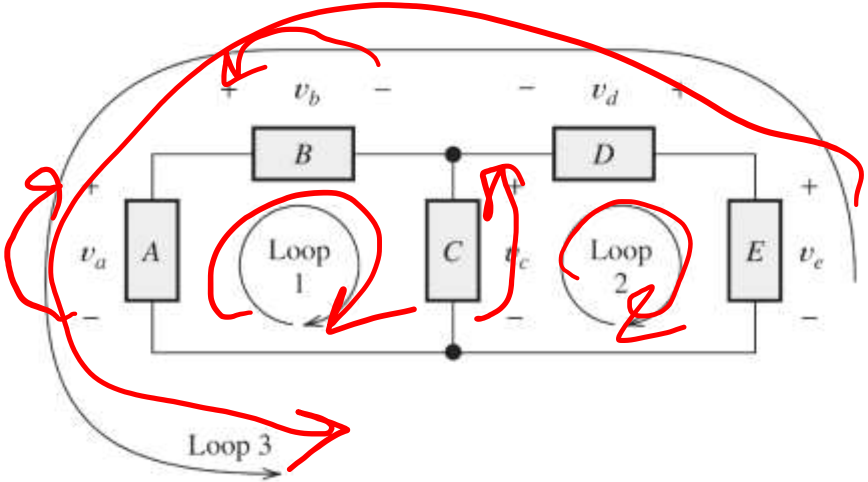




- Signs and directions do not matter so much:
  - i = -1 A
- But
  - positive current gets “out” of the positive sign of a voltage source
  - if a current “enters” a passive element, the **positive voltage** will be at the entering side

Kirchhoff's Voltage Law

- The sum of the voltages around any closed path (loop/mesh) must equal zero



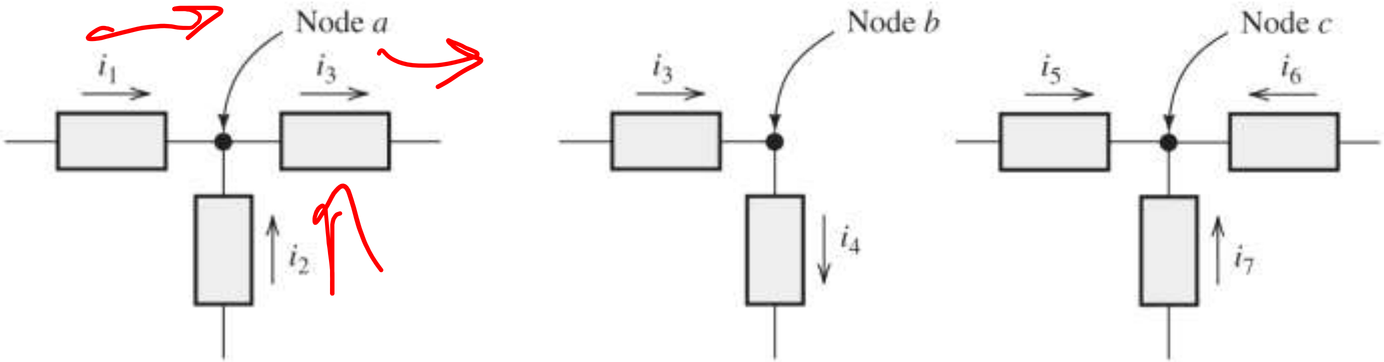
$$\text{Loop 1: } -V_a + V_b + V_c = 0$$

$$\text{Loop 2: } -V_c - V_d + V_e = 0$$

$$\text{Loop 3: } -V_e + V_d - V_b + V_a = 0$$

Kirchhoff's Current Law

- The sum of the currents entering a node is zero.



$$\text{Node a}: i_1 + i_2 - i_3 = 0$$

$$\text{Node b}: i_3 - i_4 = 0$$

$$\text{Node c}: i_5 + i_6 + i_7 = 0$$

Questions?

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Resistors in Series

- Given the three resistors in the circuit
- What is the equivalent resistor for the entire circuit?
- Tip: apply the laws we have seen before until you get to an equation of the form $v = i \cdot R_{eq}$, where R_{eq} is a function of the given R's
- Answer:
  - $R_{eq} = R_1 \cdot R_2 \cdot R_3$
  - $R_{eq} = 1/R_1 \cdot R_2 \cdot R_3$
  - $R_{eq} = 1/(1/R_1 + 1/R_2 + 1/R_3)$
  - $R_{eq} = R_1 + R_2 + R_3$

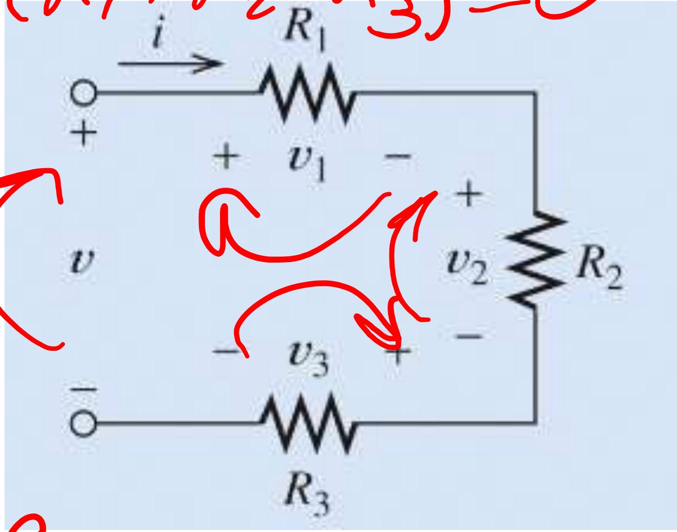
$i \cdot R_1 \quad i \cdot R_2 \quad i \cdot R_3$

