# BME2301 - Circuit Theory

## The Instructors:

Dr. Görkem SERBES (C317)

gserbes@yildiz.edu.tr

https://avesis.yildiz.edu.tr/gserbes/

## Lab Assistants:

Nihat AKKAN

nakkan@yildiz.edu.tr

https://avesis.yildiz.edu.tr/nakkan

# LECTURE 1

# Course Outline

**1. Introduction.**

Lumped circuit elements, Levels of abstraction, What are the circuits?, Course objectives.

**2. Basic Concepts.**

Units, Charge, Current, Voltage, Power, Conservation of Energy, Circuit Elements, Networks vs. Circuits, Ohm's Law, .

**3. Voltage and Current Laws.**

Circuit Terminology, Kirchhoff's Current Law, Kirchhoff's Voltage Law, The Single-Loop Circuit, Conservation of Energy, The Single-Node-Pair Circuit, Series Circuits, Parallel Circuits, Voltage Division, Current Division.

**4. Nodal and Mesh Analysis.**

Nodal (or "Node-Voltage") Analysis, Nodal Analysis with Supernodes, Mesh (Current) Analysis, Mesh Analysis with Supermeshes, Equivalent Practical Sources.

**5. Linearity & Superposition.**

Linearity, Superposition, Superposition: Voltage Sources, Superposition: Current Sources, Practical Voltage Sources, Practical Current Sources.

**6. Thevenin & Norton Equivalents.**

Thevenin Equivalent, Power from a Practical Source, Maximum Power Transfer .

**7. The Operational Amplifier.**

The Operational Amplifier, Inverting Amplifier, Noninverting Amplifier, Voltage Follower, Summing Amplifier, Difference Amplifier, Op-Amp Cascades, Op-Amp Parameters, Common Mode Rejection, Saturation, An instrumentation amplifier.

# Course Outline

**8. Capacitors and Inductors.**

Capacitance, Capacitor Current & Voltage, Capacitor Characteristics, Inductance, Inductor Current & Voltage, Inductor Characteristics, Inductor Energy Storage, DC Capacitor Circuits, DC Inductor Circuits.

**9. Basic RL and RC Circuits.**

The Source-Free RL Circuit, The Source-Free RC Circuit, Unit-Step Definition, Driven RL Circuit, Driven RC Circuit.

**10. RLC Circuits.**

Parallel RLC Circuit, Series RLC Circuit, RLC Solution: Over-damped, RLC Solution: Critically Damped, RLC Solution: Under-damped, The Complete Response Of The RLC Circuit.

**11. AC Analysis.**

Complex numbers, phasors, impedance, admittance, Sinusoidal steady-state; Ohm's Law, KVL, KCL for AC circuits, Sinusoidal steady-state: Thevenin, superposition, examples.

**12. The Frequency Response.**

Frequency response: transfer function, logarithms, Bode plots.

Frequency response: resonance, passive & active filter design

**13. Laplace Transform.**

Laplace: introduction to transforms, inverse transform.

Laplace: theorems, solving differential equations

**14. s-Domain analysis**

s-Domain analysis: transfer functions, poles, zeroes.

s-Domain analysis: nodal, mesh, additional techniques

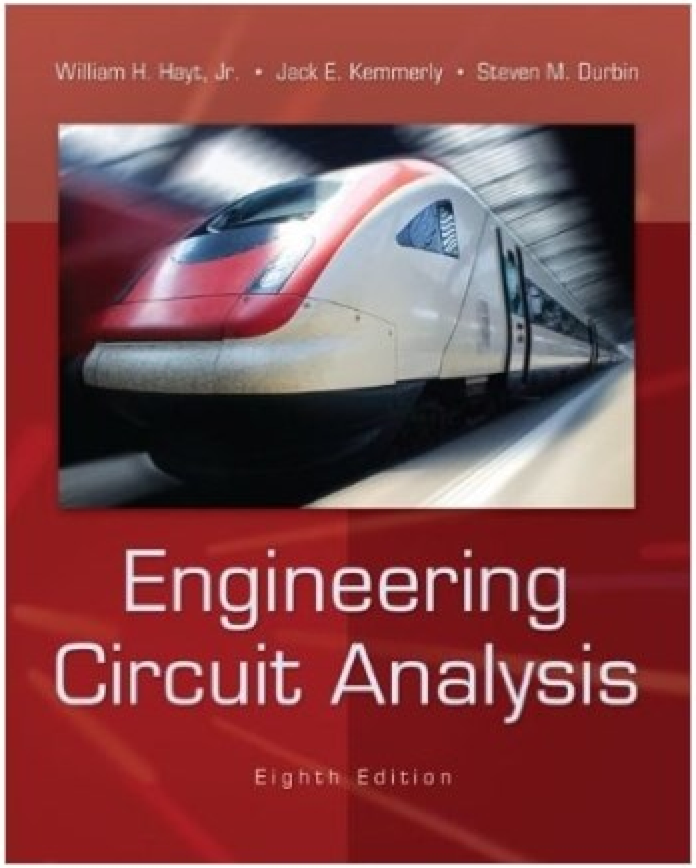
# Main course book

**Engineering Circuit Analysis**

by William Hayt, Jack Kemmerly, Steven Durbin.

Published by McGraw-Hill.

Isbn: 0073529575



# Rules of the Conduct

- No eating /drinking in class
  - *except water*
- Cell phones must be kept outside of class or switched-off during class
  - *If your cell-phone rings during class or you use it in any way, you will be asked to leave and counted as unexcused absent.*
- No web surfing and/or unrelated use of computers,
  - when computers are used in class or lab.

# Rules of the Conduct

- You are responsible for checking the class web page often for announcements.
- Academic dishonesty and cheating will not be tolerated and will be dealt with according to university rules and regulations
  - *Presenting any work, or a portion thereof, that does not belong to you is considered academic dishonesty.*
- University rules and regulations:
  - http://www.ogi.yildiz.edu.tr/category.php?id=17
  - https://www.yok.gov.tr/content/view/544/230/lang,tr_TR/

# Attendance Policy

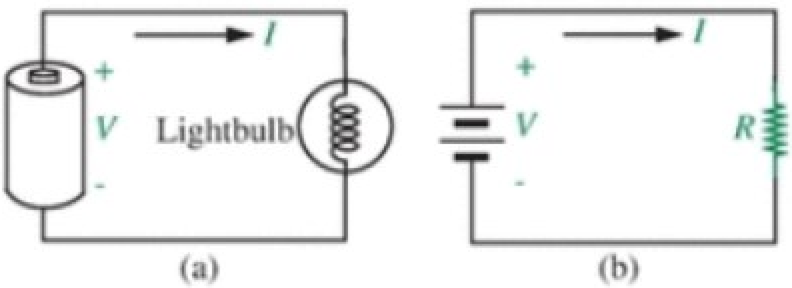
- The requirement for attendance is **70%**.
  - *Hospital reports are not accepted to fulfill the requirement for attendance.*
  - *The students, who fail to fulfill the attendance requirement, will be excluded from the final exams and the grade of* F0 *will be given.*

# Abstraction

- We have electromagnetic phenomena and this data can be expressed by using Maxwell's equations. (Scientific part)
- Electrical engineers create a new abstraction layer on top of Maxwell's equations called the lumped circuit abstraction.
- By using this lumped circuit abstraction electrical and computer systems can be designed.

