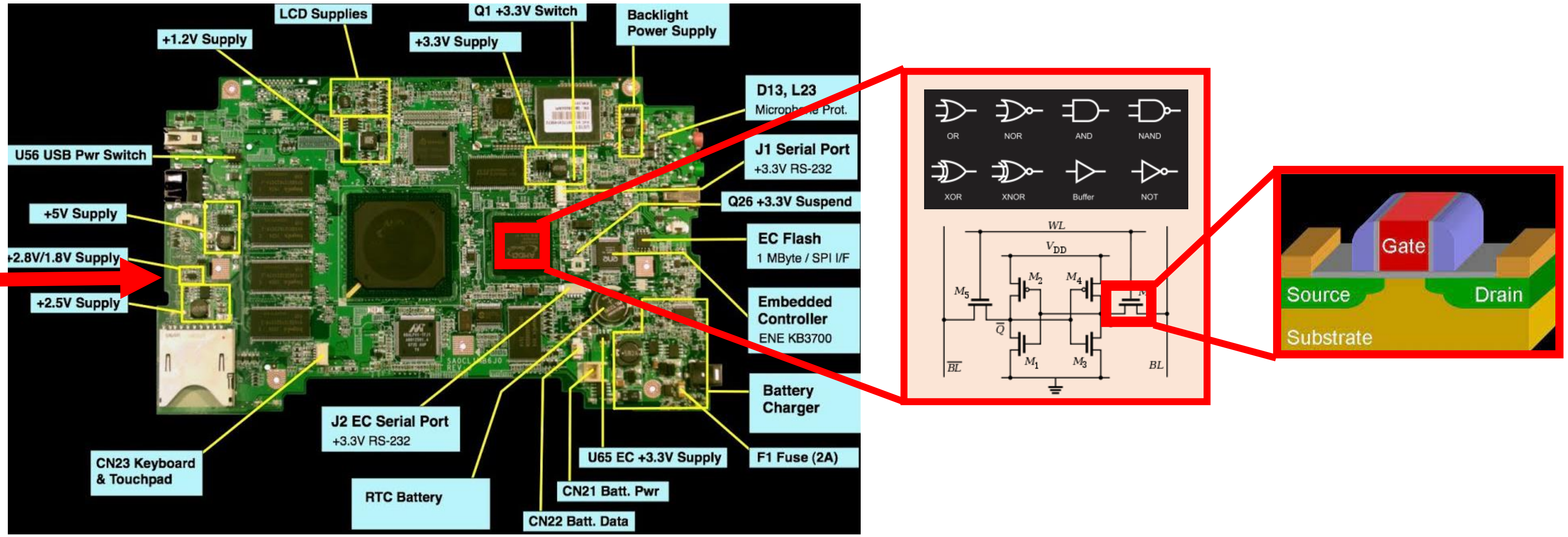

ESC201: Introduction to Electronics

Module 1: Circuit Analysis

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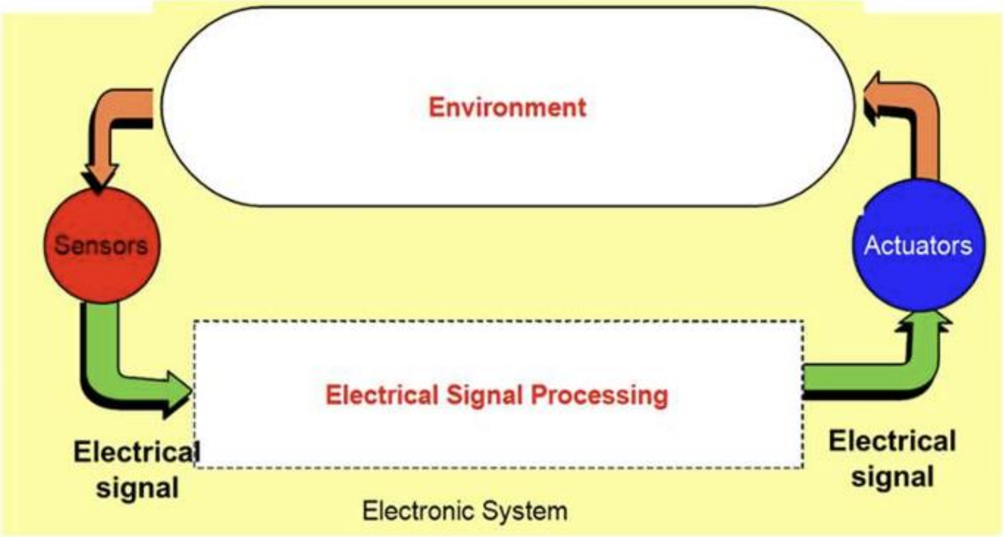
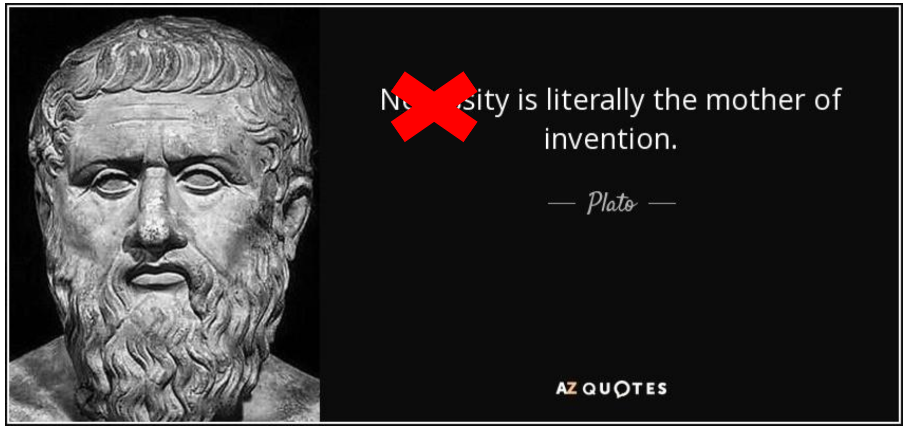
IIT Kanpur

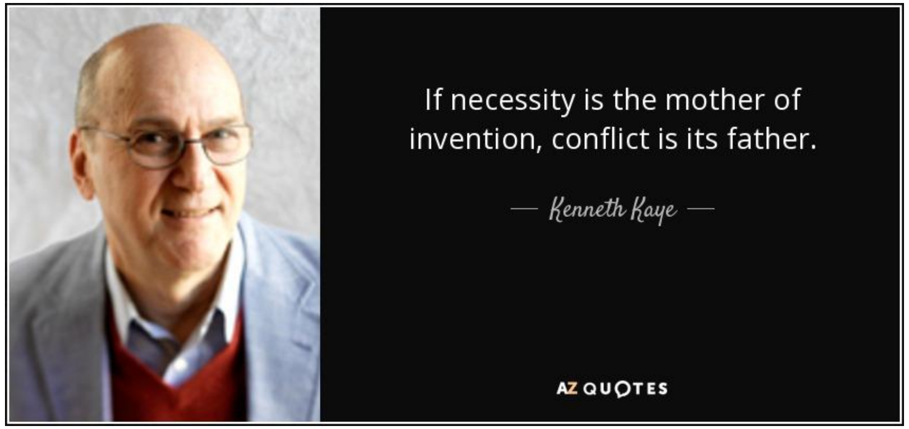
Re-cap

- Why electronics?
- Easily available electrical energy can be controlled precisely with electronics.
- 'Imagination' is the limit!
- Can solve problems in other domains: make them smart!!.

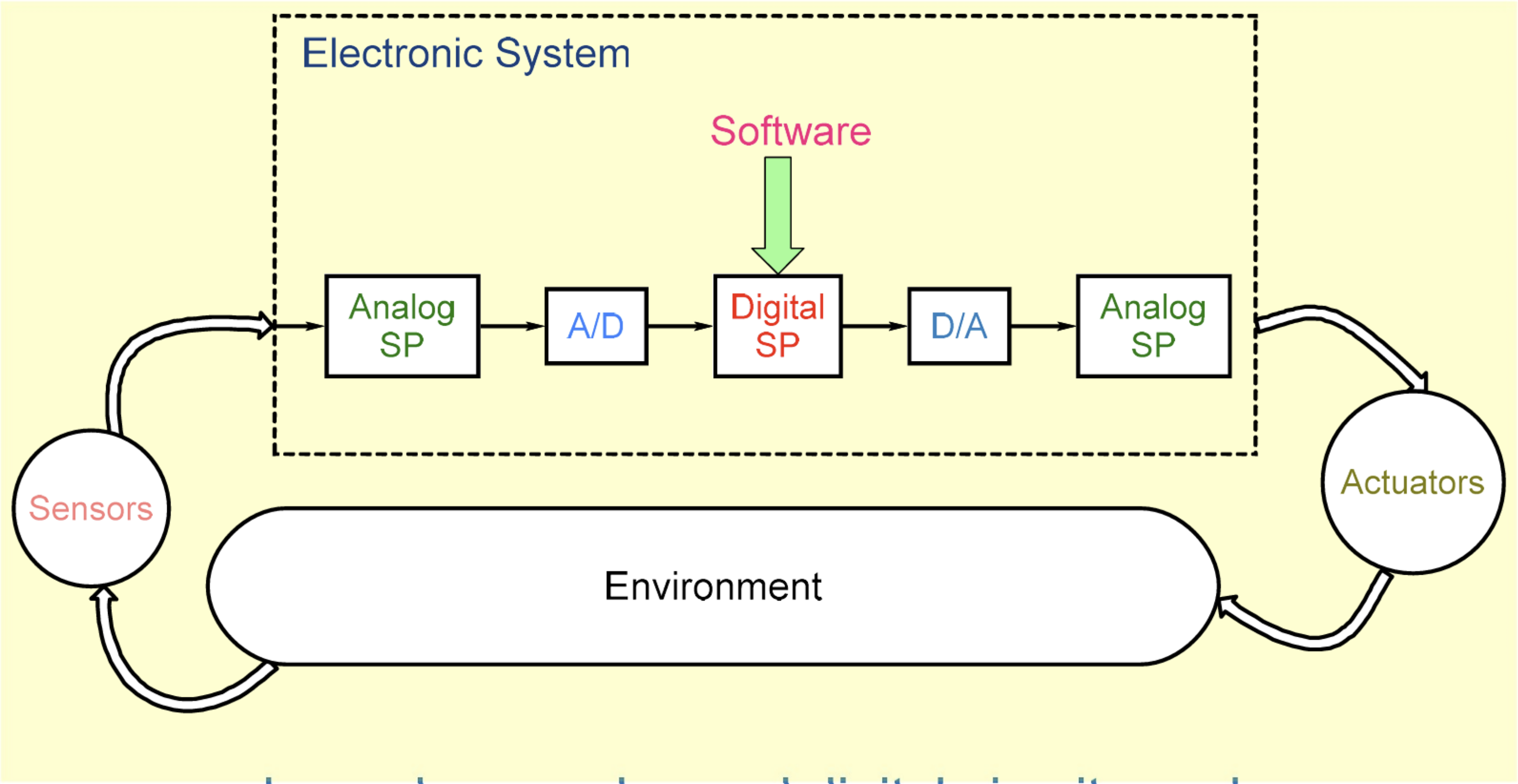


Solve Problem by transforming them to an electronics problem





Why ESC201?



Learn how analog and digital circuits work

Tools for circuit Analysis

- Fundamentals of electrical circuits--3
- Transient Analysis of RLC Circuits--2
- Sinusoidal Steady State Analysis--4

Analog Circuits

- Semiconductors, Diodes, Circuits-----3
- Transistors and Amplifiers---4
- Operational Amplifier based Analog circuits -4

Digital Circuits

- Logic gates, Combinational circuits ---4
- Flip-flops, Sequential Circuit---4
- Data Converters----3

Charge

Unit of electric charge: Coulomb

1 C = 1 A x 1 s

Common symbols: q or Q

An electronic charge: - 1.6 x 10^{-19} C

Electron carries negative charge

Proton carries positive charge

Negative charge carriers:

- electrons, negative ions, …

Positive charge carriers:

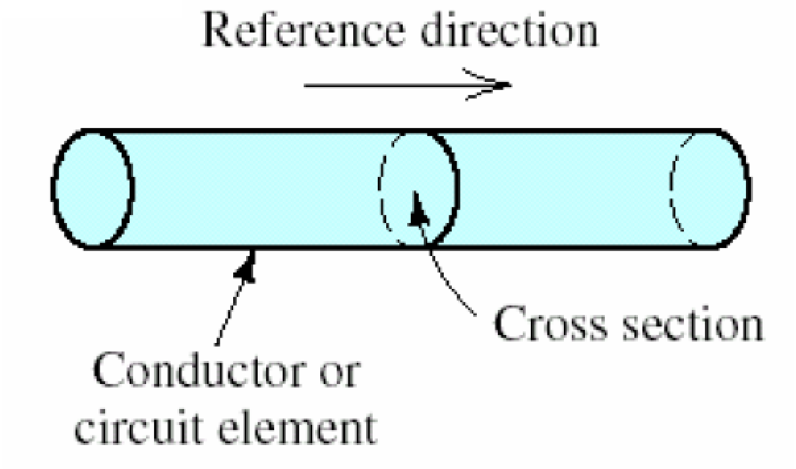
- positive ions, holes (absence of electrons), …

Charles-Augustin de Coulomb
(14 June 1736 – 23 August 1806)

Wikipedia

Current

- The time rate of flow of electrical charge
- Unit: **ampere** (A) → which is coulomb per second (C/s)
- Ampere is one of the seven basic SI units
- Popular symbol is i or I
- $$i(t) = \frac{dq(t)}{dt}$$



André-Marie Ampère
1775-1836

commons.wikimedia.org

Electrical Current

Flow of electrons through a wire or other electrical conductor gives rise to current