$v - v_1 - v_2 - v_3 = 0$

$v - i(R_1 + R_2 + R_3) = 0$

$v = i \cdot R_{eq}$

$R_1 + R_2 + R_3$



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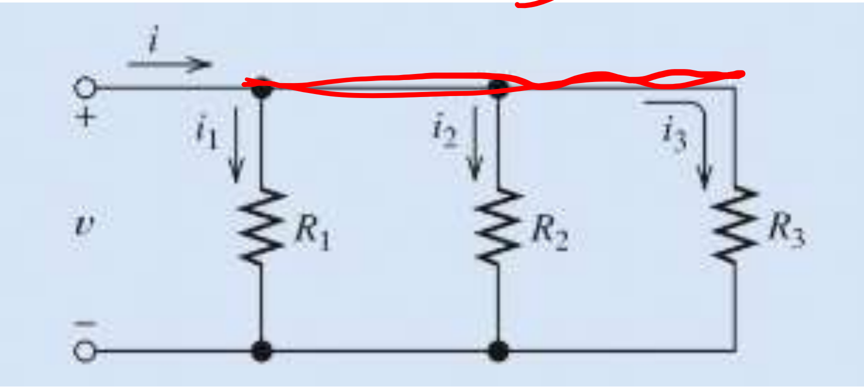
Resistors in Parallel

- Given the three resistors in the circuit
- What is the equivalent resistor for the entire circuit?
- Tip: apply the laws we have seen before until you get to an equation of the form $v = i \cdot R_{eq}$, where R_{eq} is a function of the given R's
- Answer:
  - $R_{eq} = R_1 \cdot R_2 \cdot R_3$
  - $R_{eq} = 1/R_1 \cdot R_2 \cdot R_3$
  - $R_{eq} = 1/(1/R_1 + 1/R_2 + 1/R_3)$
  - $R_{eq} = R_1 + R_2 + R_3$



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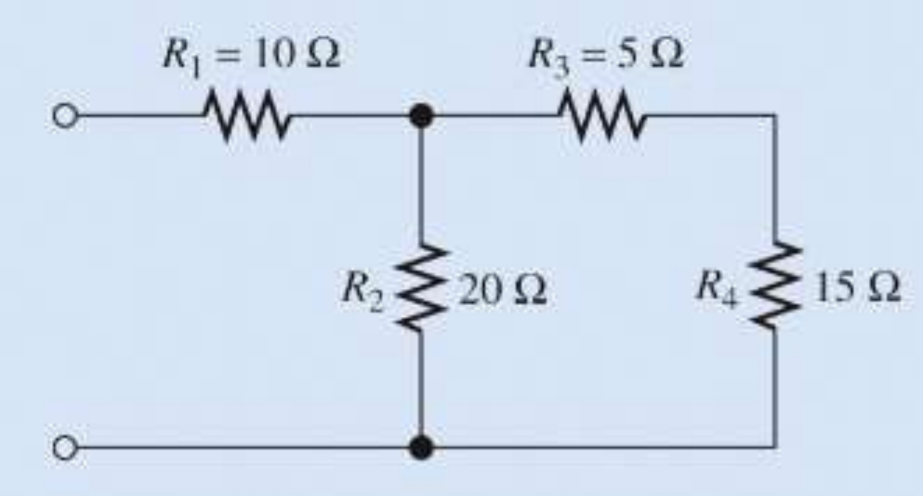
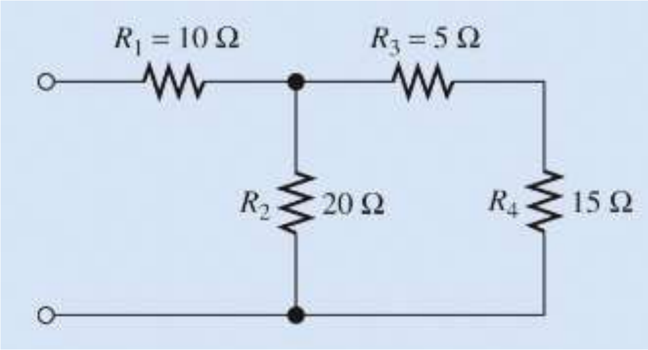
Exercise: Resistor Network

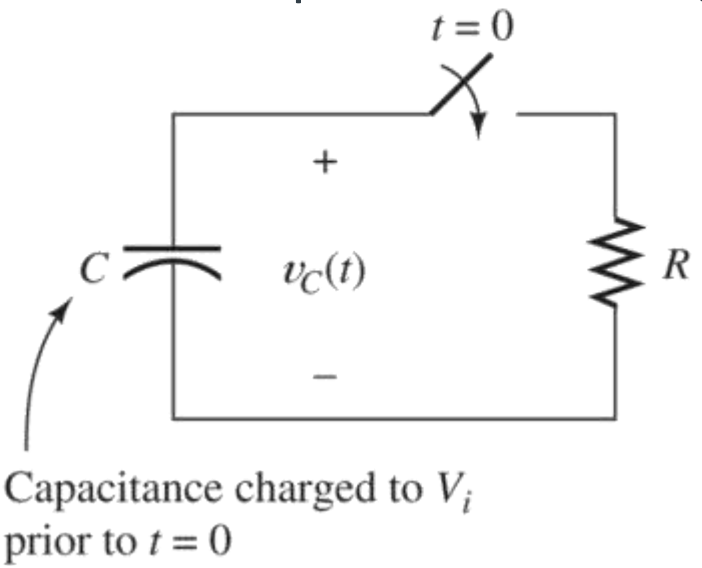
- Given the resistor network below, find the total resistance of the network
- Two alternatives:
  - simplify resistors with the parallel/series equivalents we just saw
  - compute the relationship between voltage and current at the entrance with the laws we learned
- Answer:
  - 20 Ohm
  - 10 Ohm
  - 30 Ohm
  - 35 Ohm