# Lumped circuit element

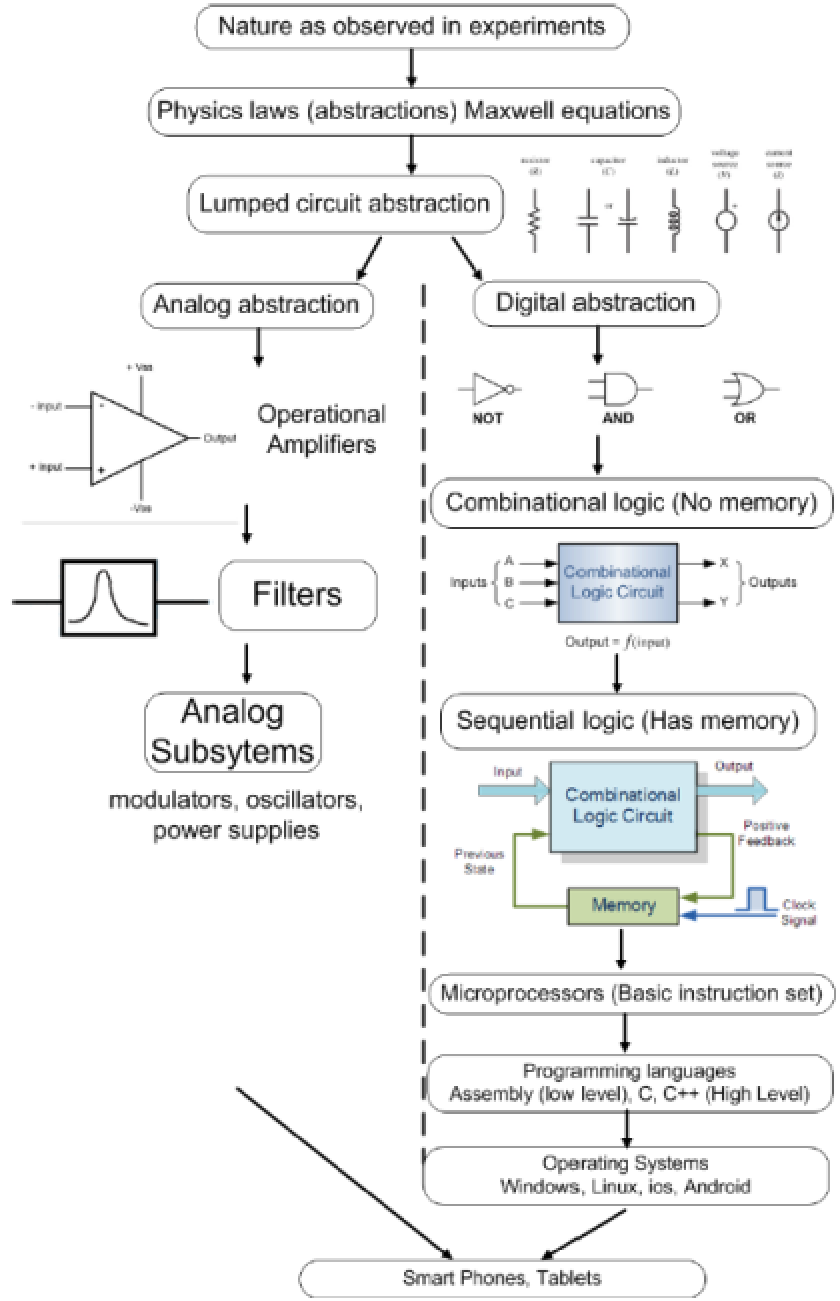
- A lumped circuit element is often used as an abstract representation or a model of a piece of material with complicated behaviour.




a) A simple light bulb circuit b) The lumped circuit represantation

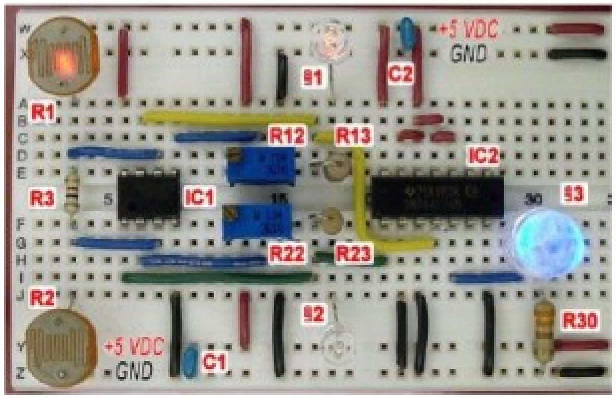
- *R* is a lumped element abstraction for the bulb.
- A lumped element is described by its *v-i* (voltage - current) relation.

# Levels of abstraction

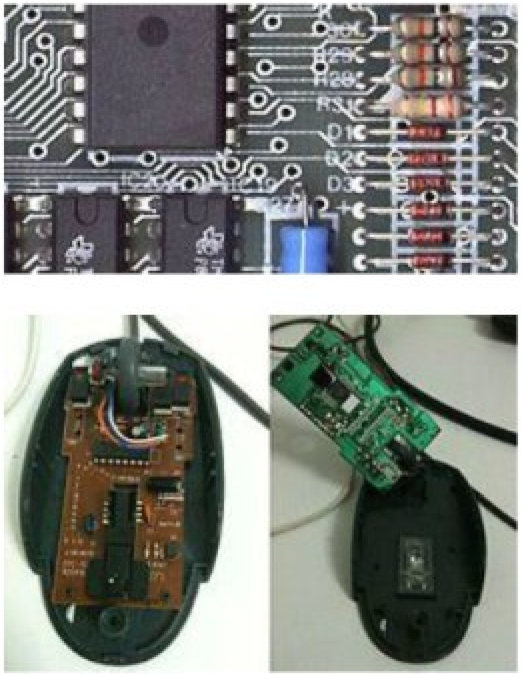


# What are the circuits?

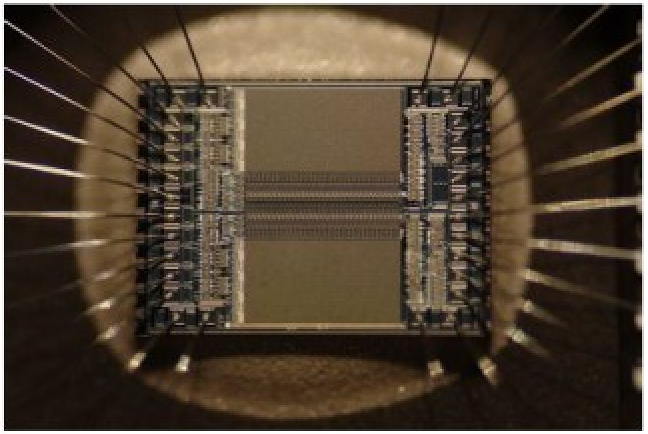
- A *circuit* consists of electrical or electronic components interconnected with metal wires.
- Every electrical or electronic device is a circuit.




Breadboard



Printed Circuit Boards (PCBs)



Integrated Circuits (ICS)

# Linear vs. Nonlinear

- Linear problems are inherently more easily solved than their nonlinear counterparts.
- For this reason, we often seek reasonably accurate linear approximations (or *models) to* physical situations.
- The linear models are more easily manipulated and understood which makes **analysis** and **design** a more straightforward process.

# Analysis and Design

- ***Analysis*** is the process through which we determine the scope of a problem, obtain the information required to understand it, and compute the parameters of interest.
- ***Design*** is the process by which we synthesize something new as part of the solution to a problem.
- A crucial part of design is analysis of potential solutions!

# Units of Measurement

- As engineers, we deal with measurable quantities.
- Measurement must be communicated in a standard language.
- The International System of Units (SI),
  - adopted by the General Conference on Weights and Measures in 1960.
- In SI, there are seven principal units from which the units of all other physical quantities can be derived.

# Units of Measurement

- Six basic SI units and one derived unit relevant to this text.

| Quantity | Basic unit | Symbol |
|---|---|---|
| Length | meter | m |
| Mass | kilogram | kg |
| Time | second | s |
| Electric current | ampere | A |
| Thermodynamic temperature | kelvin | K |
| Luminous intensity | candela | cd |
| Charge | coulomb | C |

# Units of Measurement

- One great advantage of the SI unit is that it uses prefixes based on the power of 10 to relate larger and smaller units to the basic unit.
- For example, the following are expressions of the same distance in meters (m):
  - 600 000 000 mm
  - 600 000 m
  - 600 km

The SI prefixes.

| Multiplier | Prefix | Symbol |
|---|---|---|
| $10^{18}$ | exa | E |
| $10^{15}$ | peta | P |
| $10^{12}$ | tera | T |
| $10^{9}$ | giga | G |
| $10^{6}$ | mega | M |
| $10^{3}$ | kilo | k |
| $10^{2}$ | hecto | h |
| 10 | deka | da |
| $10^{-1}$ | deci | d |
| $10^{-2}$ | centi | c |
| $10^{-3}$ | milli | m |
| $10^{-6}$ | micro | $\mu$ |
| $10^{-9}$ | nano | n |
| $10^{-12}$ | pico | p |
| $10^{-15}$ | femto | f |
| $10^{-18}$ | atto | a |