- Electrons are negatively charged particles

The charge per electron is **-1.602×10^{-19} C**

10^{16} electrons flow per second

How much current flows? $$i(t)=\frac{dq(t)}{dt}$$

$$I=\frac{Q}{t}=\frac{-1.6\times10^{-19}\times10^{16}}{1}=-1.6\times10^{-3}\,A$$

Electrical Current

Current has a magnitude and a direction

I

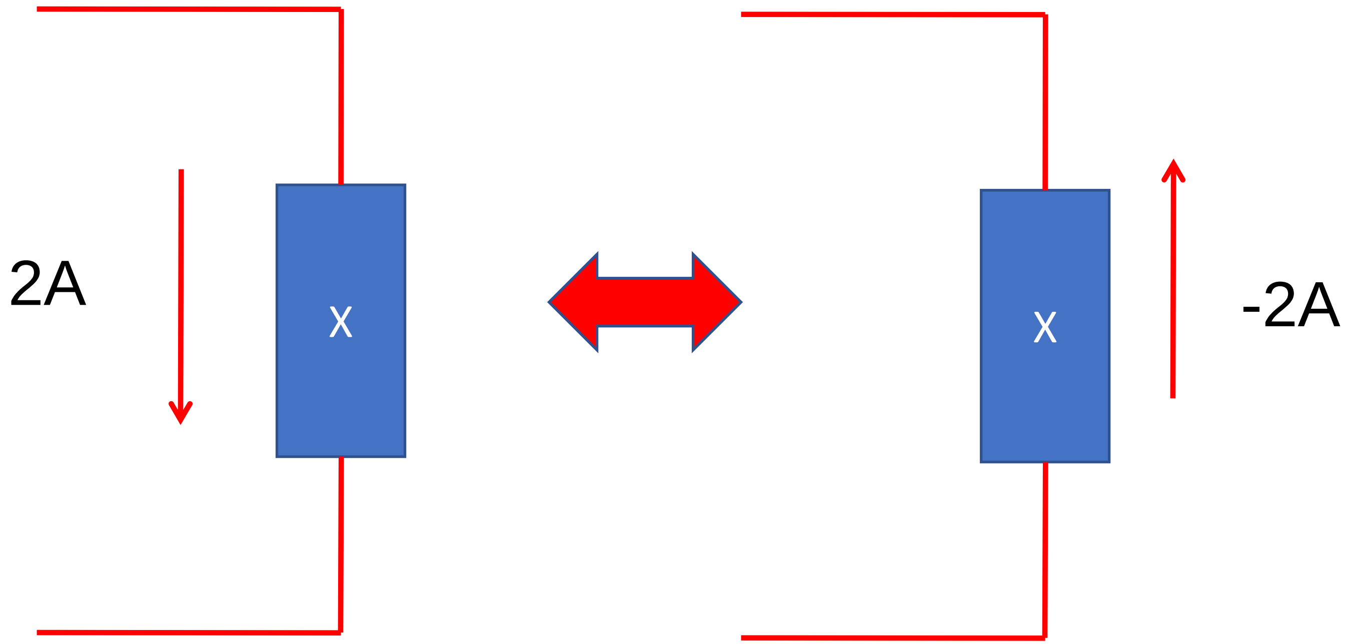
10^{16} electrons flow per second

Direction of current flow is opposite to direction of electron flow

Large number of electrons has to flow for appreciable current.

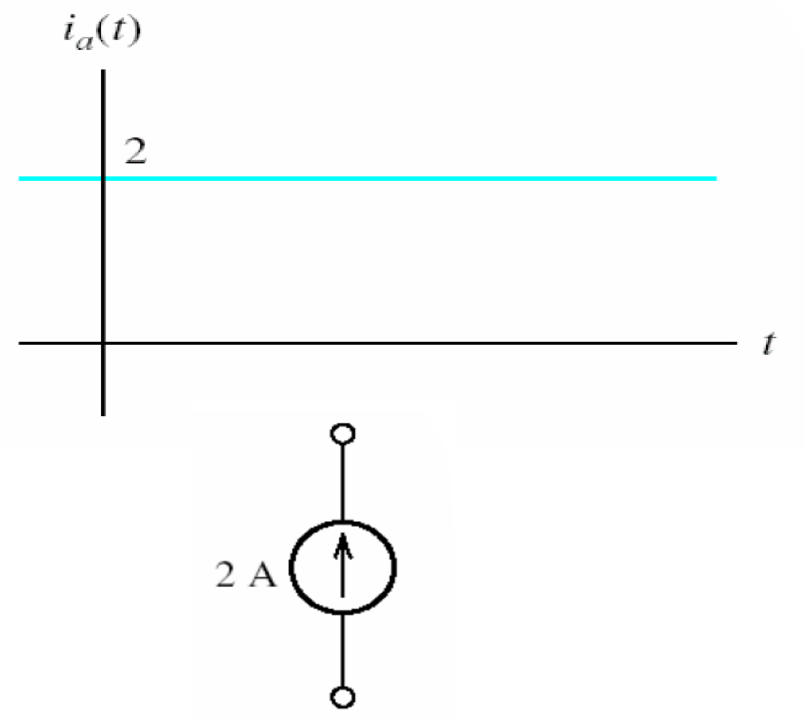
Exercise 1: For $q(t) = 2 - 2e^{-100t}$, for $t > 0$ and $q(t) = 0$ for $t < 0$, find $i(t)$.

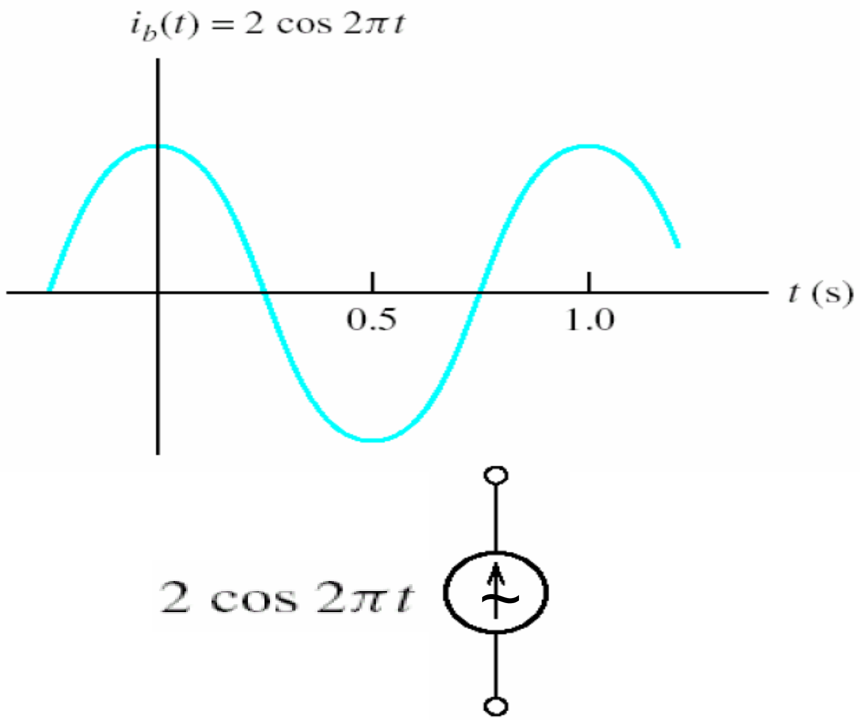
Sign of current



Direct Current (DC) & Alternating Current (AC)

When current is constant with time, we say that we have direct current, abbreviated as DC.

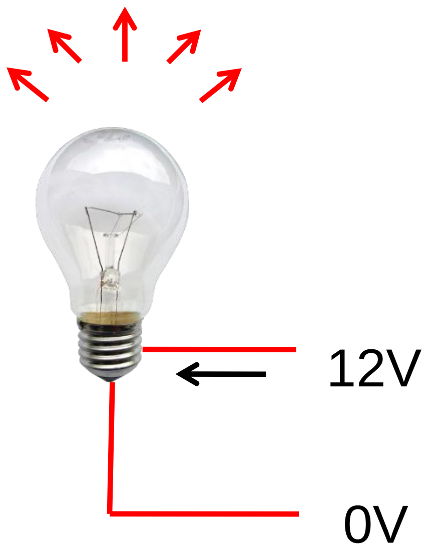




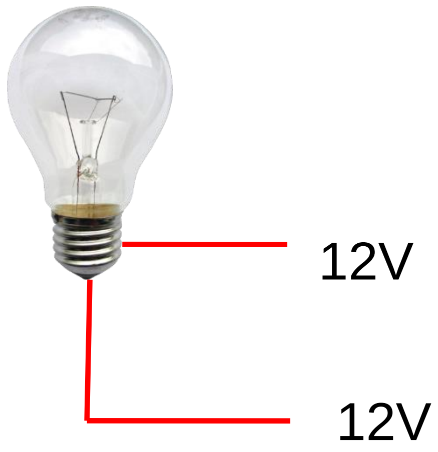
On the other hand, a current that varies with time, reversing direction periodically, is called alternating current, abbreviated as AC

Voltage

- Voltage difference causes current to flow
- Potential difference for a unit positive charge between two points
  - Work done to move unit positive charge between two points
- Units of Voltage: volt (V)
- Popular symbol: v or V



Light comes on

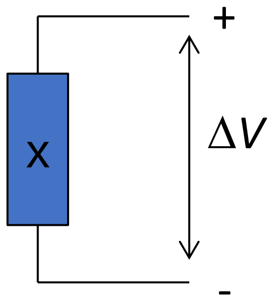


Light does not come on

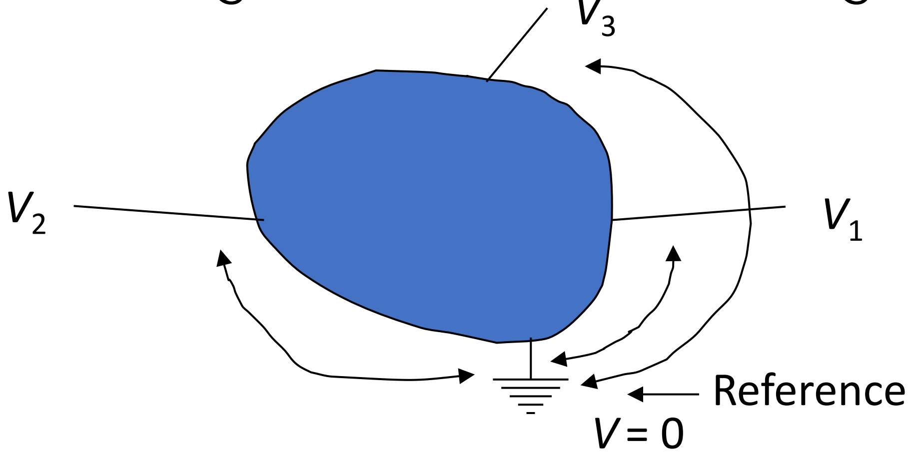
Alessandro Giuseppe Antonio Anastasio Volta 1745-1827

Voltage Is Relative

- In practice, it is ΔV that matters

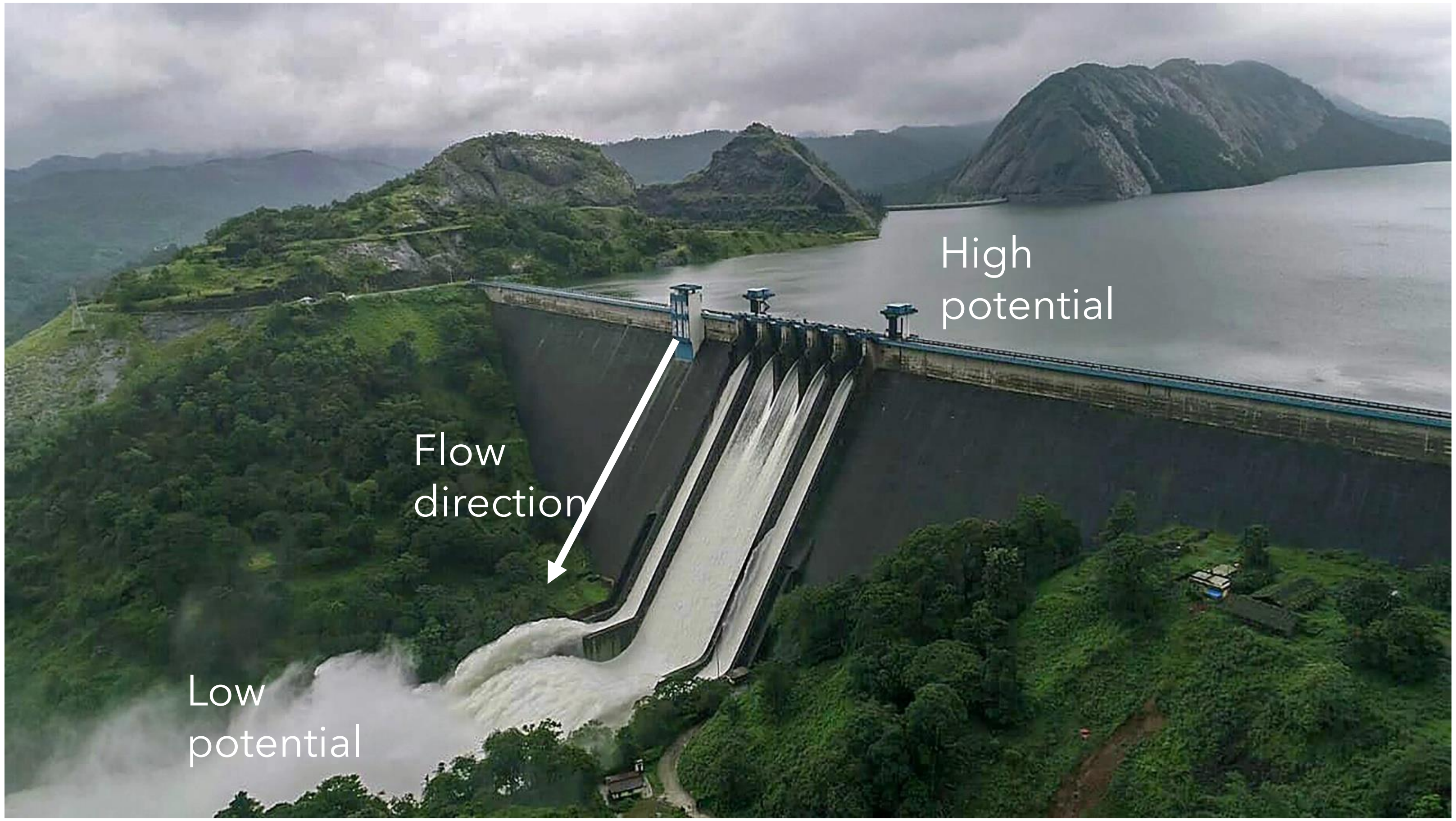


- In a circuit (system), we choose a reference
  - Reference is called "ground"
  - Rest of the voltages in the circuit are w.r.t. ground