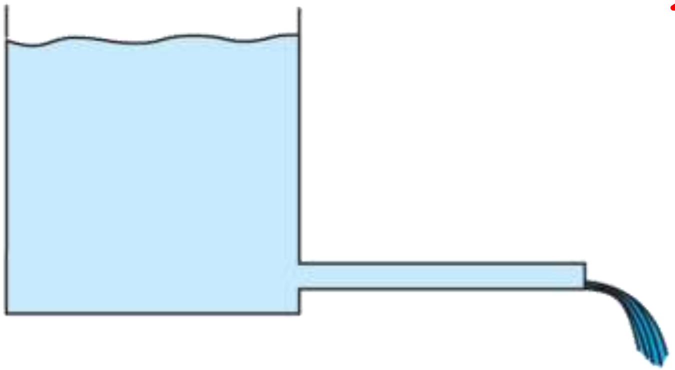


Exercise: Resistor Network



RC Circuit: Capacitor Discharge



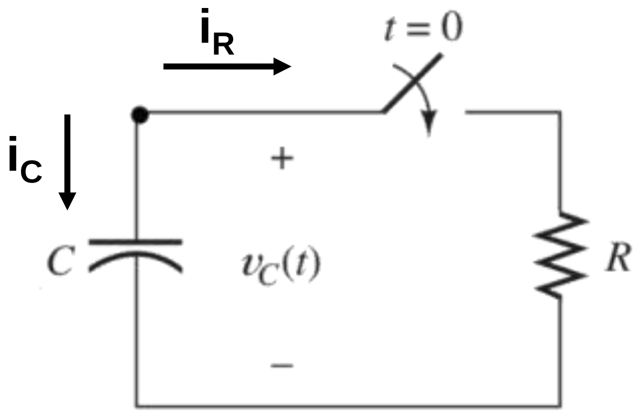


$$i_c(t) = C\frac{dV_c(t)}{dt}$$

- Unlike simple resistor circuits, the 1st order relationship means the current will change over time

RC Circuit: Capacity Discharge

- KCL at top node



$$i_C + i_R = 0$$

$$C\frac{dV_c(t)}{dt} + \frac{V_c(t)}{R} = 0$$

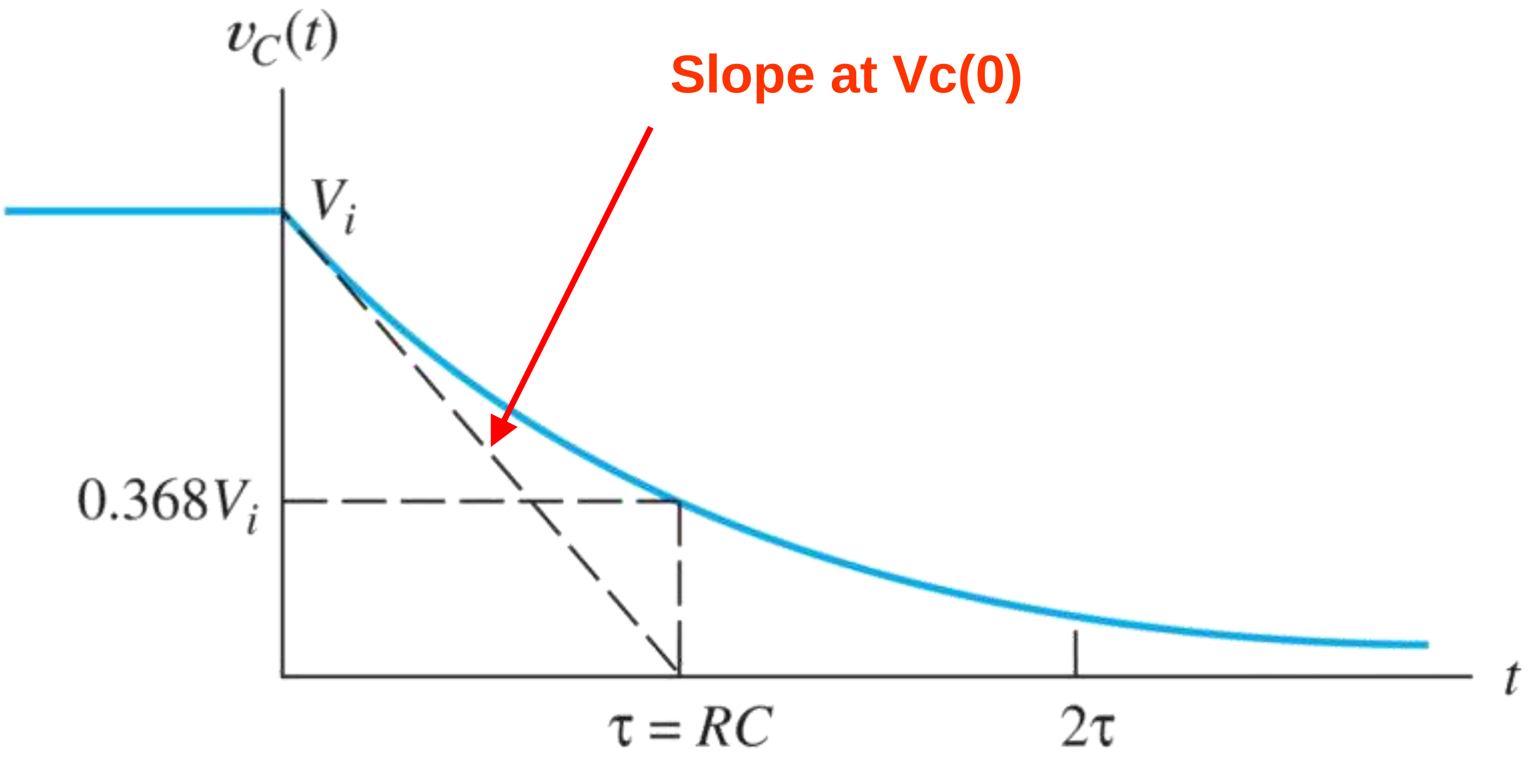
$$RC\frac{dV_c(t)}{dt} + V_c(t) = 0$$

- Solve the 1st order differential equation with the initial condition *V(0)=V*$_i$