# Units of Measurement

- The numerical value substituted into an equation must have the unit of measurement specified by the equation.
- For example,
  - consider the equation for the velocity $v = d / t$.
    - v: velocity, *d*: distantance, *t*: time
  - Assume that the following data are obtained for a moving object: $d = 4000$ m, $t = 1$ min and $v$ is desired in km per hour.
  - Incorrect answer:
    - $v = 4000 / 1 = 4000$ kmh
  - Correct answer:
    - $v = 4000 \times 10^{-3} / (1/60) = 240$ kmh

# Units of Measurement

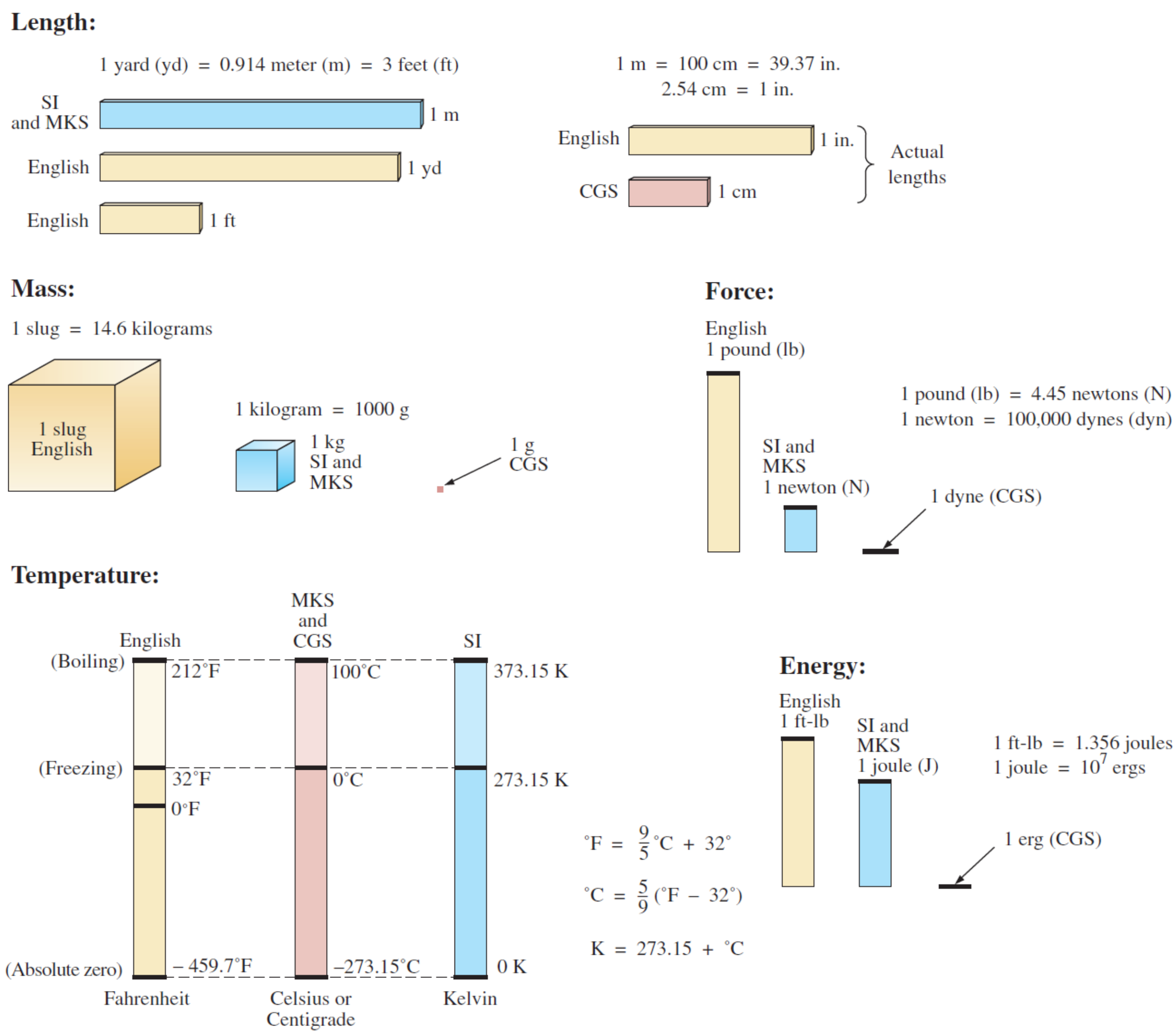
- Before substituting numerical values into an equation, be absolutely sure of the following:
  - Each quantity has the proper unit of measurement as defined by the equation.
  - The proper magnitude of each quantity as determined by the defining equation is substituted.
  - Each quantity is in the same system of units (or as defined by the equation).
  - The magnitude of the result is of a reasonable nature when compared to the level of the substituted quantities.
  - The proper unit of measurement is applied to the result.

# Systems of Units

- Comparison of the English and metric systems of units.

| English | Metric | | |
|---|---|---|---|
| | **MKS** | **CGS** | **SI** |
| *Length:*<br>Yard (yd)<br>(0.914 m) | Meter (m)<br>(39.37 in.)<br>(100 cm) | Centimeter (cm)<br>(2.54 cm = 1 in.) | **Meter (m)** |
| *Mass:*<br>**Slug**<br>(14.6 kg) | Kilogram (kg)<br>(1000 g) | Gram (g) | **Kilogram (kg)** |
| *Force:*<br>**Pound** (lb)<br>(4.45 N) | Newton (N)<br>(100,000 dynes) | Dyne | **Newton (N)** |
| *Temperature:*<br>Fahrenheit (°F)<br>$\left(= \frac{9}{5}°C + 32\right)$ | Celsius or<br>Centigrade (°C)<br>$\left(= \frac{5}{9}(°F - 32)\right)$ | Centigrade (°C) | **Kelvin (K)**<br>K = 273.15 + °C |
| *Energy:*<br>Foot-pound (ft-lb)<br>(1.356 joules) | Newton-meter (N•m)<br>or joule (J)<br>(0.7376 ft-lb) | Dyne-centimeter or erg<br>(1 joule = $10^7$ ergs) | **Joule (J)** |
| *Time:*<br>Second (s) | Second (s) | Second (s) | **Second (s)** |

# Comparison of units of the various systems of units



# Standards of some units

- The meter is defined with reference to the speed of light in a vacuum, which is **299792458** m/s.
  - It was originally defined in 1790 to be 1/**10000000** the distance between the equator and either pole at sea level, a length preserved on a platinum-iridium bar at the International Bureau of Weights and Measures at Sèvres, France.
- The kilogram is defined as a mass equal to 1000 times the mass of one cubic centimeter of pure water at 4°C.
  - This standard is preserved in the form of a platinum-iridium cylinder in Sèvres.

# Standards of some units

- The second is redefined in 1967 as 9**192**631**770** periods of the electromagnetic radiation emitted by a particular transition of cesium atom.
  - It was originally defined as 1/86**400** of the mean solar day.
  - However, Earth's rotation is slowing down by almost 1 second every 10 years.

# Significant Figures, Accuracy, Round off

- Two types of numbers:
  - Exact
    - For example 12 apples
  - Approximate
    - Any reading obtained in the laboratory should be considered approximate
- The precision of a reading can be determined by the number of significant figures (digits) present.
- Accuracy refers to the closeness of a measured value to a standard or known value
- For approximate numbers, there is often a need to round off the result
  - that is, you must decide on the appropriate level of accuracy and alter the result accordingly.
    - For example, $3.186 \cong 3.19 \cong 3.2$

# Powers of ten

- To express very large and very small numbers
- The notation used to represent numbers that are integer powers of ten is as follows:

$$
\begin{aligned}
1 &= 10^0 & 1/10 &= 0.1 = 10^{-1} \\
10 &= 10^1 & 1/100 &= 0.01 = 10^{-2} \\
100 &= 10^2 & 1/1000 &= 0.001 = 10^{-3} \\
1000 &= 10^3 & 1/10{,}000 &= 0.0001 = 10^{-4}
\end{aligned}
$$

# Powers of ten

- Some important mathematical equations and relationships pertaining to powers of ten:

$$\frac{1}{10^n} = 10^{-n} \qquad \frac{1}{10^{-n}} = 10^n$$

$$(10^n)(10^m) = (10)^{(n+m)}$$

$$\frac{10^n}{10^m} = 10^{(n-m)}$$

$$(10^n)^m = 10^{nm}$$

# Powers of ten

- Addition and subtraction

$$A \times 10^n \pm B \times 10^n = (A \pm B) \times 10^n$$

- Multiplication

$$(A \times 10^n)(B \times 10^m) = (A)(B) \times 10^{n+m}$$

- Division

$$\frac{A \times 10^n}{B \times 10^m} = \frac{A}{B} \times 10^{n-m}$$

- Power

$$(A \times 10^n)^m = A^m \times 10^{nm}$$

# Scientific notation vs. Engineering notation

- Scientific notation and engineering notation make use of powers of ten, with restrictions on the mantissa (multiplier) or scale factor (power of ten).
  - Scientific notation requires that the decimal point appear directly after the first digit greater than or equal to 1 but less than 10.
  - Engineering notation specifies that all powers of ten must be multiples of 3, and the mantissa must be greater than or equal to 1 but less than 1000.