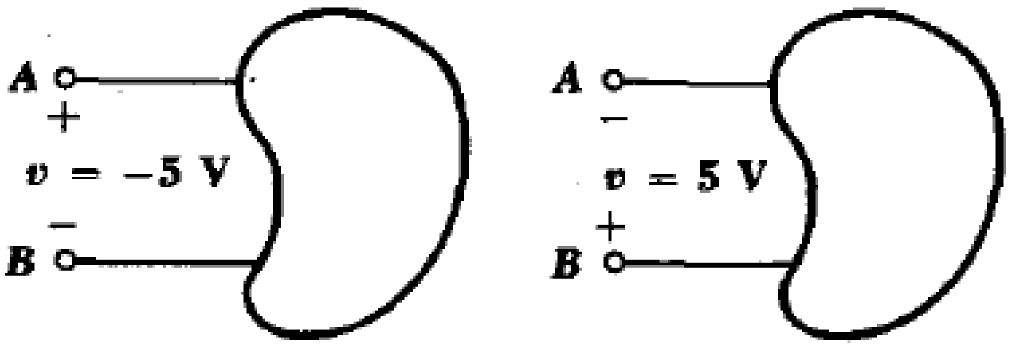


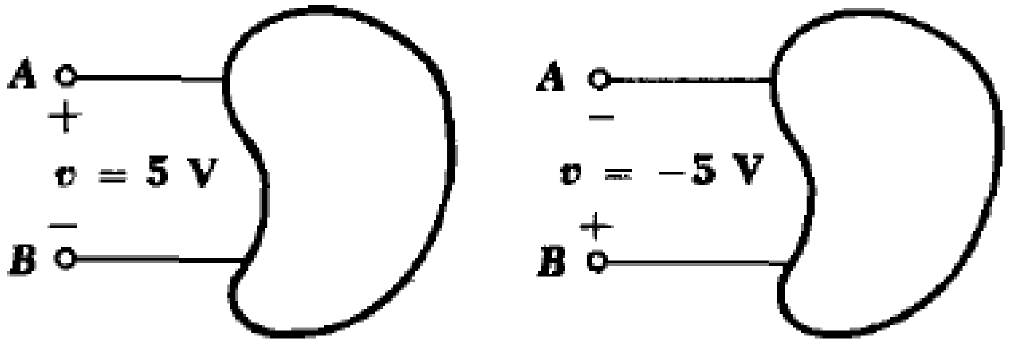
Water Analogy

- Current flow from high voltage to low voltage
- (Potential) energy is consumed in the path
- Higher resistance: smaller flow



Voltage Sign

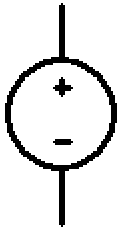




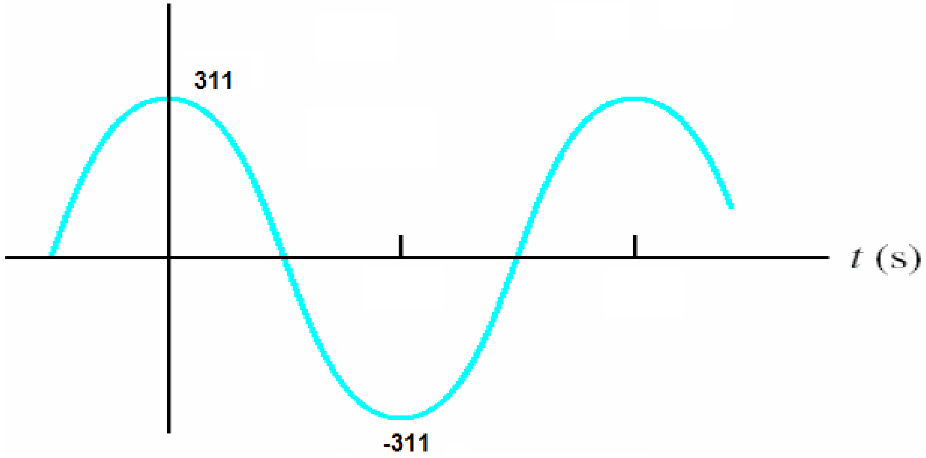
Terminal B is 5 V higher than terminal A

Terminal A is 5 V higher than terminal B

DC and AC voltages

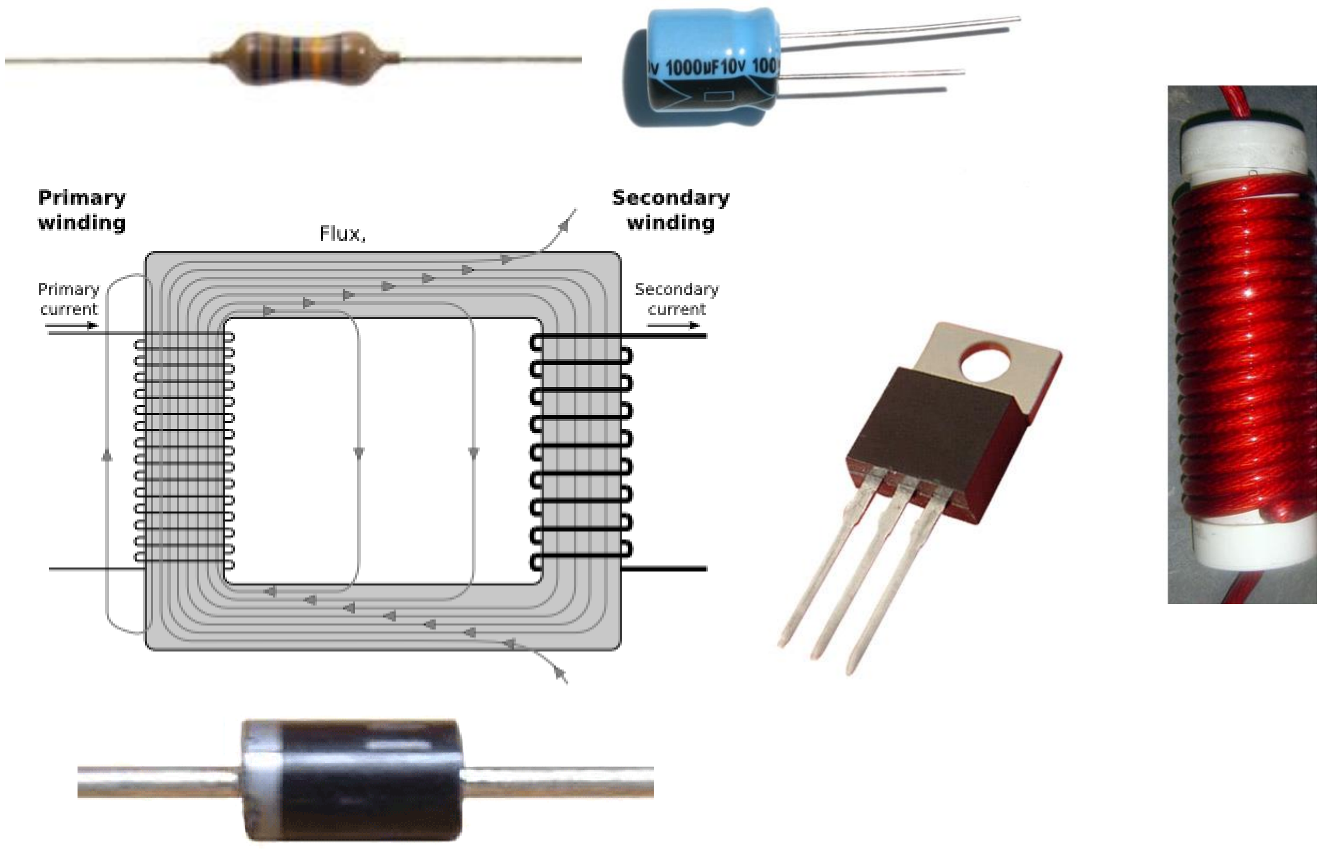


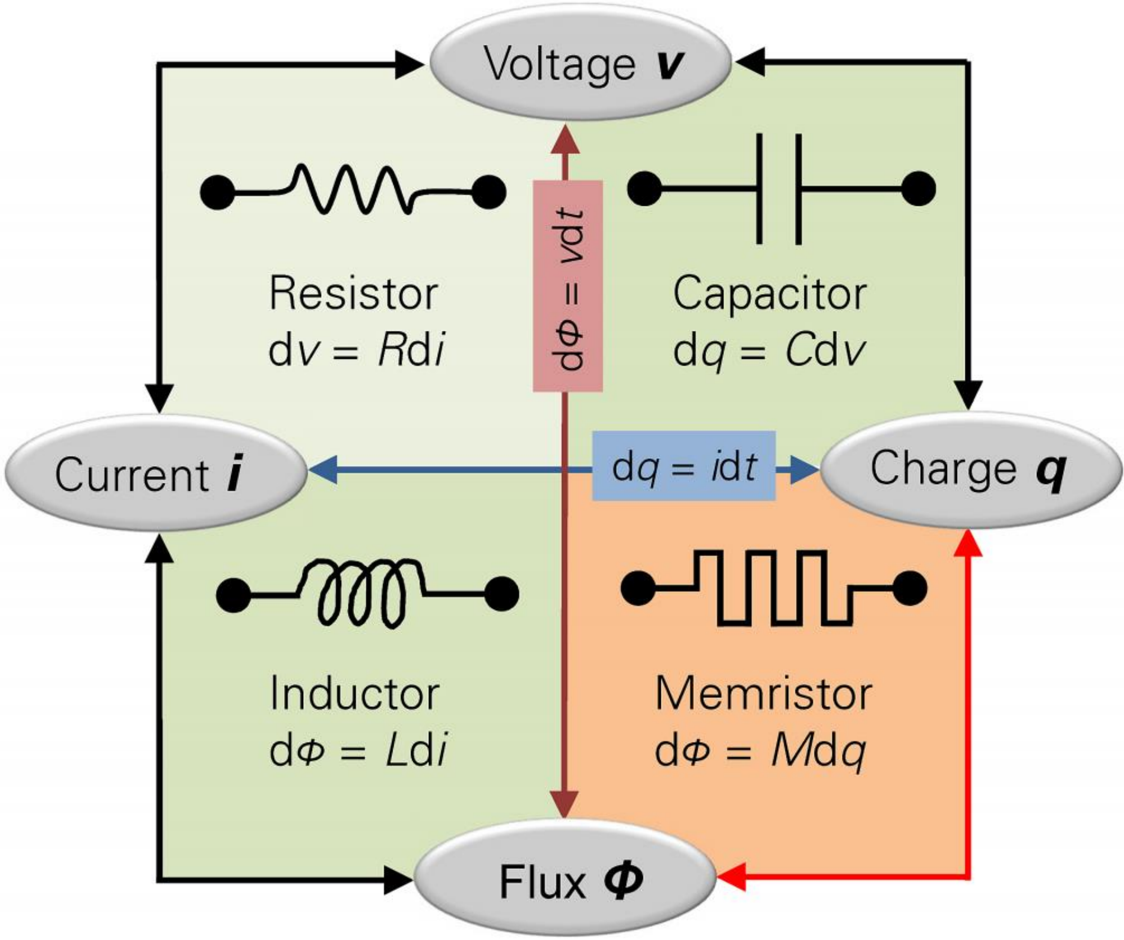
$$V_+ - V_- = 12V$$



Electrical elements

Electrical Systems are made of Voltage sources, wires and a variety of electrical elements





A Circuit

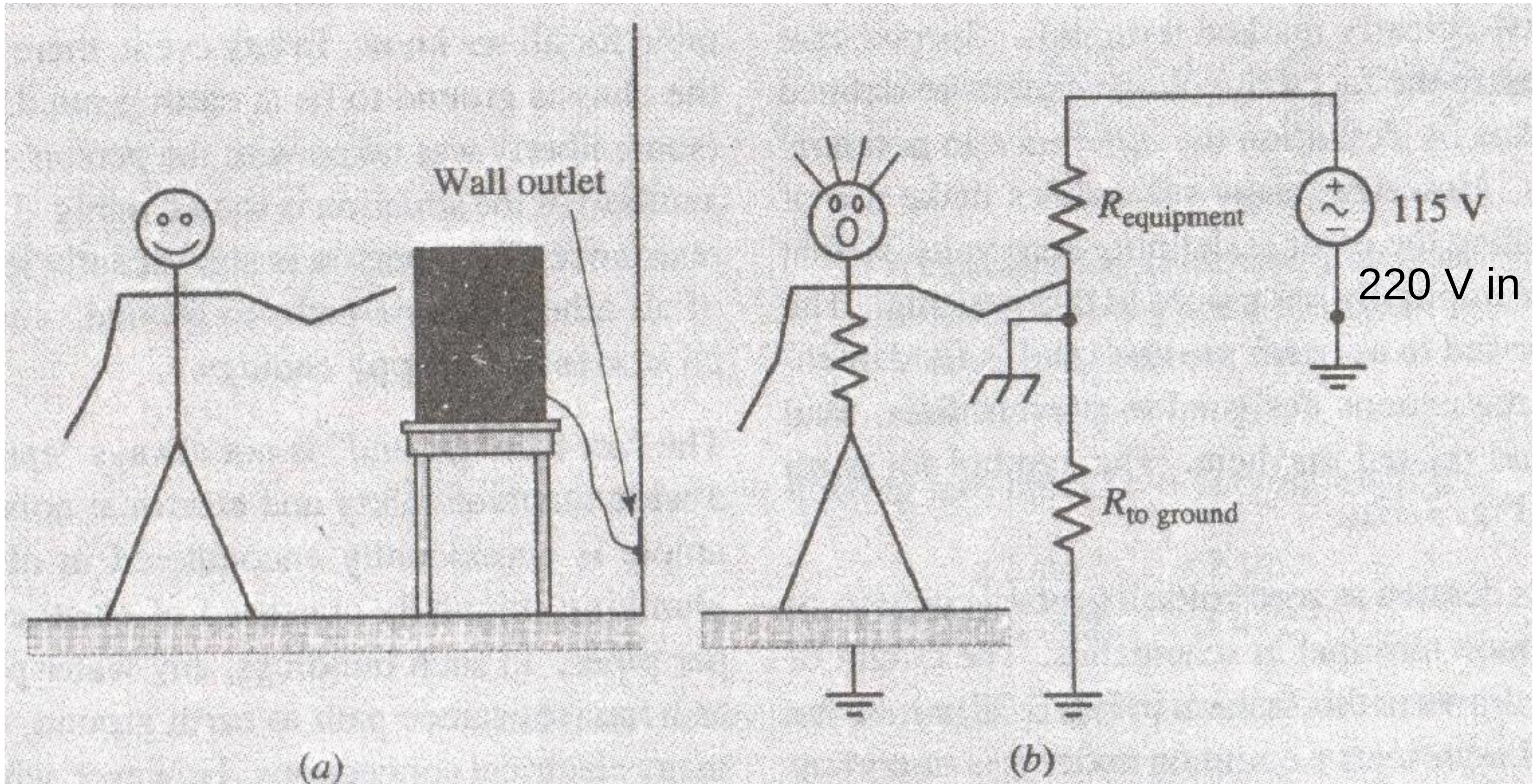
A path for current to flow

https://www.britannica.com/technology/electric-circuit

Electrical systems with closed current paths are often called electrical circuits