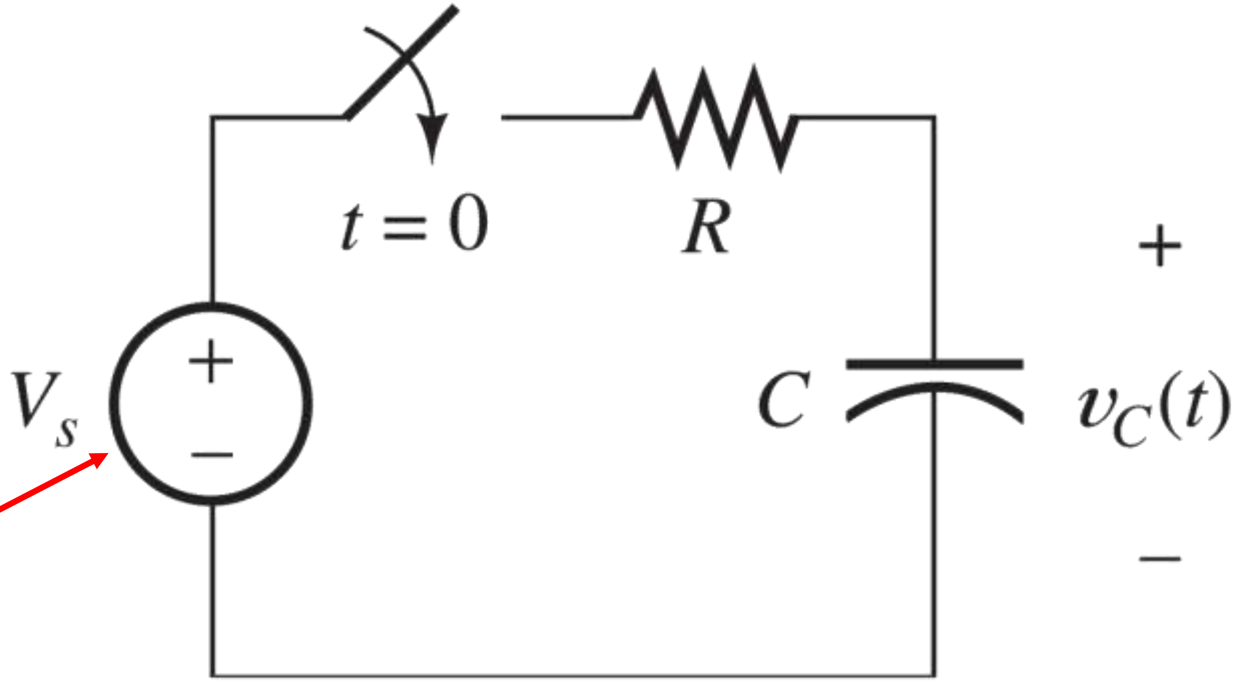
$$V_c(t) = V_i \cdot e^{\frac{-t}{RC}}$$

$$RC = \tau = \text{time constant}$$

RC Circuit: Capacitor Discharge

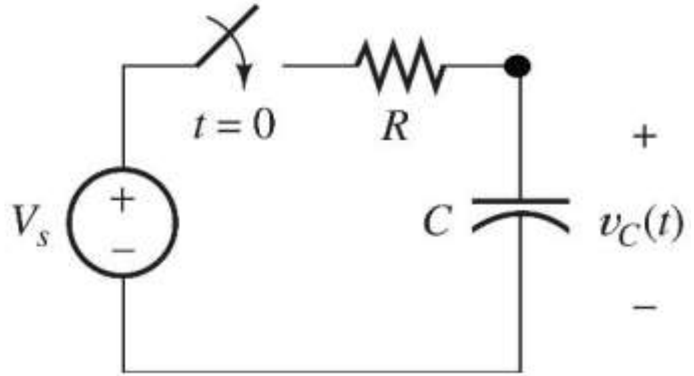


RC Circuit: Charging a Capacitor



D.C. Source

RC Circuit: Charging a Capacitor



- KCL at top right node

$$C\frac{d\upsilon_c(t)}{dt} + \frac{\upsilon_c(t) - V_s}{R} = 0$$

$$RC\frac{d\upsilon_c(t)}{dt} + \upsilon_c(t) = V_s$$

- Assume a solution of the form…

$$\upsilon_c(t) = K_1 + K_2 e^{st}$$

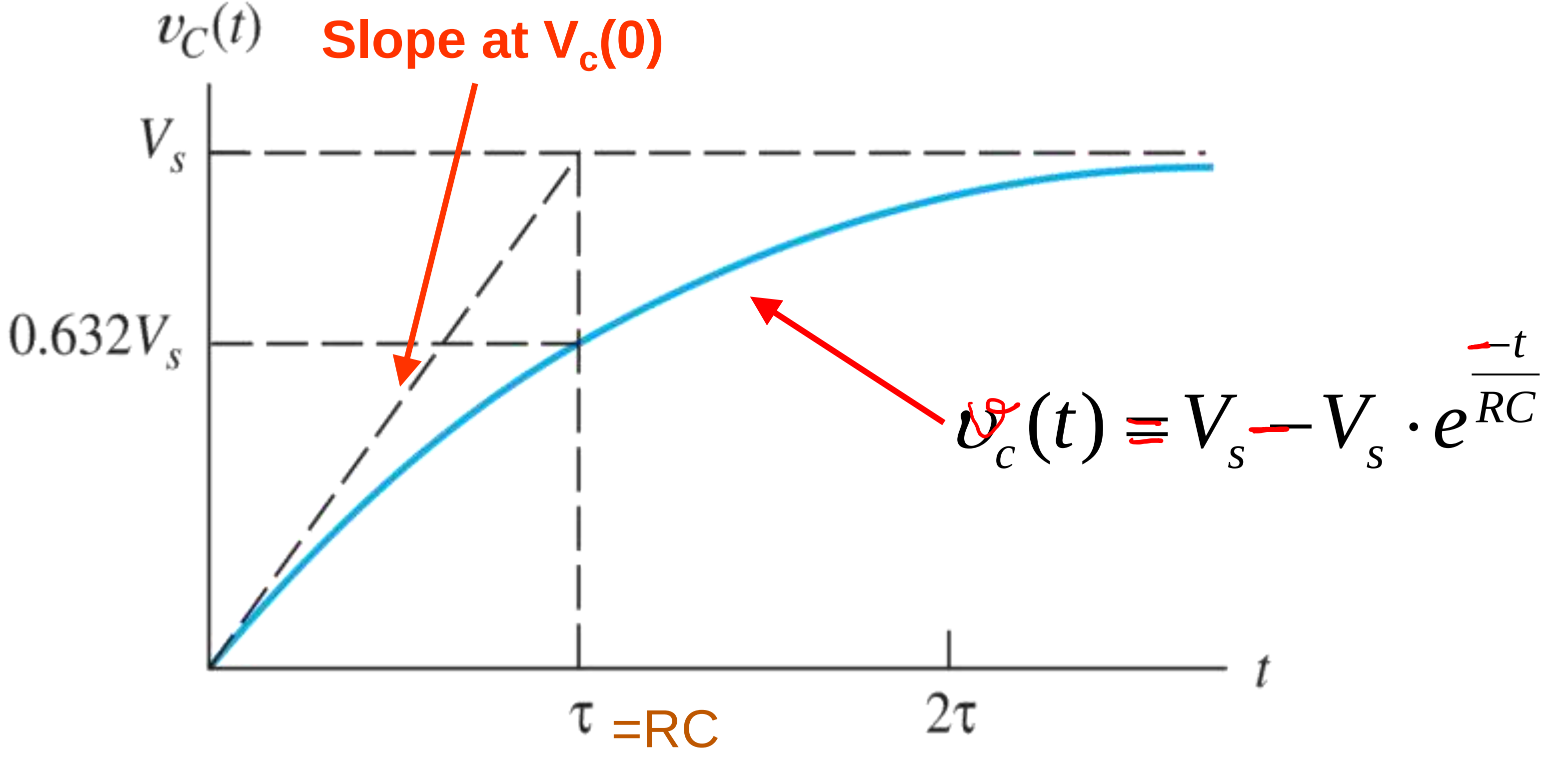
$$s = \frac{-1}{RC}, \quad K_1 = V_s, \quad K_2 = -V_s$$