# Scientific notation vs. Engineering notation

- Scientific notation example:

$$\frac{1}{3} = 3.3333333333E{-1} \quad \frac{1}{16} = 6.25E{-2} \quad \frac{2300}{2} = 1.15E3$$

$$\frac{1}{3} = 3.33E{-1} \quad \frac{1}{16} = 6.25E{-2} \quad \frac{2300}{2} = 1.15E3$$

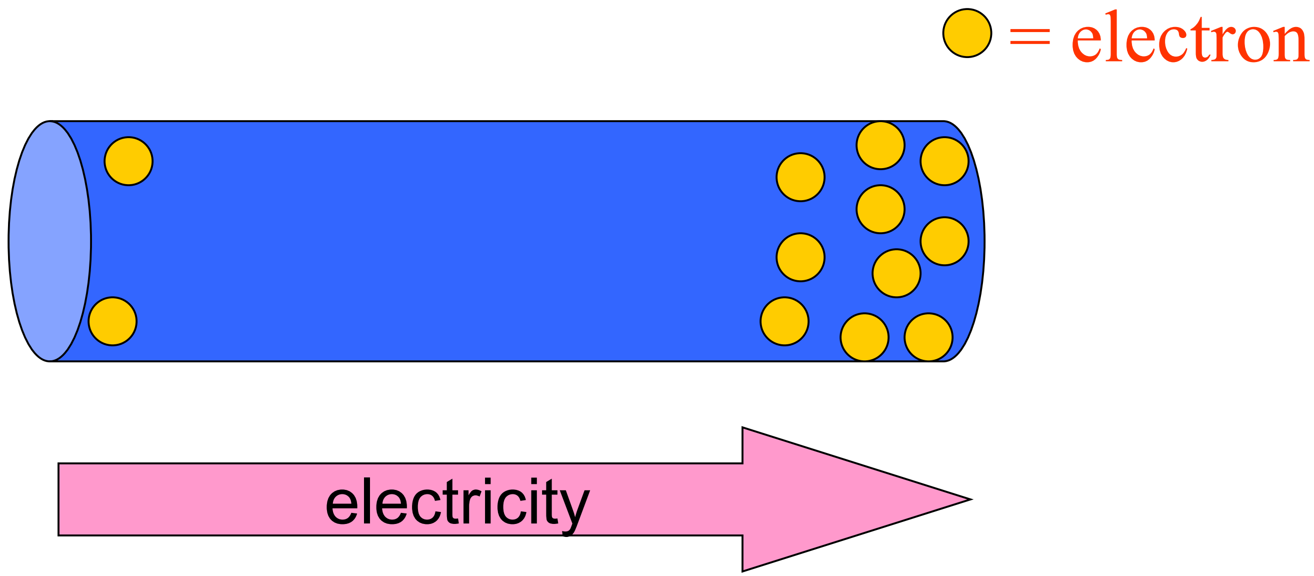
- Engineering notation example:

$$\frac{1}{3} = 333.333333333E{-3} \quad \frac{1}{16} = 62.5E{-3} \quad \frac{2300}{2} = 1.15E3$$

$$\frac{1}{3} = 333.33E{-3} \quad \frac{1}{16} = 62.50E{-3} \quad \frac{2300}{2} = 1.15E3$$

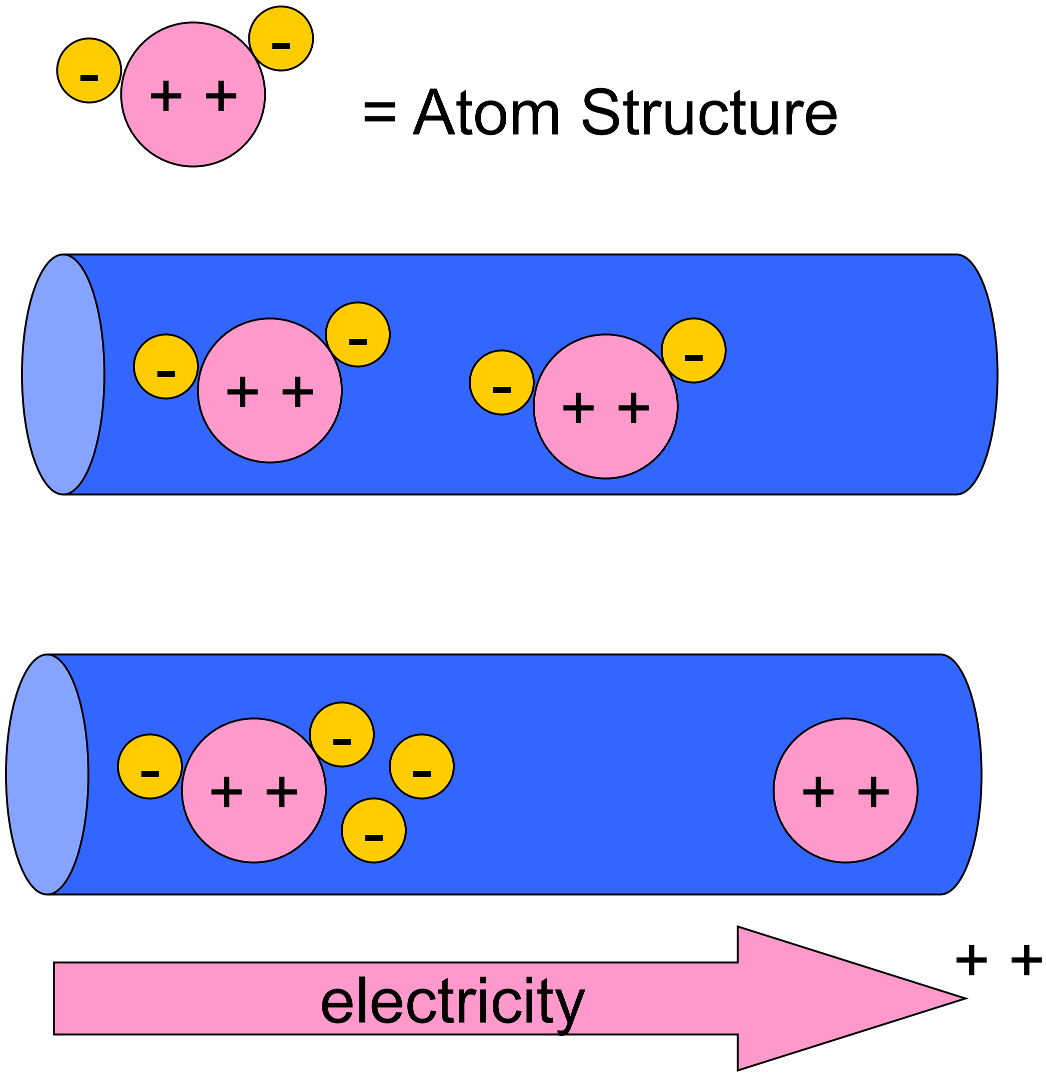
# Electricity

- Electricity is a result from the flow of electrons.




  – Electricity flows in the opposite direction of electron flow.