Electric Shocks

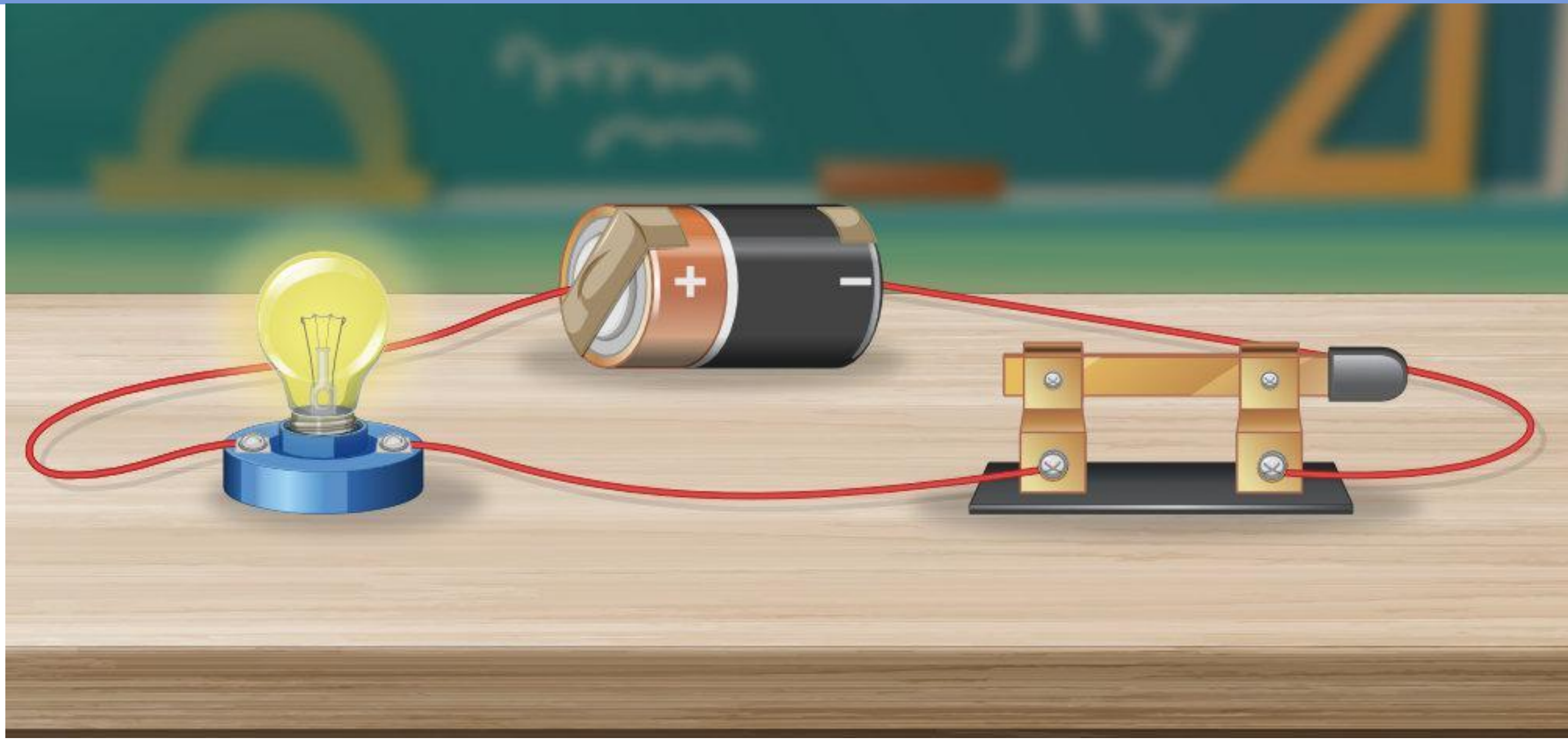
Small currents (70–700 mA) can trigger fibrillation in the heart.
Larger currents will permanently damage the heart



Page 54 Hayt, Kemmerly, Durbin

Electrical Circuit

Analyze circuit



Questions
Compute current given voltage
Compute light intensity generated from bulb

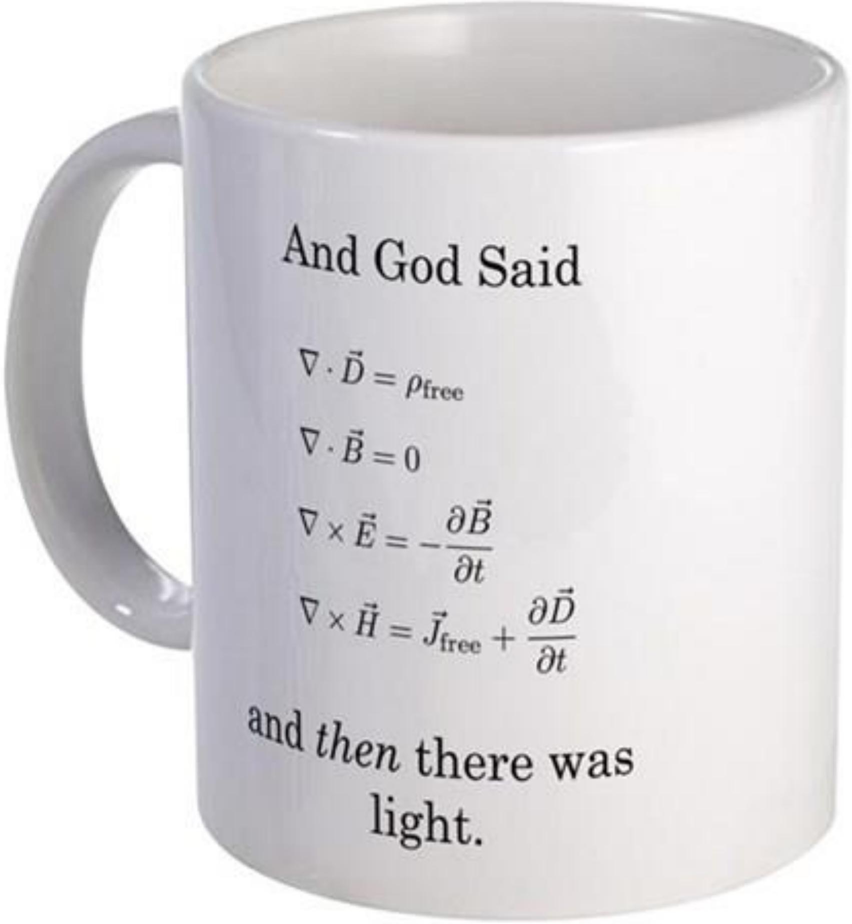
How to solve these questions?

Back to Maxwell's Equations

- Should we write Maxwell's equations everytime

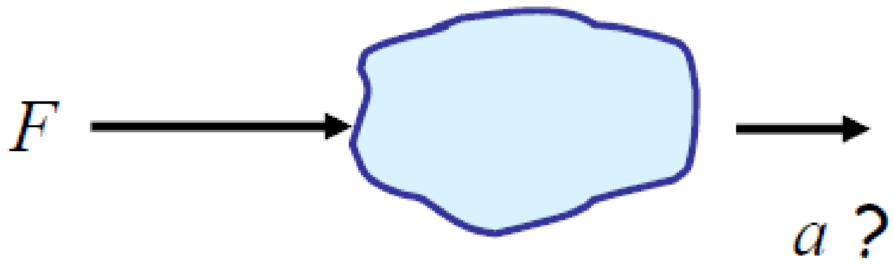
- Gainful employment of Maxwell's equations to build interesting systems

- Create an abstraction layer
  - Avoid dealing with Maxwell's eq



Abstraction

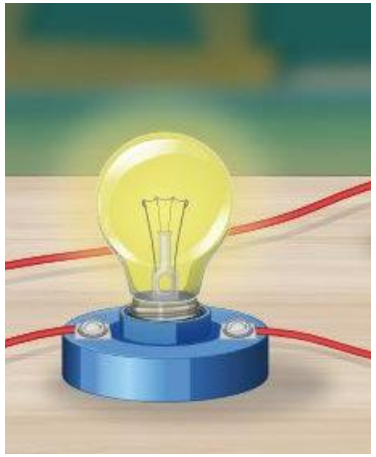
- Example: point mass abstraction



- What is the acceleration? $a = F/m$
- Ignoring the object's shape, rigidity, temperature
- Point-mass discretization or *lumping*
- Useful at all levels

Lumped Circuit Abstraction

1. $\nabla \cdot \mathbf{D} = \rho_V$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$
4. $\nabla \times \mathbf{H} = \dfrac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$



V	I
3	1
6	2
9	3
12	4

Ohm's Law

$$V = I * R$$

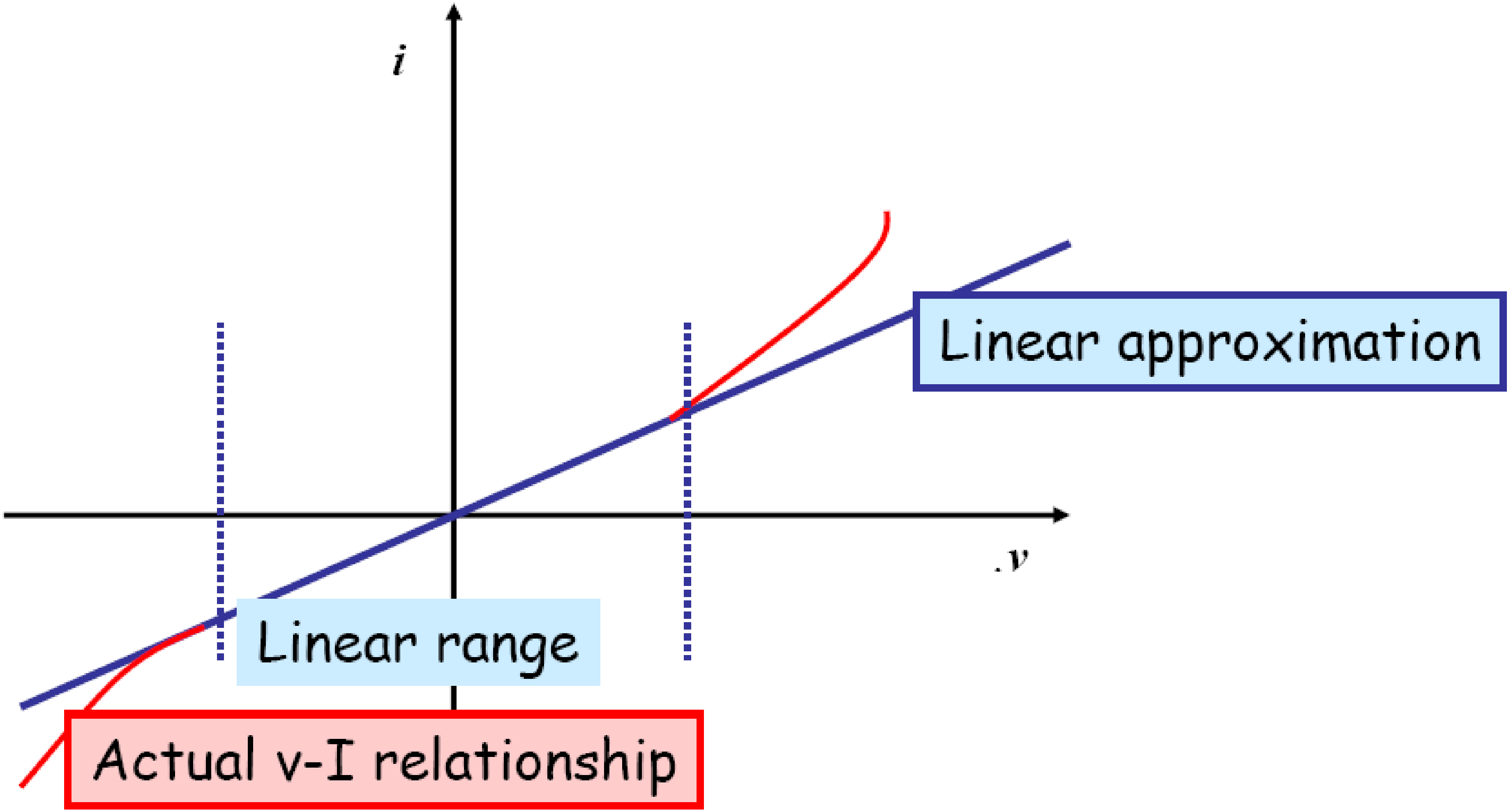
voltage in volts

current in amps

resistance in ohms

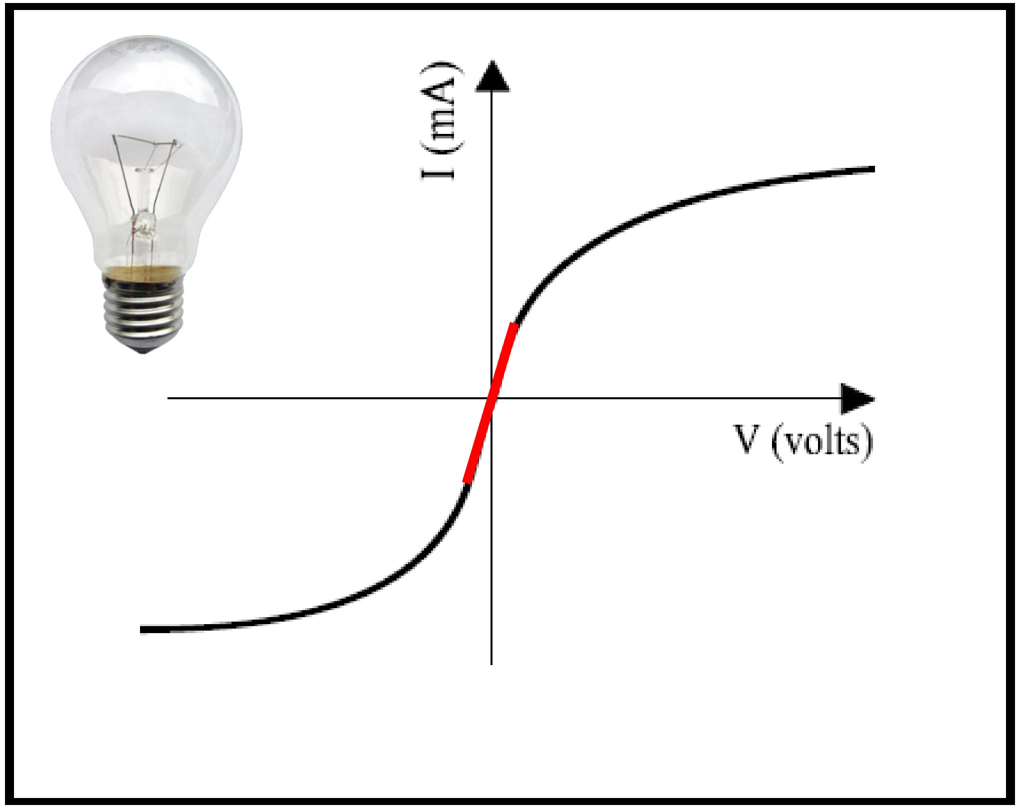
Bulb's behavior

Any electrical element which obeys ohms law can be modeled as a resistor



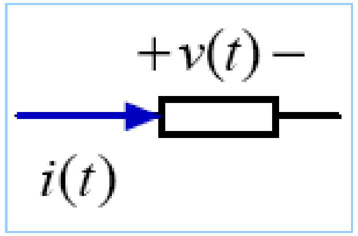
Can we model an electric bulb as a resistor?