$$\upsilon_c(t) = V_s - V_s \cdot e^{\frac{-t}{RC}}$$

Steady-State Response

Transient Response

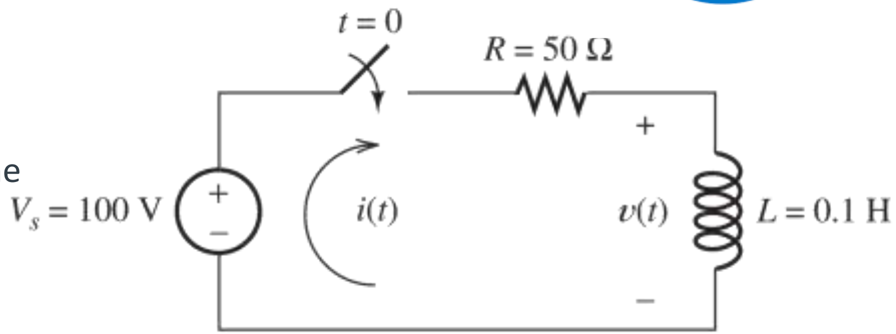
RC Circuit: Charging a capacitor



https://pollev.com/robertomartinmartin739

Exercise: RL Circuit

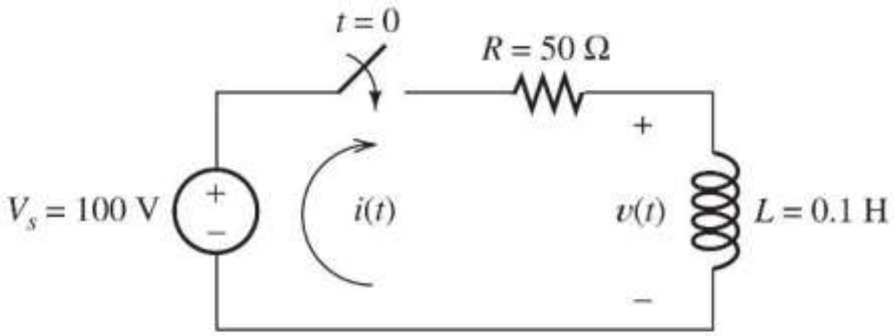
- Given the circuit of the diagram, what are:
  - The time constant
    - 2 s
    - 1 ms
    - 0.1 ms
    - 2 ms
  - The solution for the current as a function of time
    - $i(t) = \frac{V_s}{R} - \frac{V_s}{R} e^{-\frac{tR}{L}}$
    - $i(t) = V_s - V_s e^{-\frac{tR}{L}}$
    - $i(t) = V_s - V_s e^{-\frac{t}{RL}}$
    - $i(t) = R(V_s + V_s e^{-\frac{tR}{L}})$
- Tip: use the KVL



Reminder:

$$v_L(t) = L\frac{di}{dt}$$

Exercise: RL Circuit



$$Vs = 100V$$
$$R = 50\Omega$$
$$L = 0.1\ H$$
$$\tau = \frac{L}{R} = \text{time constant}$$
$$\tau = 2\ \text{msec.}$$

KVL around loop:

$$R \cdot i(t) + L\frac{di(t)}{dt} = Vs$$

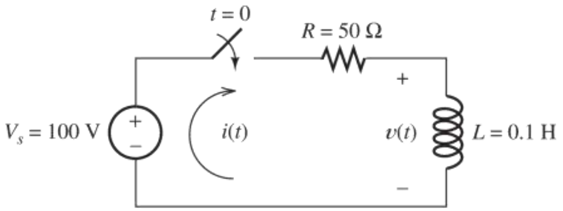
$$\frac{L}{R}\frac{di(t)}{dt} + i(t) = \frac{Vs}{R}$$

Solution (recall general form):