# Electric Current vs. Electron Current



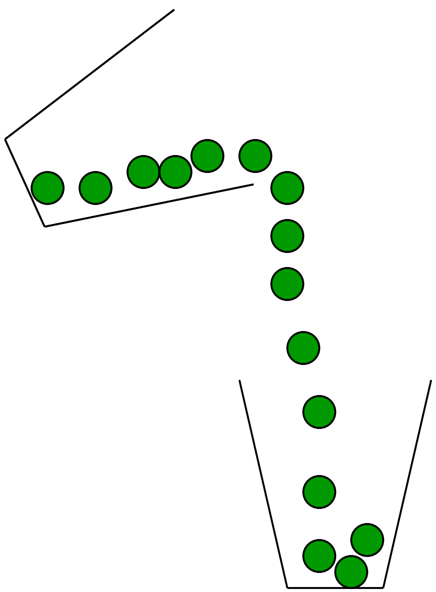
# Electric current

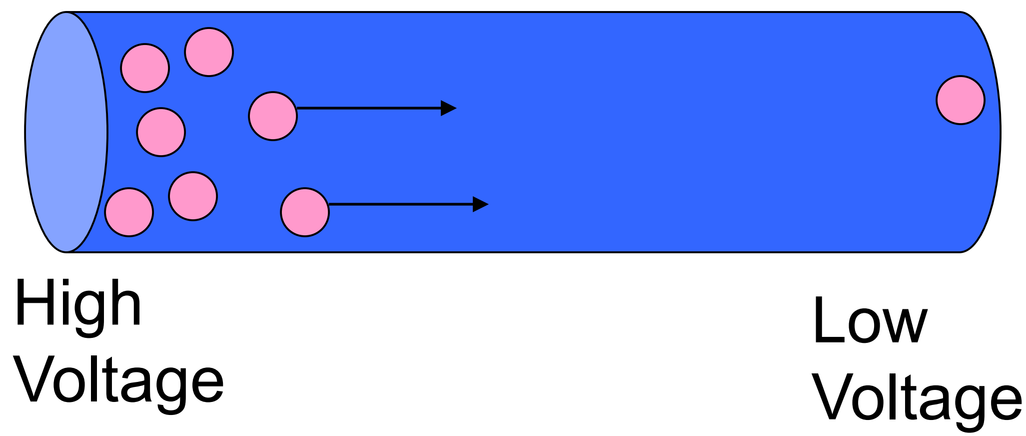
- We cannot see electric current.
- We need a metaphor.
- Which thing has similar property with electricity??


Water

# Electric current

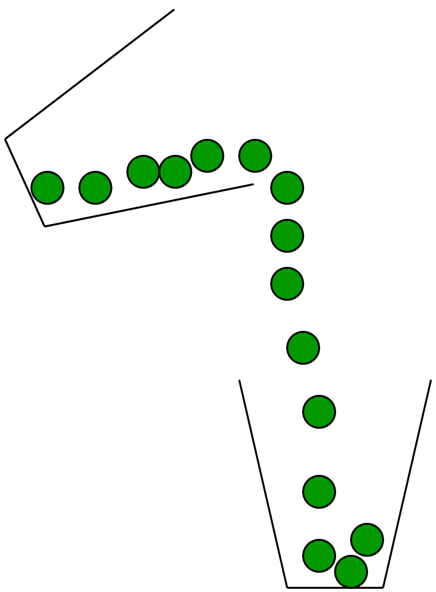
- Electricity is similar to water flow.
  - Water flows from high level to low level.
  - Electricity flows from high voltage to low voltage.

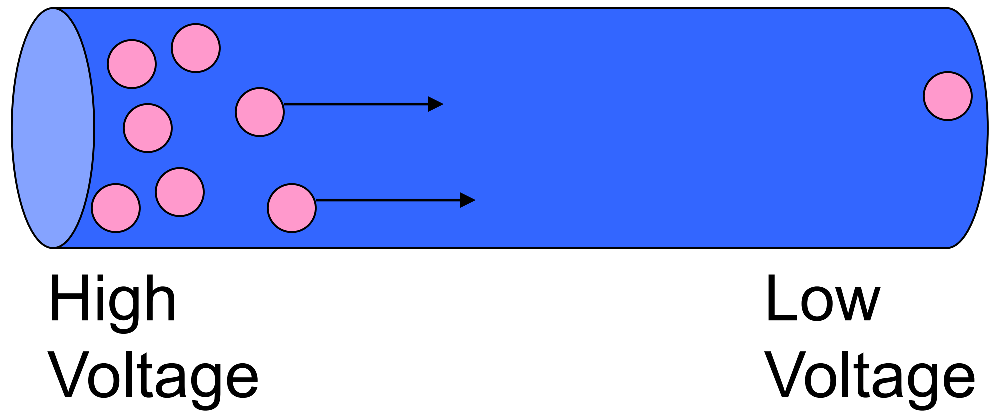




# Measurement of Electricity

- Since we use electricity to do work for us, how can we measure its energy?
- How can we measure the water power?
  - Think about a water gun.





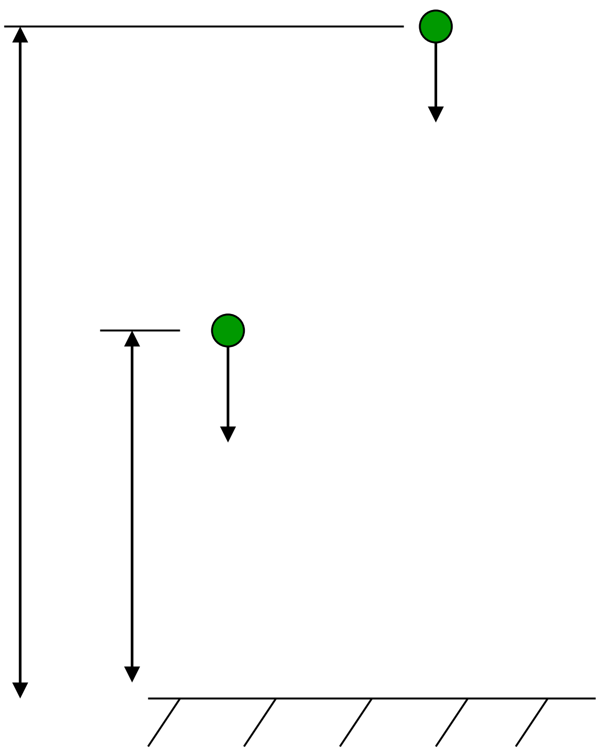

- strong (fast, high kinetic energy) Voltage
- amount of water Current

# Measurement of Electricity

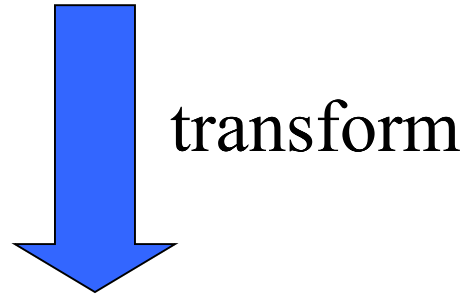
- Imagine the water power at the outlet

# Electric Potential

- Which water drop has more impact force at the ground?



- Potential Energy-Height




- Kinetic Energy-Velocity
  - Electric potential can be compared with the height of the water drop from the reference ground

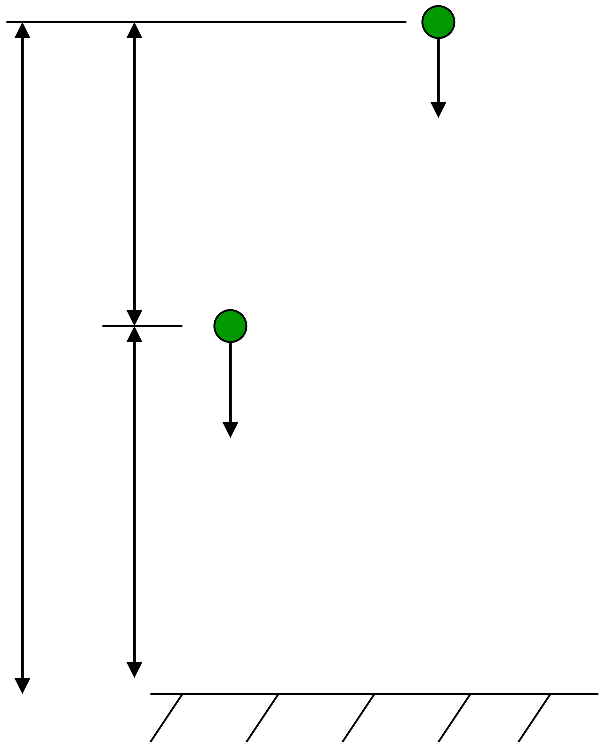
# Ground: Reference Point

- Normally, we measure height compared to the sea level.
- Also, electric potential at a point can be measured compared to the electric potential at the ground.