Bulb's behavior



Even though characteristics are non-linear, over a certain range, the bulb can be thought of as a resistor

Resistor



$$v(t) = R \times i(t)$$

Ohm's law

The constant, *R, is called the resistance of the component and is* measured in units of Ohm (Ω)

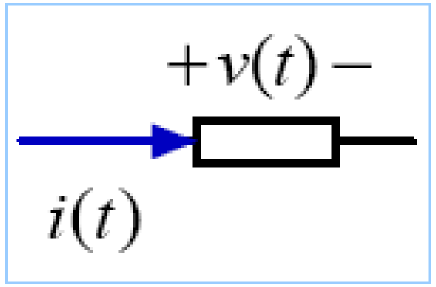
Standard Multiples of Ohm

$M\Omega$	Mega Ohm ($10^6\,\Omega$)
$k\Omega$	Kilo Ohm ($10^3\,\Omega$)

Georg Simon Ohm
1789-1854

Resistor Symbol:

Conductance



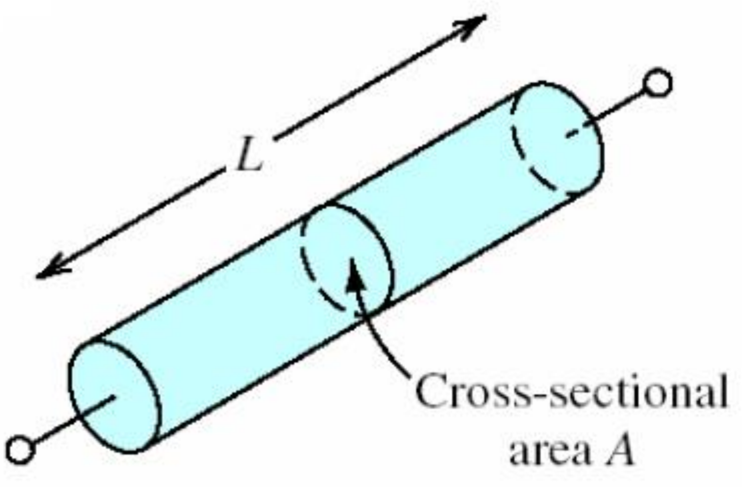
$$v(t) = R \times i(t)$$

$$i(t) = \frac{v(t)}{R} = G \times v(t)$$

G = 1/R is called conductance and its unit is Siemens (S)

Ernst Werner von Siemens
1816-1892

Resistance Related to Physical Parameters



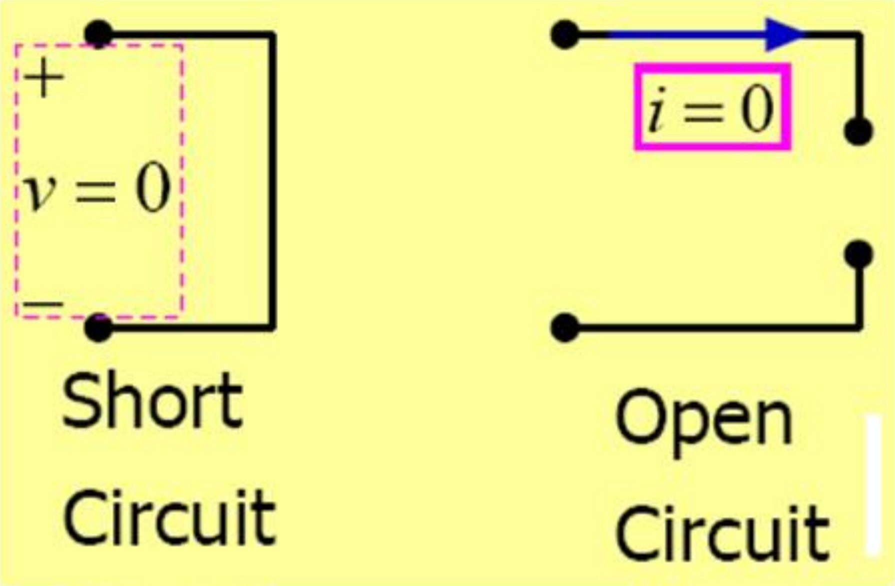
$$R = \rho \times \frac{L}{A}$$

Resistance is affected by the dimensions and geometry of the resistor as well as the particular material used

ρ is the resistivity of the material in ohm meters [Ω-m]
– Conductors (Aluminum, Carbon, Copper, Gold)
– Insulators (Glass, Teflon)
– Semiconductors (Silicon)

Short vs Open Circuit

Two special resistor values

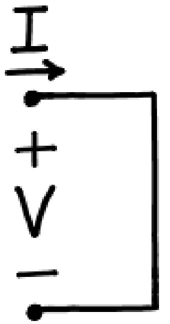


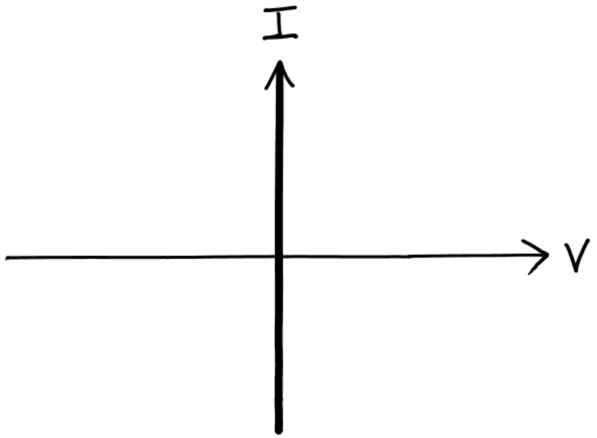
Short Circuit	Open Circuit
$R = 0$	$R = \infty$
$G = \infty$	$G = 0$

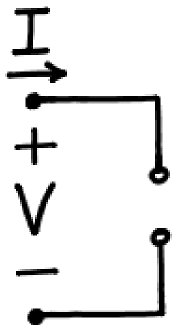
$$R = \frac{v}{i}$$

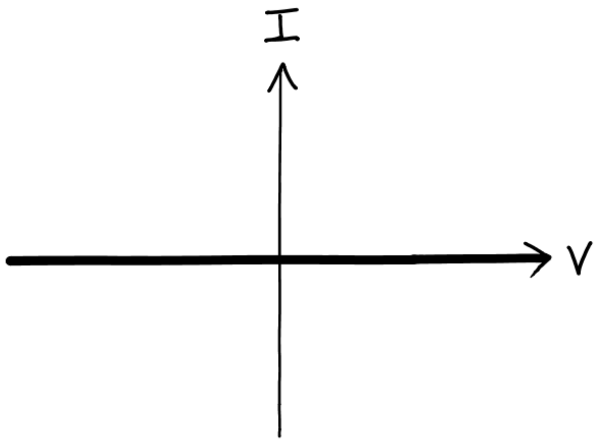
$$G = \frac{i}{v}$$

Short & open circuit

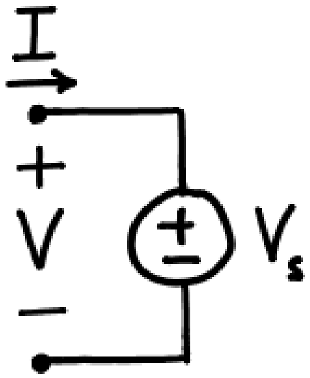


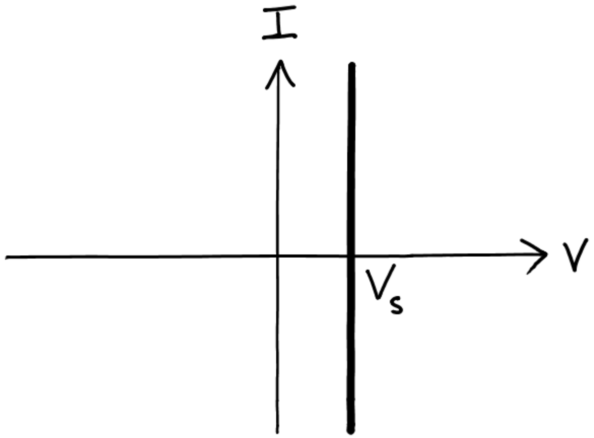




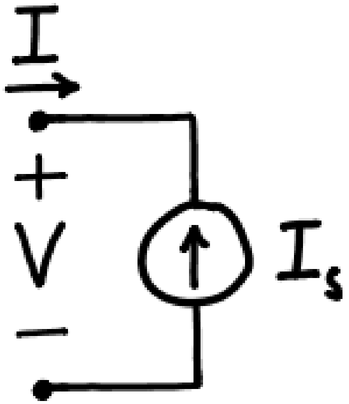


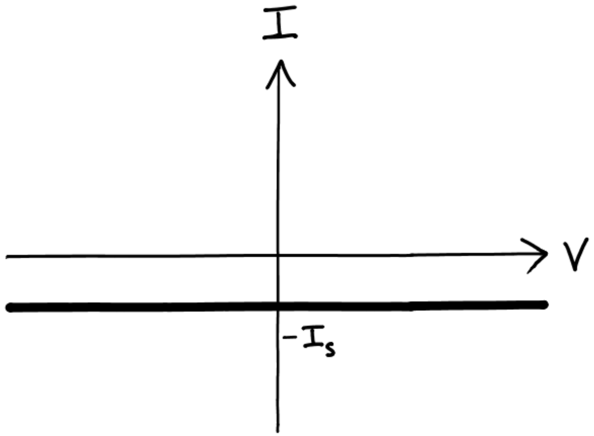
Voltage Source





Current Source

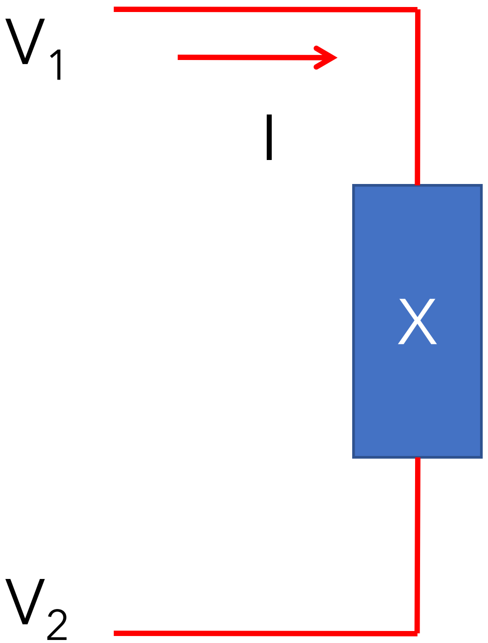




Power

- A battery stores energy (measured in Joules)
- Power delivered by the battery = V x I
- Power delivered by battery when current flows out of the positive terminal (discharging)
- Otherwise, battery consumes energy (charging)

Variable Convention



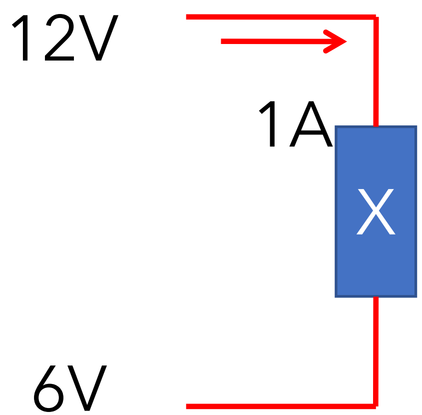
$$P = (V_1 - V_2) \times I$$

If $V_1 > V_2$ then P is positive and it means that power is being delivered to the electrical element X

If $V_1 < V_2$ then P is negative and it means that power is being extracted from the electrical element X.

X is a source of power !

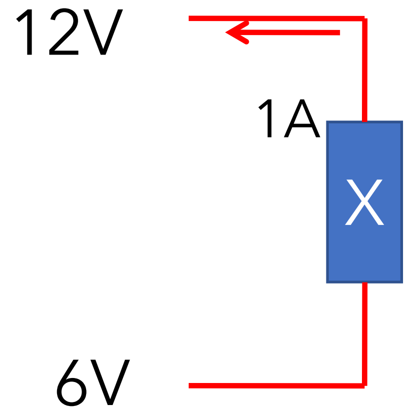
Associated variables convention



P = ?

$$P = (V_1 - V_2) \times I$$
$$= (12 - 6) \times 1 = 6W$$

Power is being delivered to the electrical element X



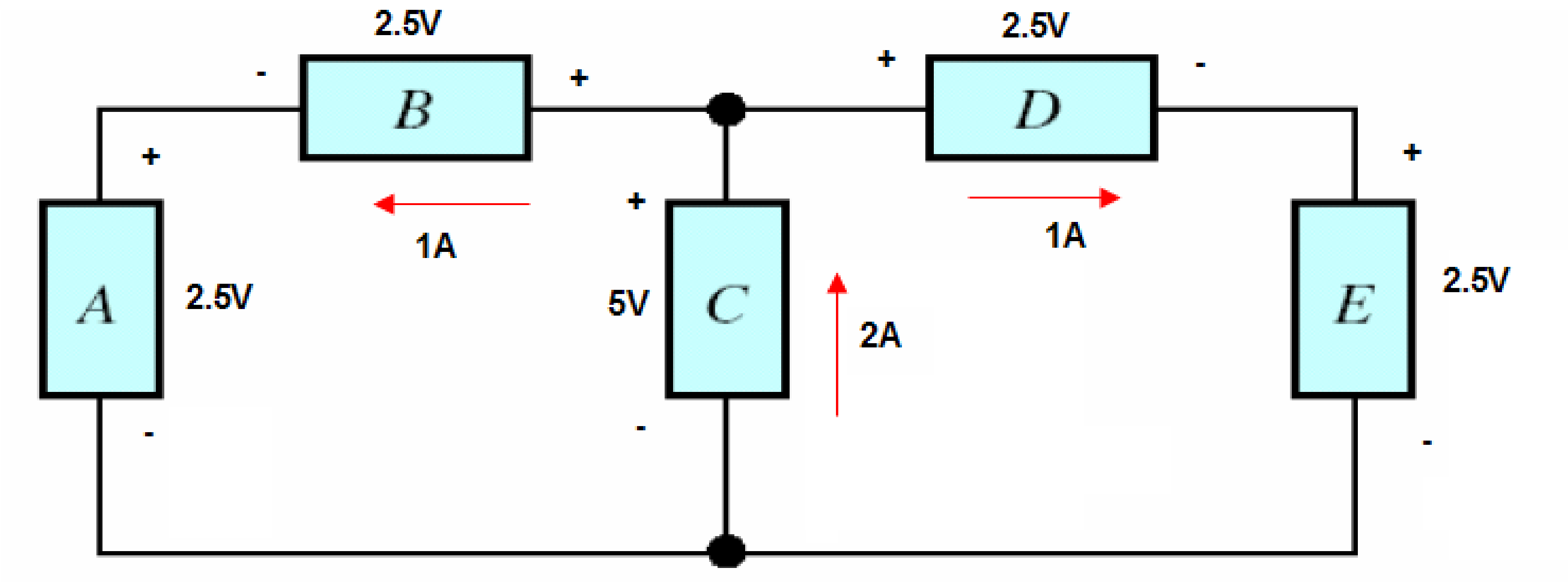
P = ?