$$i(t) = \frac{Vs}{R} - \frac{Vs}{R} \cdot e^{\frac{-tR}{L}}$$

RL Circuit Example

$$i(t) = \frac{Vs}{R} - \frac{Vs}{R} \cdot e^{\frac{-tR}{L}}$$



Vs = 100V

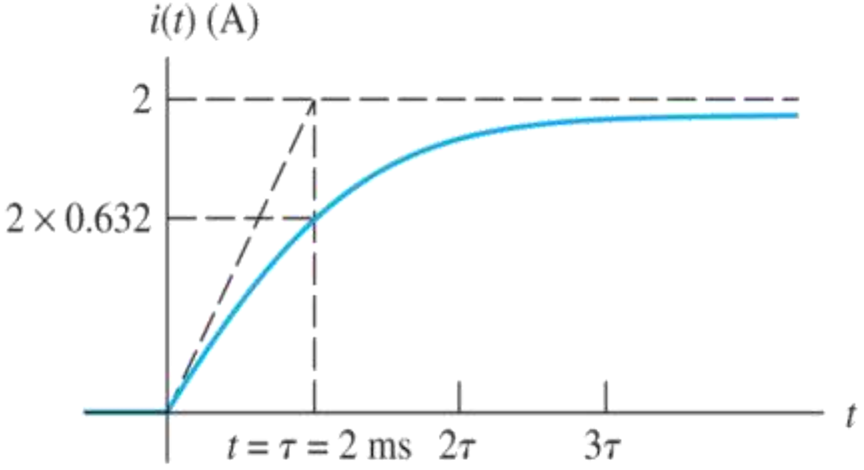
R = 50Ω

L = 0.1 H

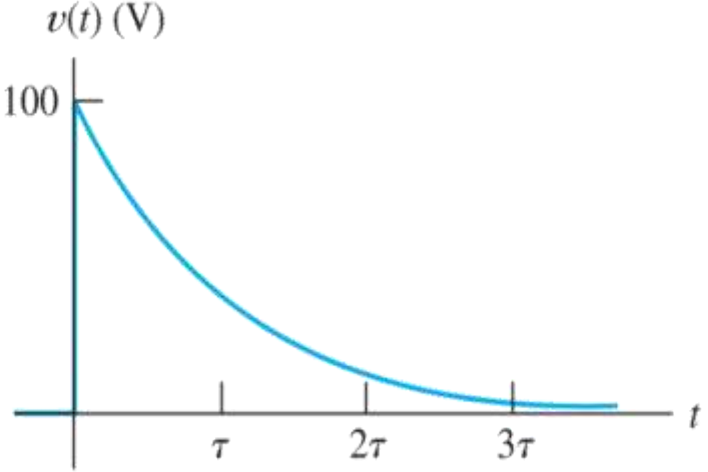
$\tau = \frac{L}{R}$ = time constant

τ = 2 msec.

$$v(t) = L\frac{di(t)}{dt} = 100e^{\frac{-t}{\tau}}$$

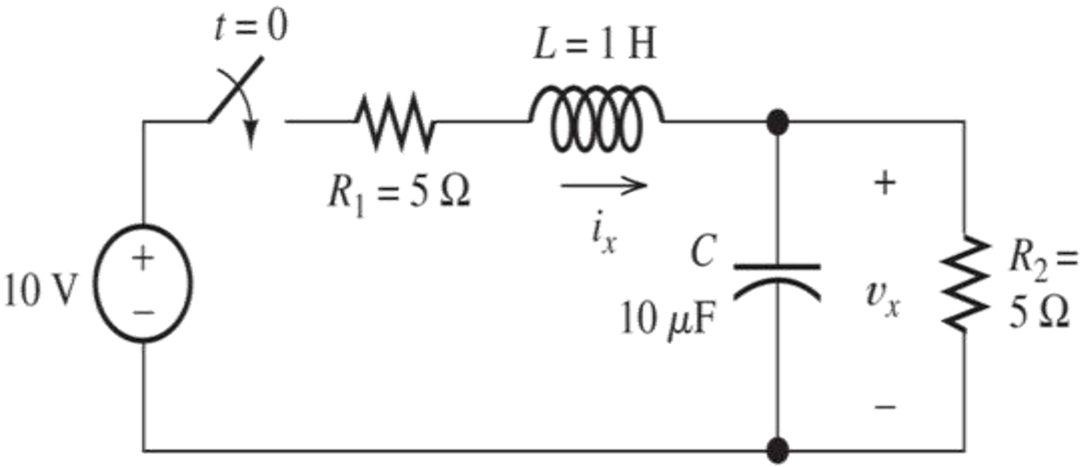


Current through L



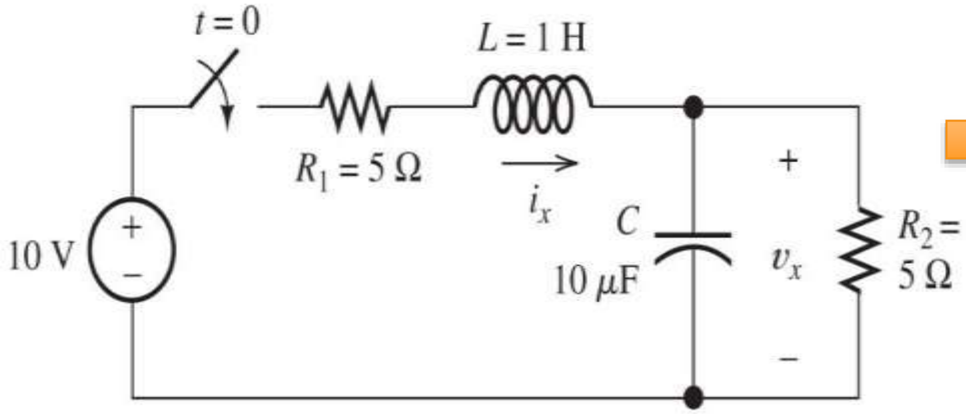
Voltage across L

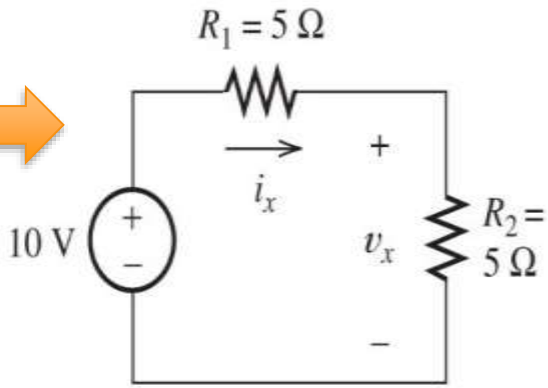
Example RLC Circuit



- RLC circuits form the basis for modeling circuits with motors
- RLC circuits will produce 2nd order differential equations
  - Can be solved by assuming a solution, but no time for that here
- BUT at ***Steady State*** (t>> τ) with DC sources, capacitors become open circuits and inductors become short circuits
  - It is easy to calculate the *steady state* solution if we are not to worried about the *transient* solution.