- Electric potential, or voltage has a unit volt(V).
- Ground always has 0 volts.

# Voltage

- Voltage is a difference of electric potential between 2 points

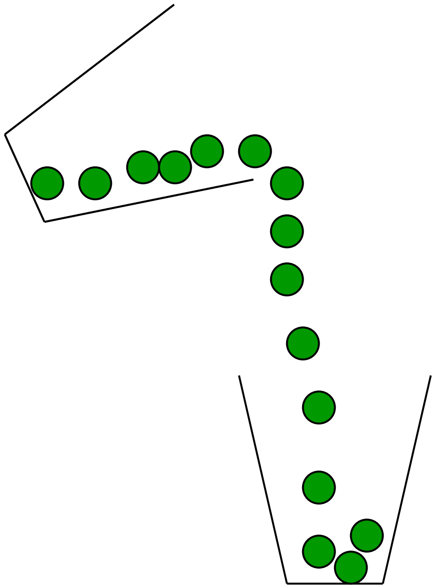


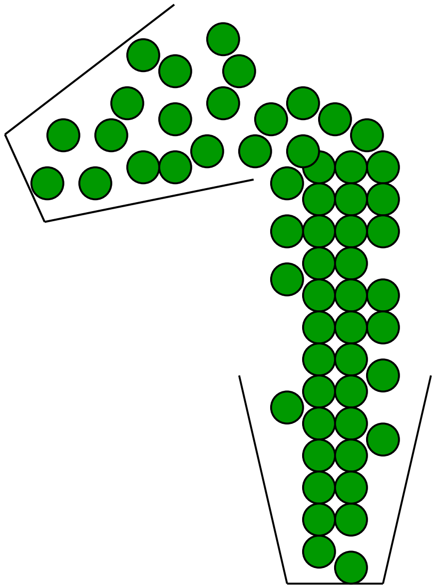
Unit: Volt

- Compare to the height of 2 water drops

# Electric Current

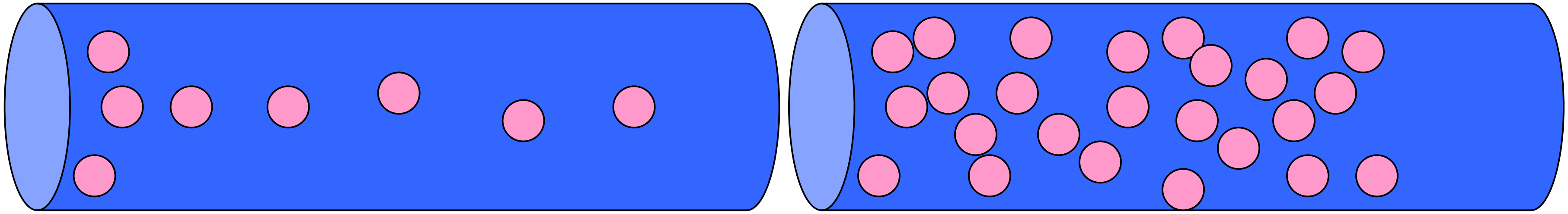
Unit: Ampere, Amp (A)





Low current

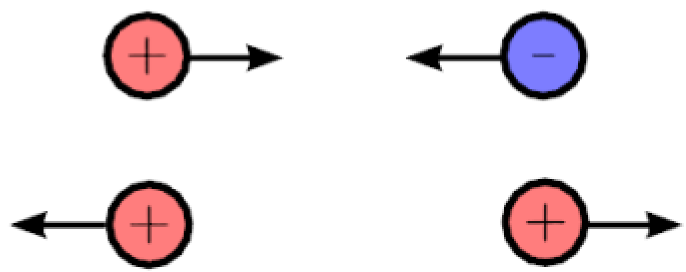
High current



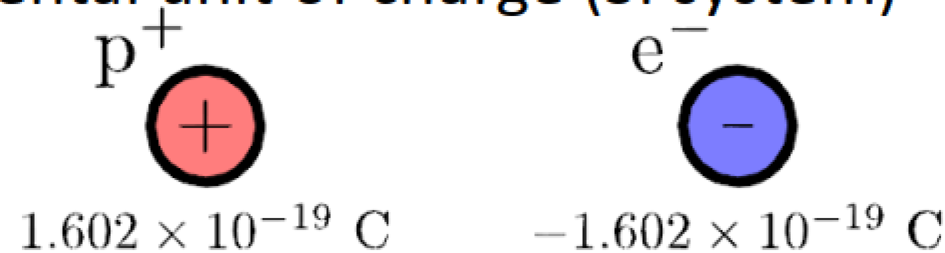
# Charge

| Charge | |
|---|---|
| Units | coulomb (C) |
| Variable | $q$, $Q$ |

- is the fundamental property of matter that causes it to experience a force when placed in electro magnetic field and refers to electrons & protons
  - particles that attract each other (opposite "charge") or repel each other (same "charge")



  - fundamental unit of charge (SI system) = coulomb

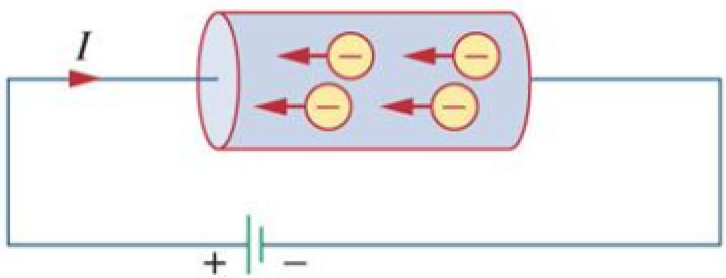


# Current

| Current | |
|---|---|
| Units | ampere ($A = \frac{C}{s}$) |
| Variable | $i$ |

- The movement of charge is called a current
- Historically the moving charges were thought to be positive

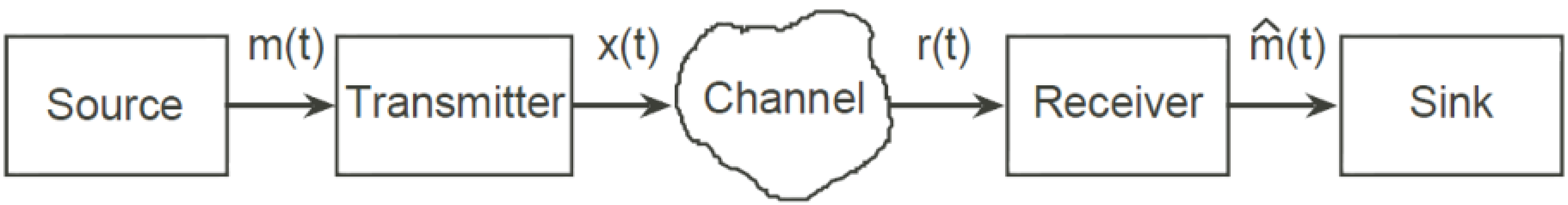





- The mechanism by which electrical energy is transferred

  - Send power from generation point to consumption point

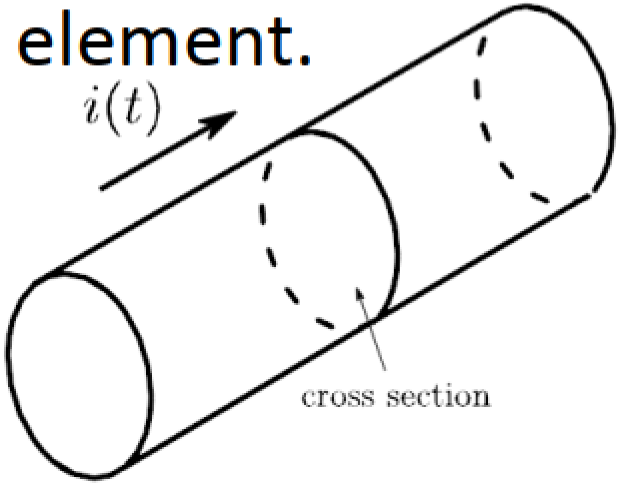
  - Send signals from source to sink



# Current

- Current, *i*, is measured as charge moved per unit time through an element.