$$P = (V_1 - V_2) \times I$$
$$= (12 - 6) \times -1 = -6W$$

Power is supplied by element x instead of dissipation

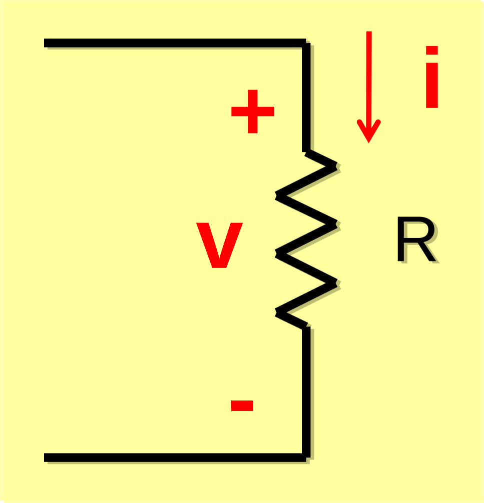
Spot the battery!

- Given that there is only one battery, which one is it?



A battery is a source of power, so power dissipated is negative

Power dissipated in a resistor



$$v = i \times R$$

$$i = \frac{v}{R}$$

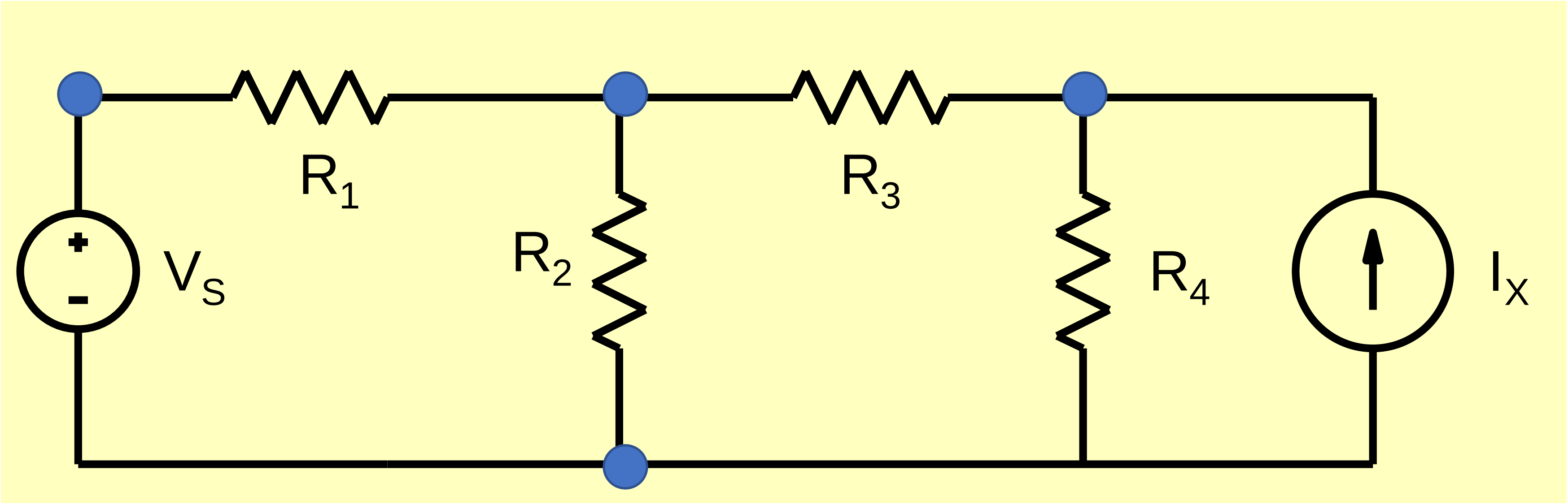
$$P = v \times i$$

$$P = i^2 \times R$$

$$P = \frac{v^2}{R}$$

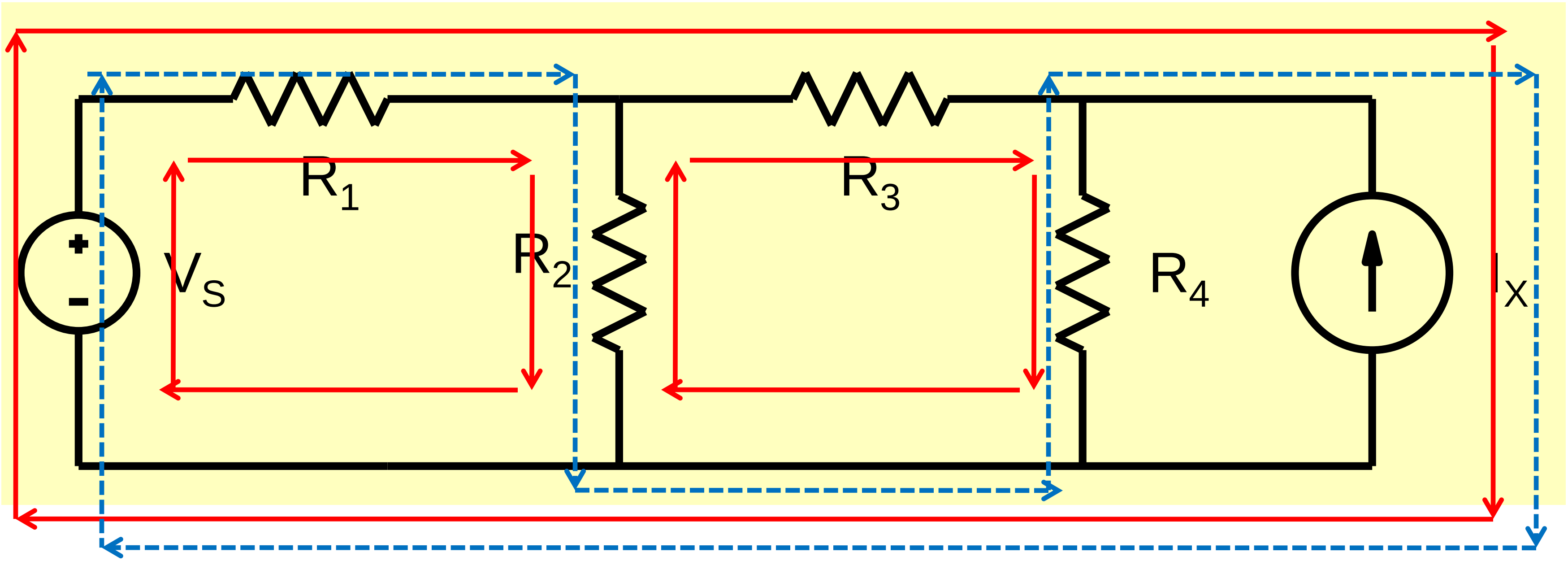
Nodes

Node: A point where 2 or more circuit elements are connected.



What is a Loop?

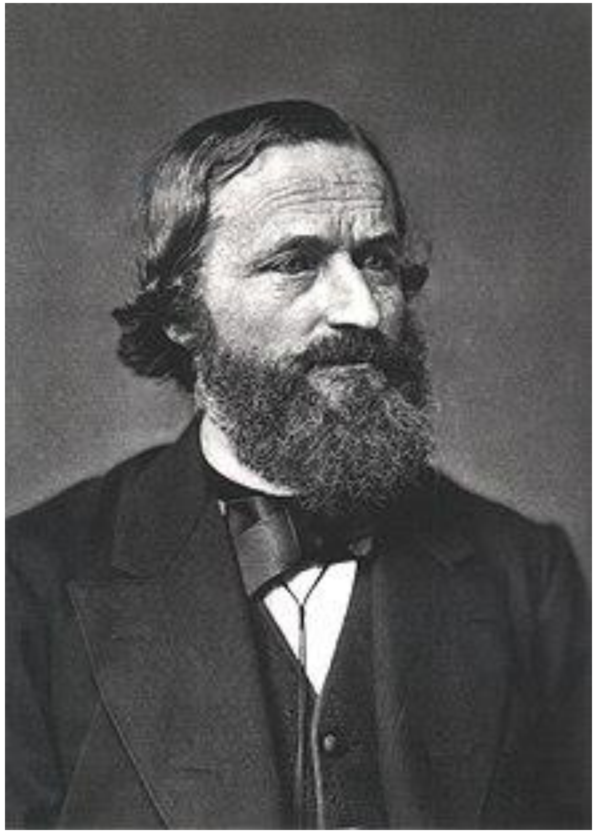
A ***loop is formed by tracing a closed path*** through circuit elements without passing through any intermediate node more than once



This is not a valid loop !

Circuit Analysis

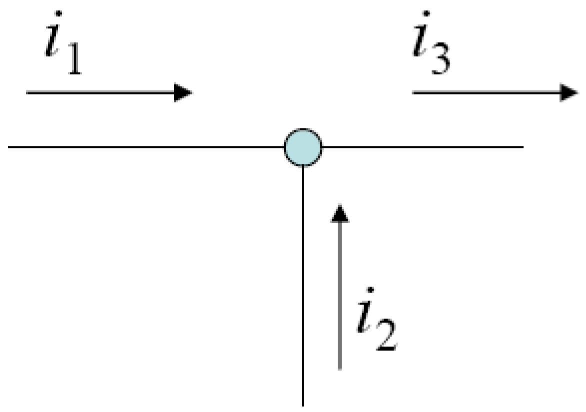
- Kirchhoff's Laws
- KCL and KVL
- Conservation of Charge and Energy



Gustav Kirchhoff

Kirchoff's Current Law (KCL)

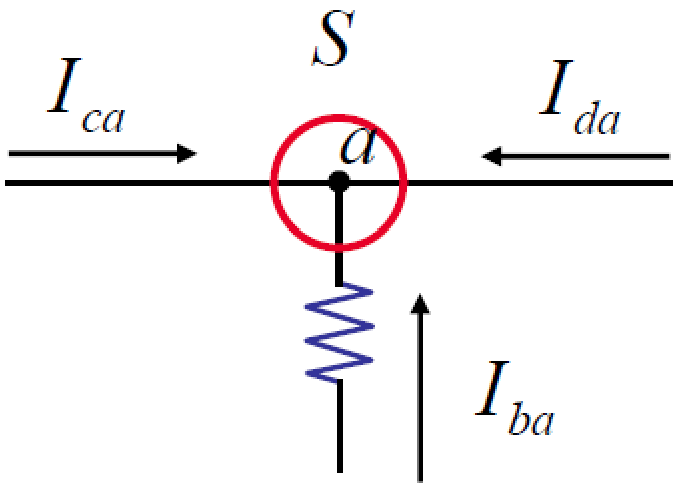
Sum of currents entering a node is equal to sum of currents leaving a node



$$i_1 + i_2 = i_3$$

A direct result of conservation of charge

Kirchhoff's Current Law (KCL)

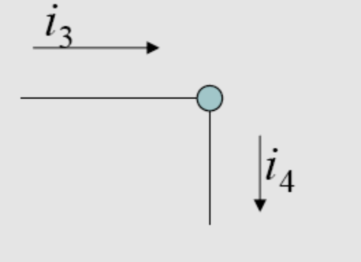


$$I_{ca} + I_{da} + I_{ba} = 0$$

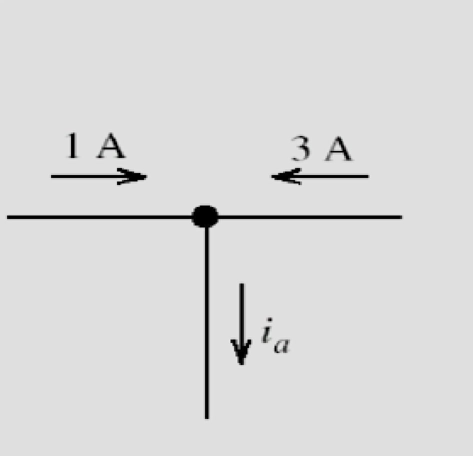
At any node in a circuit, the sum of all current arriving is 0

$$\boxed{\sum_{1}^{N} i_j = 0}$$

KCL: examples



$$i_3 = i_4$$



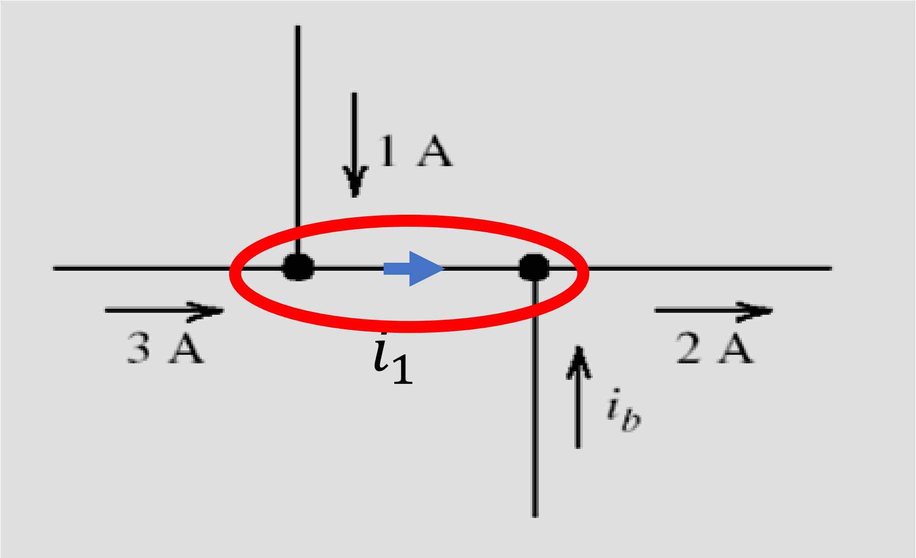
(a)