RLC Circuit: Steady State Example





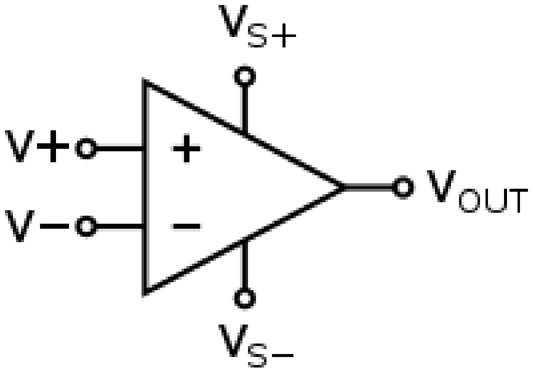
- Steady State ⇒ no change ⇒ *d/dt = 0*
  - C: i_c = *dq/dt =0* ⇒no current ⇔open circuit
  - L: *V=Ldi/dt = 0* ⇒no voltage drop⇔ short circuit

$$i_x(t \to \infty) = \frac{10V}{R_1 + R_2} = 1A$$

$$V_x(t \to \infty) = i_x R_2 = 5\ V$$

Differential Amplifier

- Amplifies the difference between the input voltages
- $V_{out} = A(V^{+} - V^{-})$
- Common application: control of motors
- Other (many!) applications in signal processing



Did I mention that this is also an entire course(s) in both ME and ECE?

Solve more complicated circuits with MATLAB's Simulink

- Graphical extension of MATLAB for the modeling and simulation of dynamic systems.
  - Circuits & Mechatronic Systems
  - Includes ability to add inputs (function generators, steps, impulses, etc.) and outputs (oscilloscopes, tachometers, etc.)
  - Block Diagram editing
  - Nonlinear simulation
  - Continuous and discrete models
- Great support and visualizations tools for controls.
- You won't need for this course, but good to know it is out there.
  - http://www.engin.umich.edu/group/ctm/working/mac/simulink_basics/index.htm

Power

- This is what we really care about!
  - Our circuits are providing power (and/or transmitting signals)
- Power = How much energy is used in a span of time

  = (more commonly) the maximum produced or allowed power.

  = Voltage x Amperes

  = **V***i*

  = (joules/coulomb) x (coulomb/second)

  = joules/second

  = Watts

$$P = i \cdot V$$

Power dissipated by a load

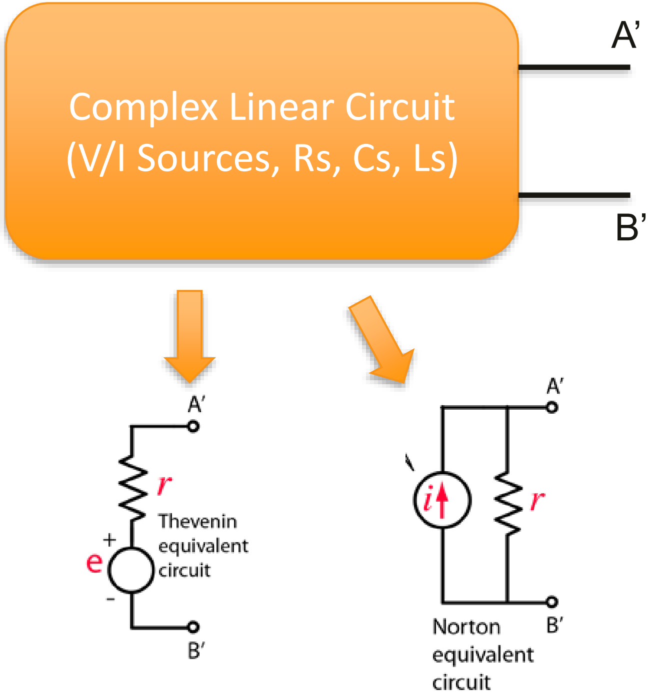
- Larger voltage across resistor increases power dissipated

$$P(t) = \upsilon(t) \cdot i(t) = R \cdot i^2 = \frac{\upsilon^2}{R}$$

- **Resistor Power Rating**: maximum power safely dissipated by resistor.
- **Safety rule**: select resistor with power rating twice expected power dissipation.
  - If not, wire overheats, smoke, odor, fire!