$$i = \frac{dq}{dt}$$



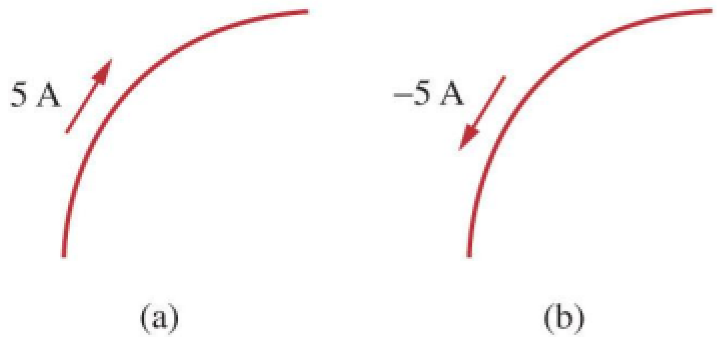

- Amount of charge that has passed a given point:

$$q(t) = \int_{t_0}^{t} i(\tau)d\tau + q(t_0)$$

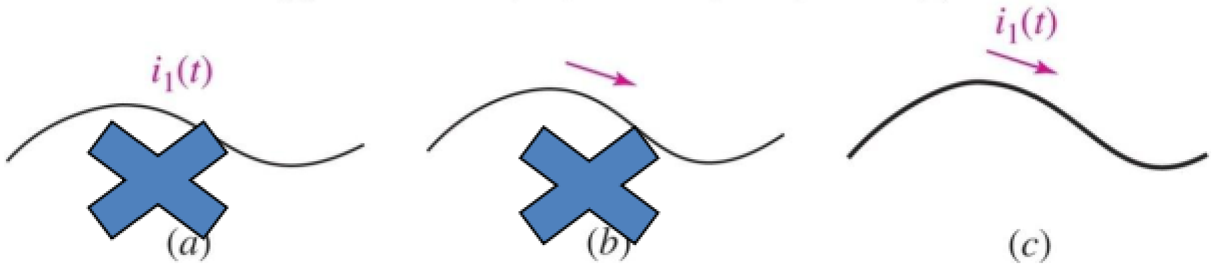
# Direction of Current

- defined as the flow of *positive* charge in a conductor (i.e. in reality, a positive forward current means the electrons are flowing backwards)
- when written, current must be labeled with **direction** & **value**:





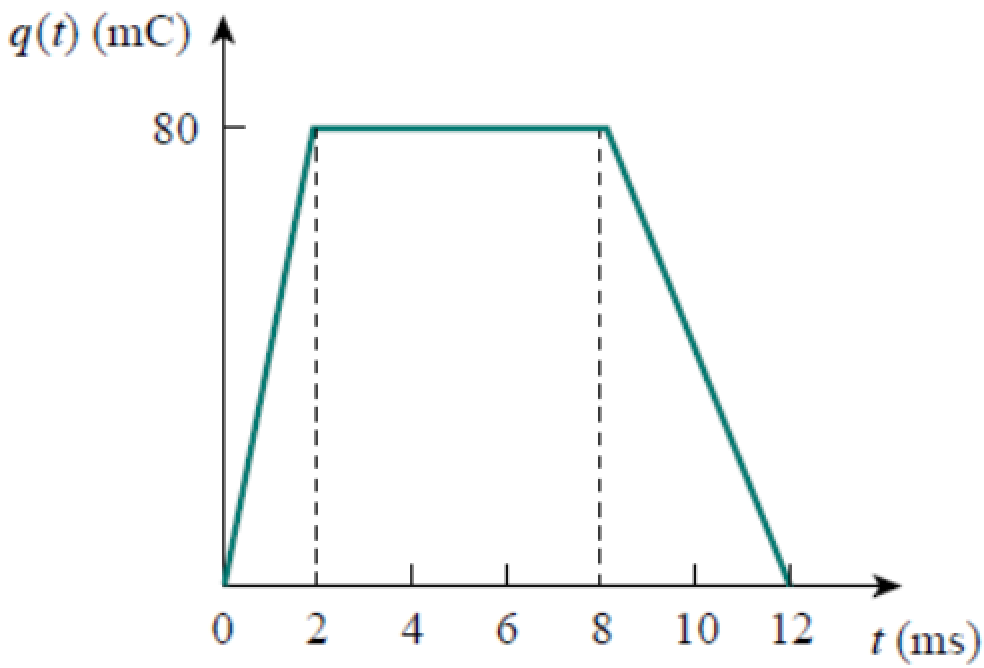


# Examples

- The charge entering a certain element is shown in below Figure. Find the current at:

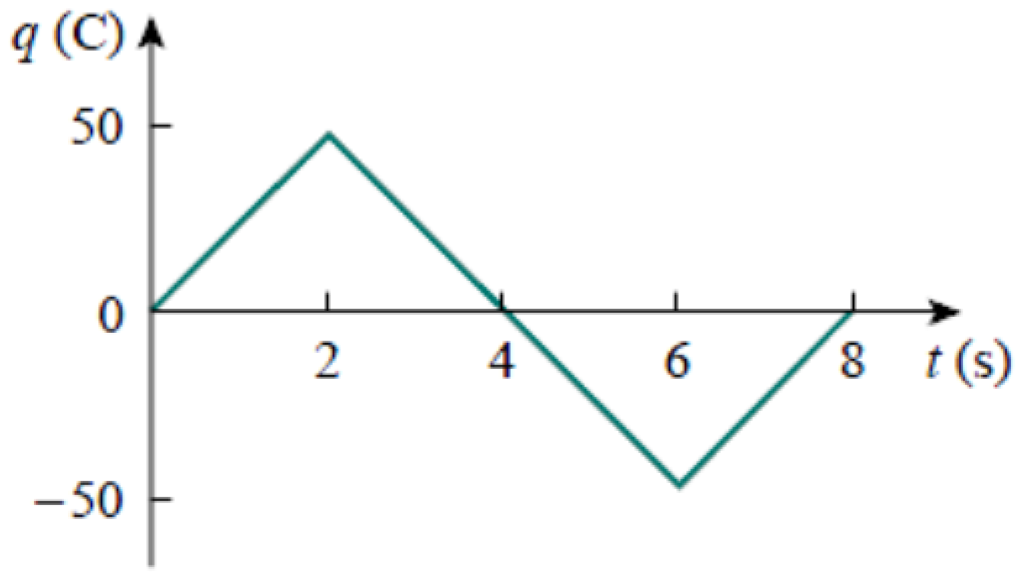
  (a) $t = 1\ ms$ (b) $t = 6\ ms$ (c) $t = 10\ ms$




- The slope is defined as the ratio of the vertical change between two points, to the horizontal change between the same two points.

# Examples

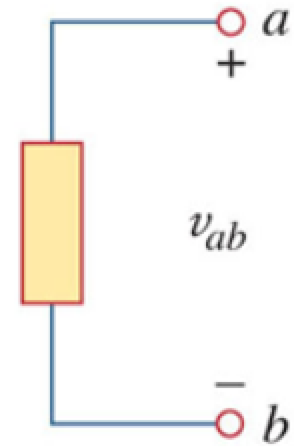
- The charge flowing in a wire is plotted in below Figure. Sketch the corresponding current.



# Voltage

| Voltage | |
|---|---|
| Units | volt ($V = \frac{J}{C}$) |
| Variable | $v$ |

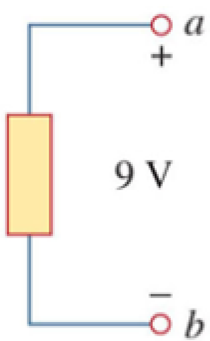
- Electrons move when there is a difference in charge between two locations.
- Voltage (or potential difference) is the energy required to move a unit charge through an element, measured in **volts** (V) (from *a* to *b*).