$$1 + 3 - i_a = 0$$

$$i_a = 4A$$

KCL: examples

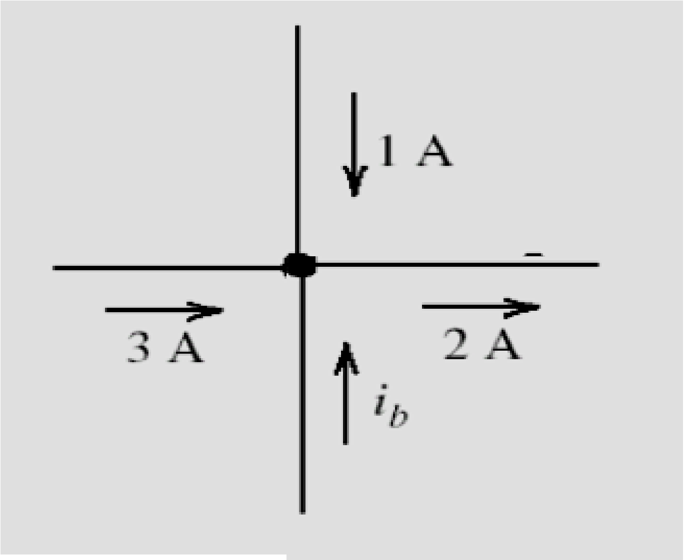
$1 + 3 - i_1 = 0$



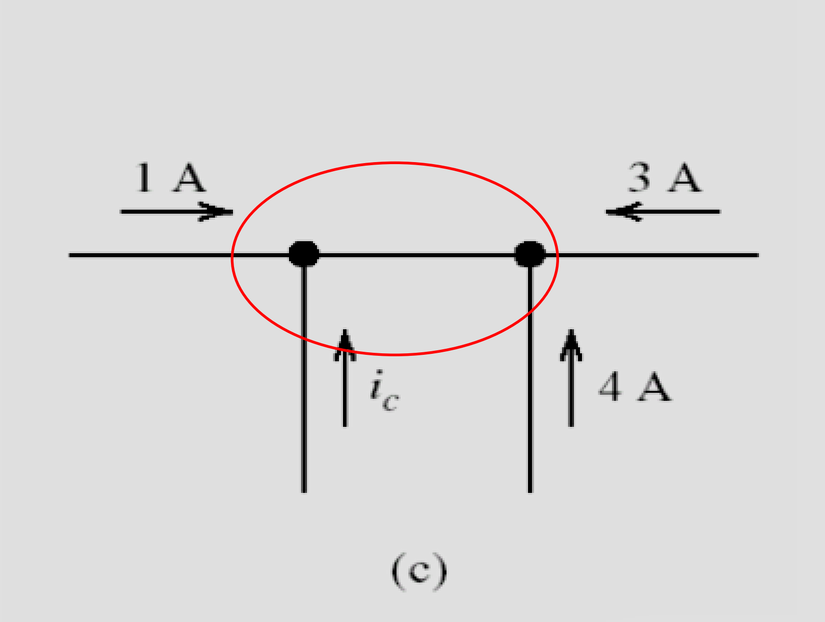
$i_b - 2 + i_1 = 0$

$1 + 3 + i_b - 2 = 0$

$i_b = -2A$



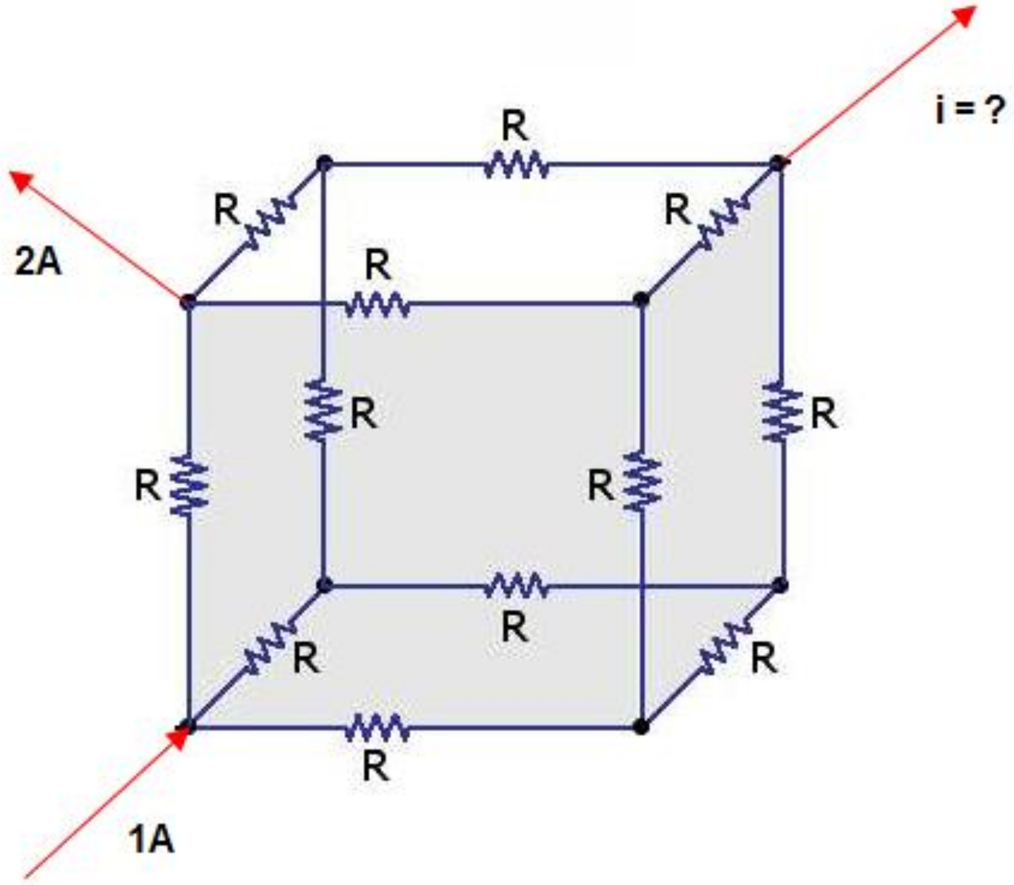
KCL: combining nodes



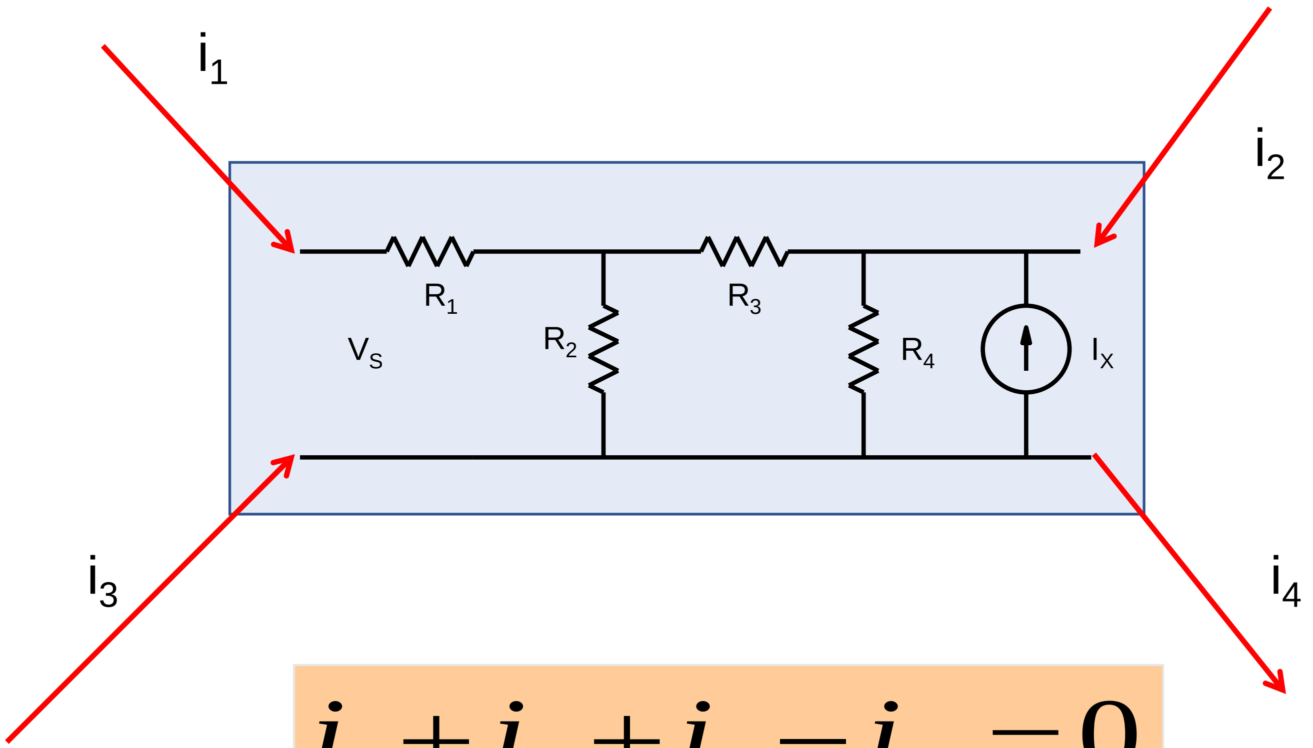
$$1 + 3 + i_c + 4 = 0$$

$$i_c = -8A$$

KCL: generalization



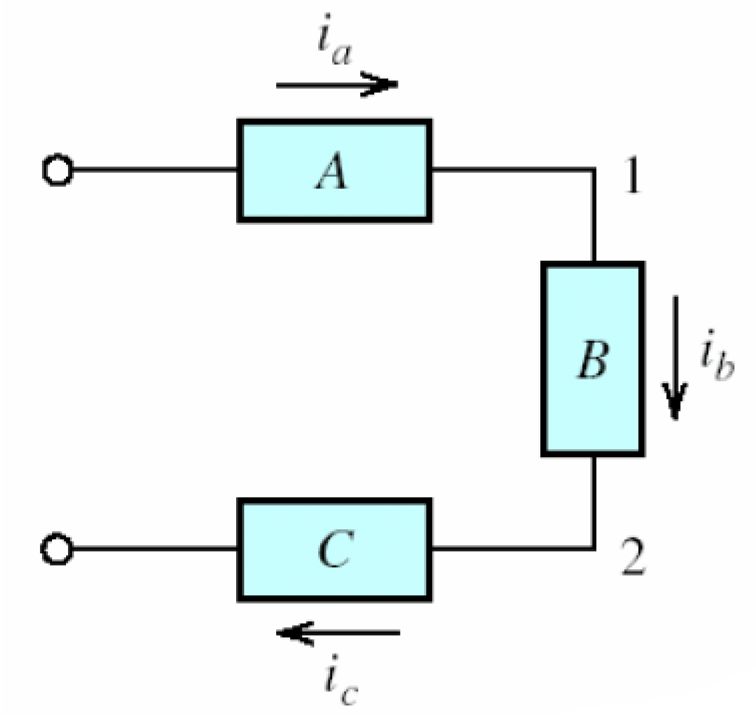
KCL: general form



$$i_1 + i_2 + i_3 - i_4 = 0$$

Series Circuit

Two elements are connected in series if there is no other element connected to the node joining them



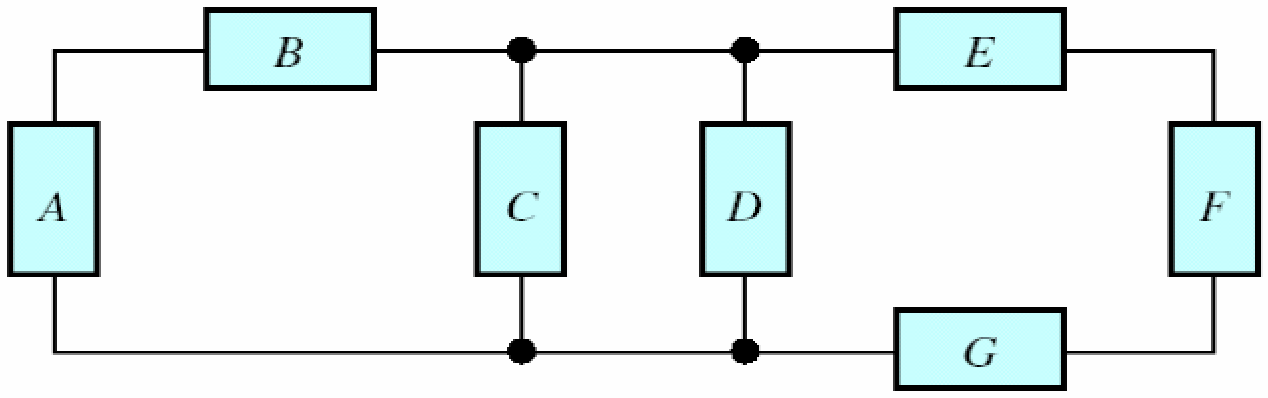
A, B and C are in series

The elements have the same current going through them

$$i_a = i_b = i_c$$

Example:

Identify the groups of elements connected in series



A and B are in series

E, F and G are in series

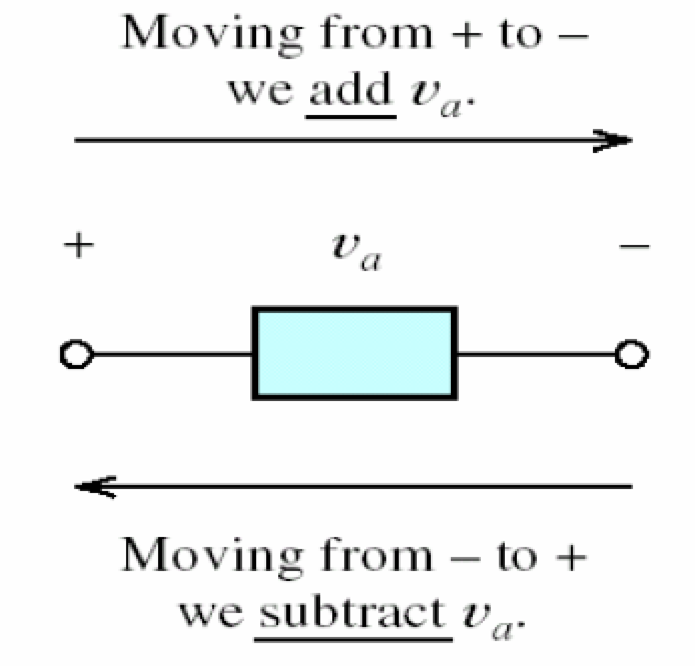
Kirchhoff's Voltage Law (KVL)

The algebraic sum of the voltages equals zero for any closed path (loop) in an electrical circuit.