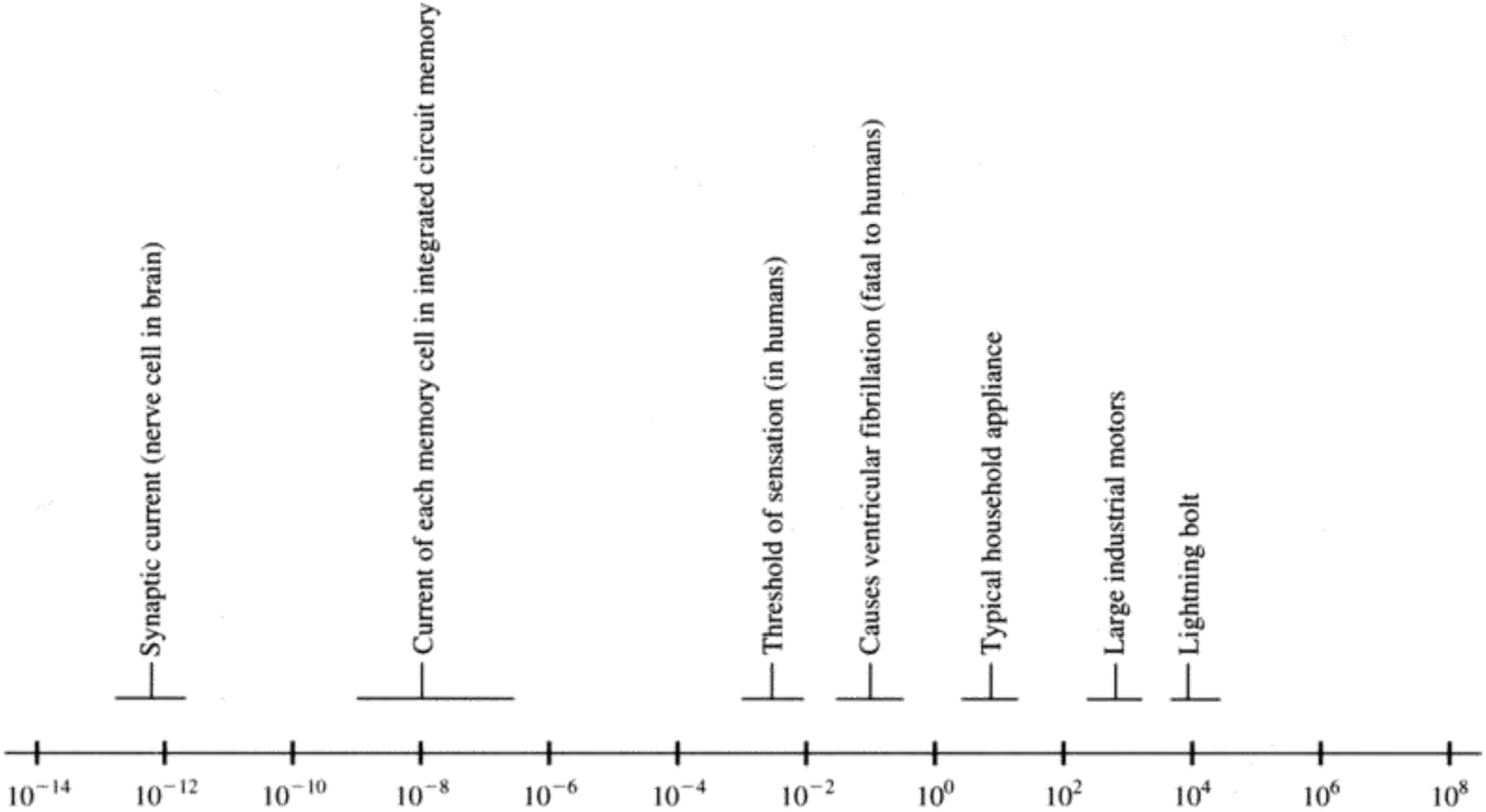
Thevenin and Norton Theorems

- Thevenin theorem:
  - *any linear circuit can be simplified to an equivalent circuit consisting of a single voltage source with a series resistance connected to a load*
- Norton theorem:
  - *any linear circuit can be simplified to an equivalent circuit consisting of a single current source and parallel resistance*

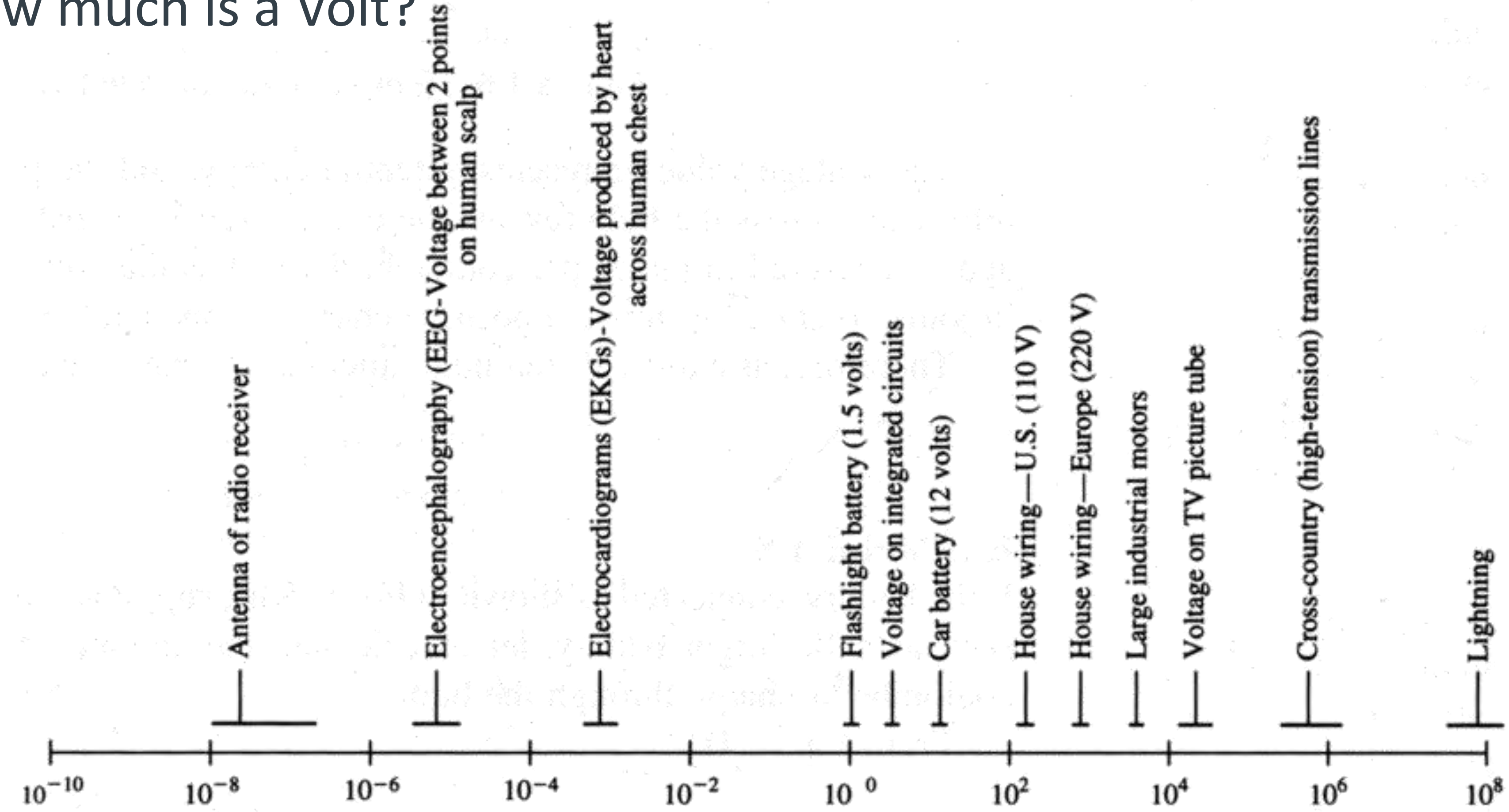



GTI LAB

How much is an AMP?



How much is a Volt?



Final Remarks

- Almost all robots use electricity to move
  - Every component (computer, sensor, motor) requires power
- The circuits that provide power can be complex
  - To fully understand them requires its own course
- All roboticists must understand
  - how the power is transmitted matters, and the common source of problems,
  - real components (sources, capacitors, etc.) do not act like ideal components,
  - too much power demand may create issues in your components.
  - fuses are there for a reason, so don't replace one until you know why it blew, and
  - **An unpowered robot (or any electrical device) can still be dangerous**.