In applying KVL to a Loop

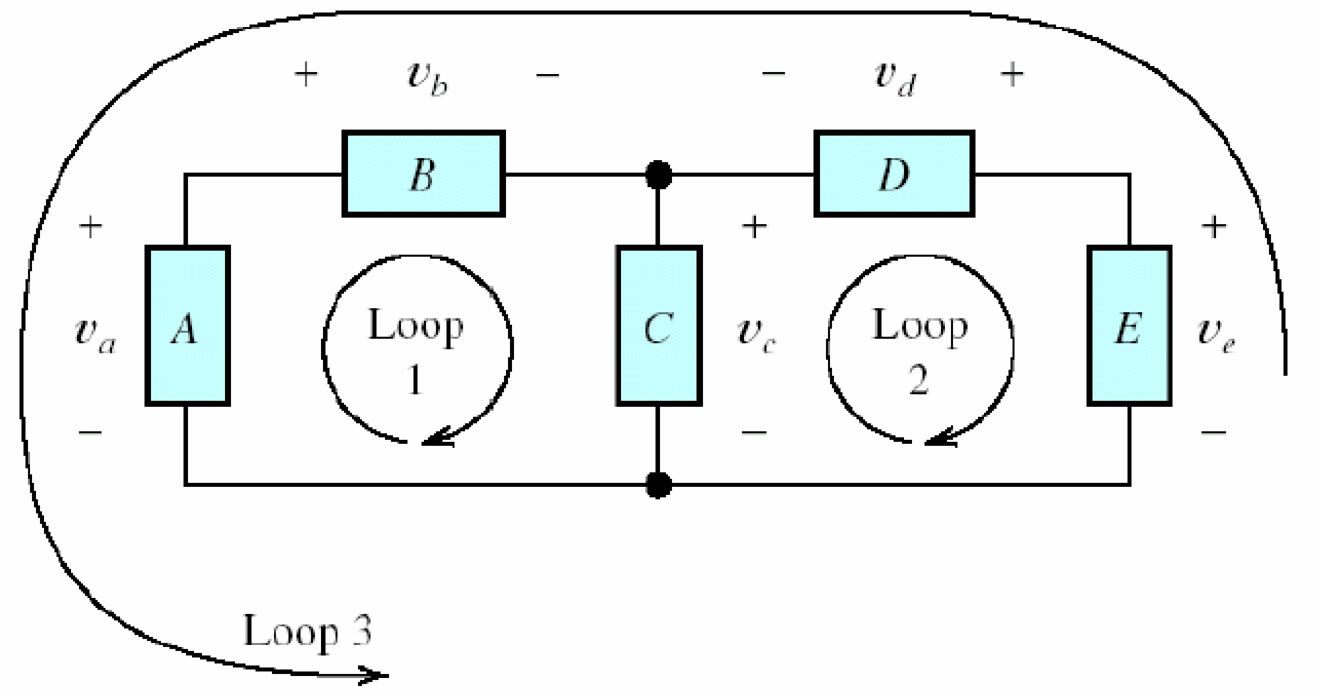
voltages are added (or subtracted)

depending on their polarities relative to the direction of travel around the loop



Conservation of energy!

KVL: example



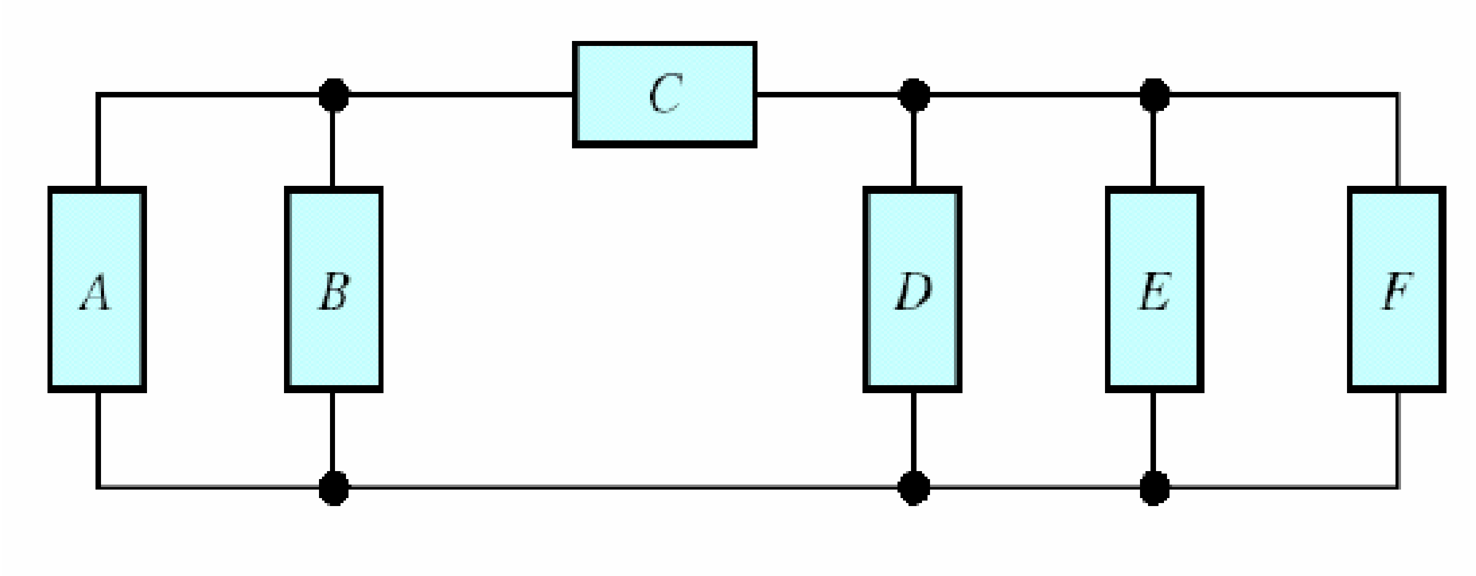
$$\text{Loop1}: -v_a + v_b + v_c = 0$$

$$\text{Loop2}: -v_c - v_d + v_e = 0$$

$$\text{Loop3}: - v_e + v_d - v_b + v_a = 0$$

Parallel Circuits

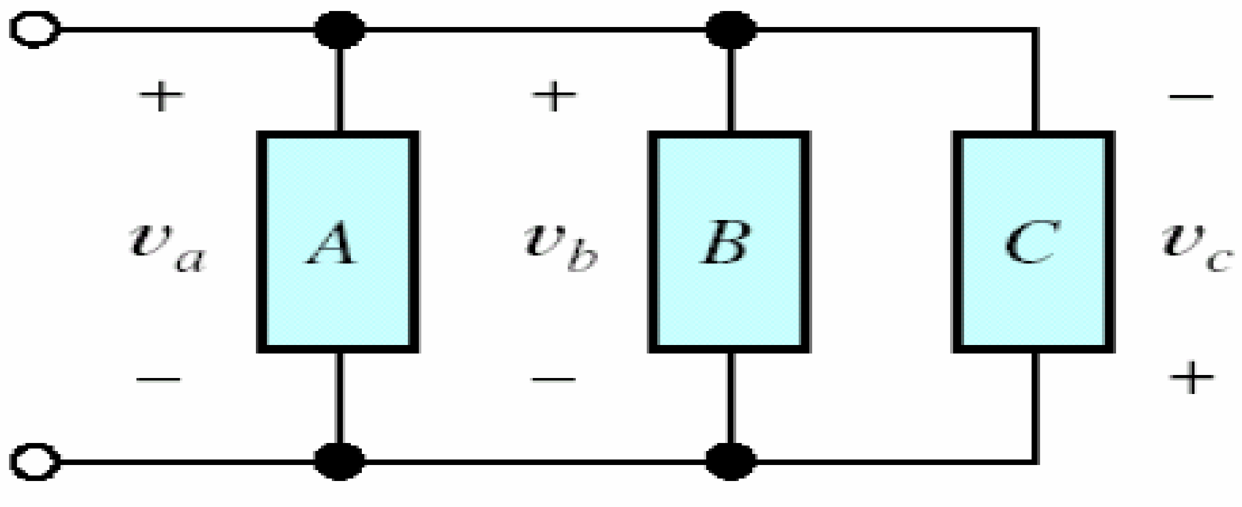
Two elements are connected in parallel if both ends of one element are connected directly to corresponding ends of the other



A and B are connected in parallel

D, E and F are connected in parallel

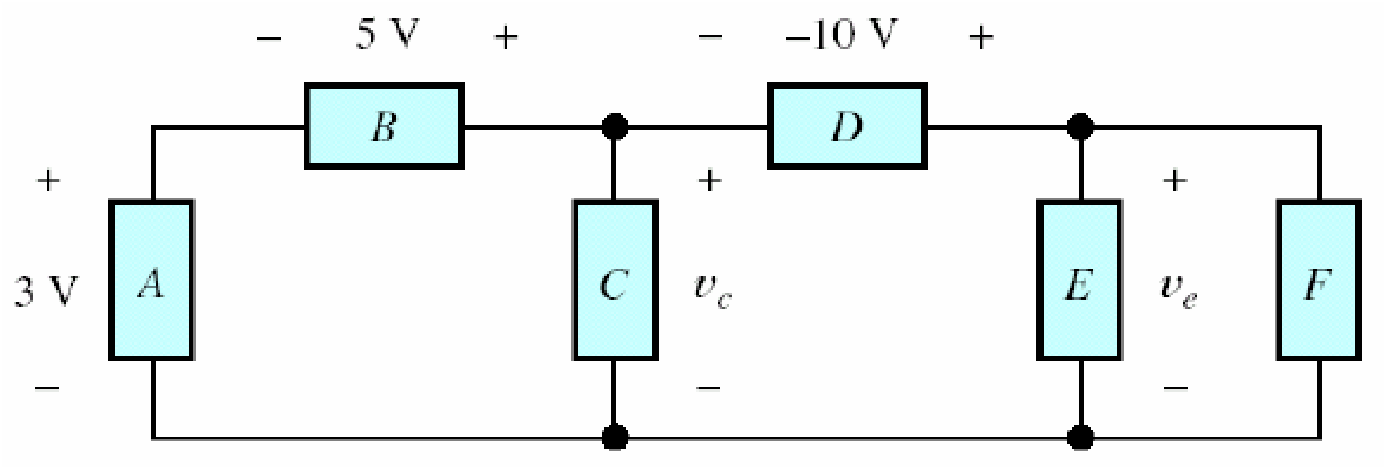
The voltage across parallel elements are equal (both magnitude and polarity)



$$v_a = v_b = -v_c$$

Example

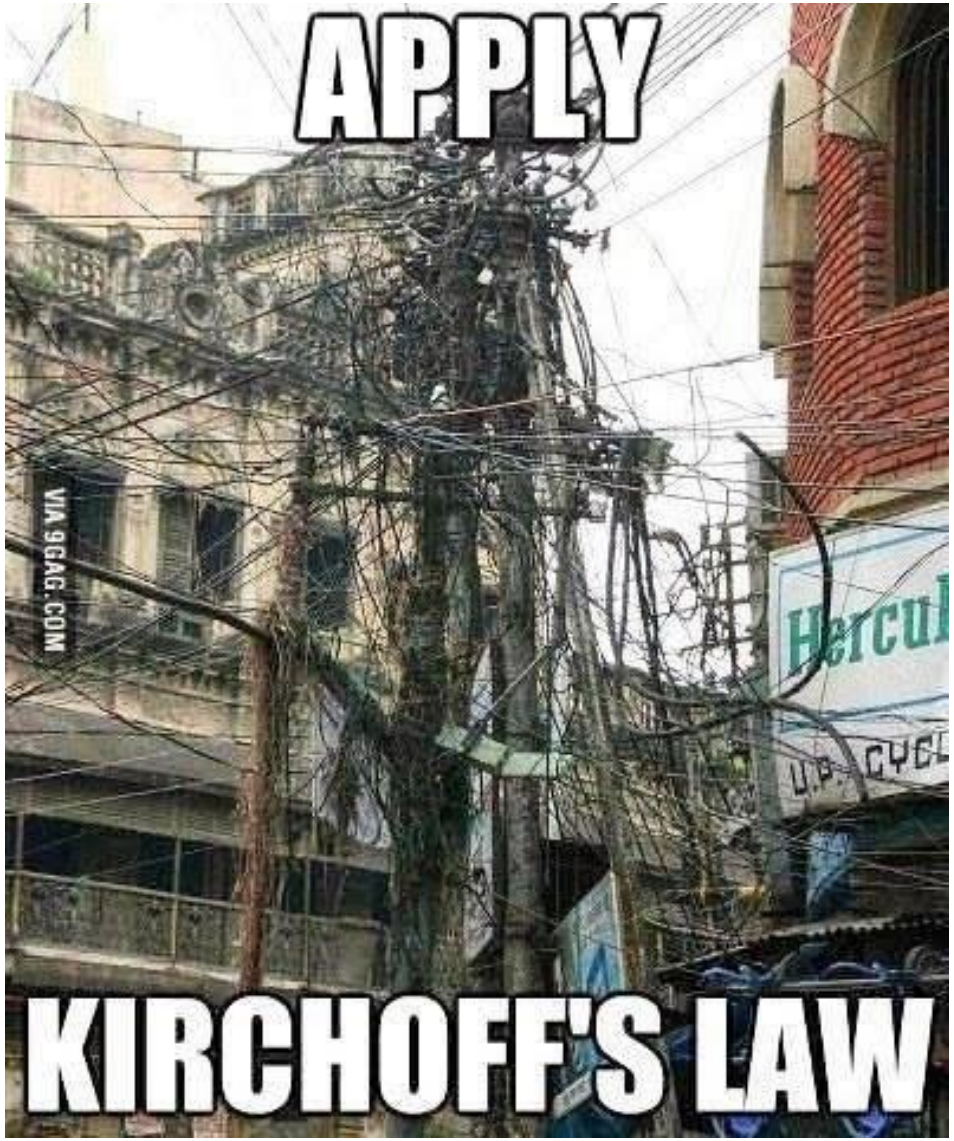
Use KVL to find v_c and v_e



$$-3-5+v_c=0 \Rightarrow v_c=8V$$

$$-v_c-(-10)+v_e=0 \Rightarrow v_e=-2V$$

Ready to use KCL-KVL?



Tidy circuits are easier to understand