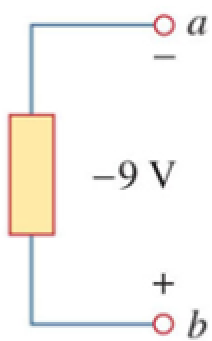



- $V_{ab}$

- point a is at *a* potential of $V_{ab}$ volts higher than point *b*

$$V_{ab} = -V_{ba}.$$



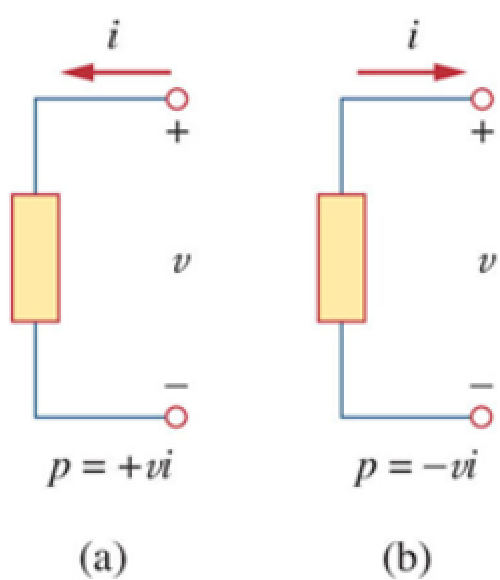
# Power

| Power | |
|---|---|
| Units | watt $(\mathrm{W}=\frac{\mathrm{J}}{\mathrm{s}})$ |
| Variable | $p$ |

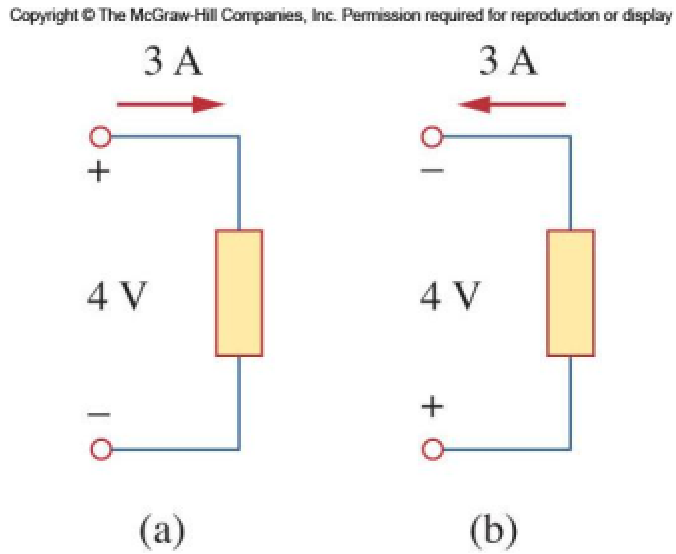
- Power is the product of voltage and current

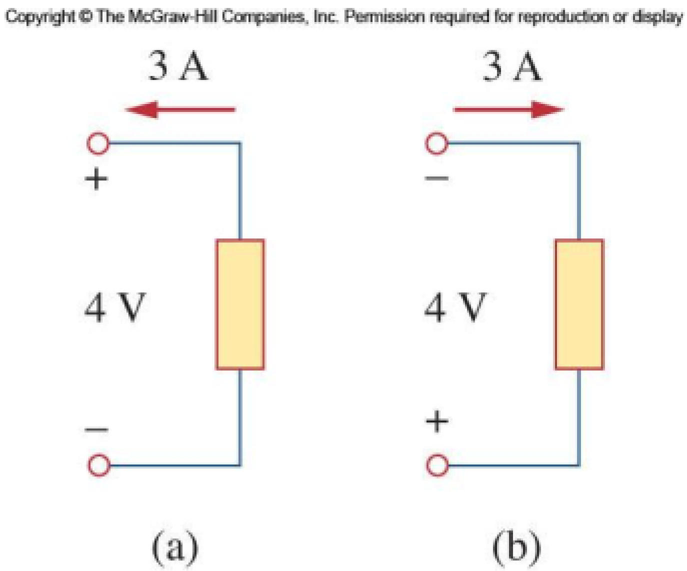
$$p = vi$$

- It is equal to the rate of energy provided or consumed per unit time.
- It is measured in Watts (W)
- Passive sign convention
  - current into positive terminal
  - positive for power *absorbed*
  - negative for power *supplied*



# Power




Two cases of an element with an absorbing power of 12 W

Two cases of an element with an supplying power of 12 W

# Conservation of Energy (Tellegen's Theorem )

- The sum of all power supplied must be absorbed by the other elements.
- For this reason, the algebraic sum of power in a circuit, at any instant of time, must be zero

$$\sum p = 0$$

- The energy absorbed or supplied by an element from time $t_0$ *to time t is*

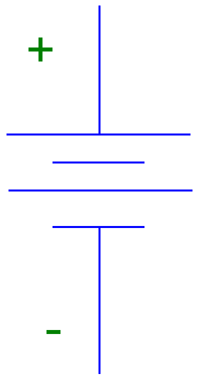
$$w = \int_{t_0}^{t} p\, dt = \int_{t_0}^{t} vi\, dt$$

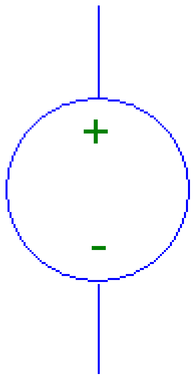
# Circuit Components

- Active elements
  - Independent power sources
    - voltage, current
  - Dependent power sources
    - voltage, current
- Passive Elements
  - Resistors
  - Capacitors
  - Inductors
- Measurement Devices
  - Ampermeters:
    - measure current
  - Voltmeters:
    - measure voltage
- Ground
  - reference point
- Electric Wire
- Switches
- Protective devices
  - Fuse

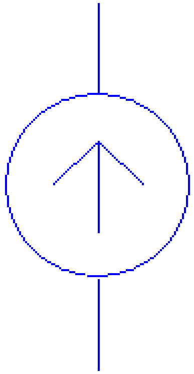
# Independent Power Sources

- Independent voltage source outputs a voltage, either dc or time varying, to the circuit no matter how much current is required.





- Independent current source outputs a dc or ac current to the circuit no matter how much voltage is required.



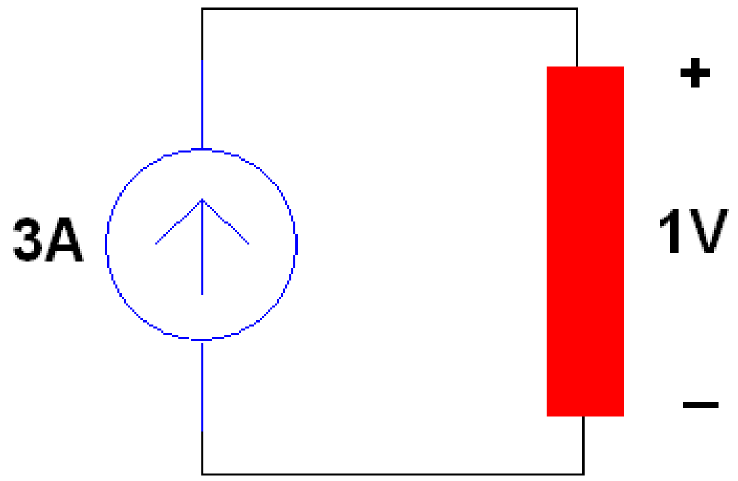
# Independent Power Sources

- Current can flow in and out of an independent voltage source, but the polarity of the voltage is determined by the voltage source.

- There is always a voltage drop across the independent current source and the direction of positive current is determined by the current source.

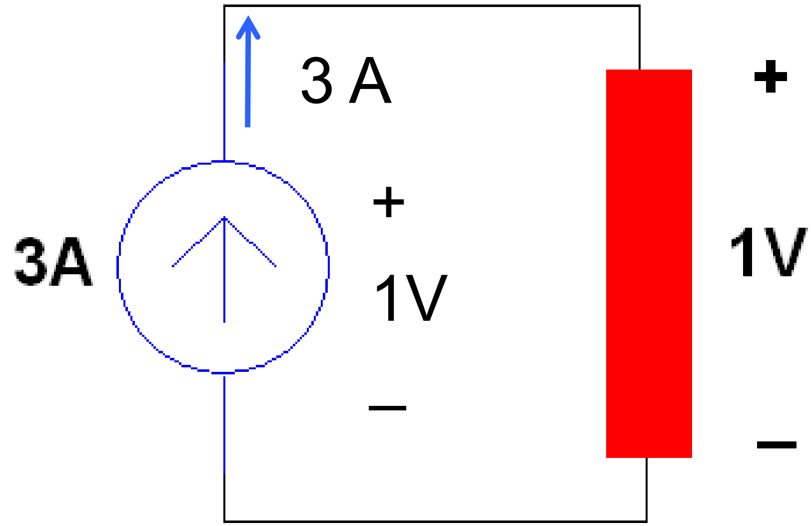
# Example 1

- 1V is dropped across some element (in red) and the wires to that element are connected directly to the independent current source.

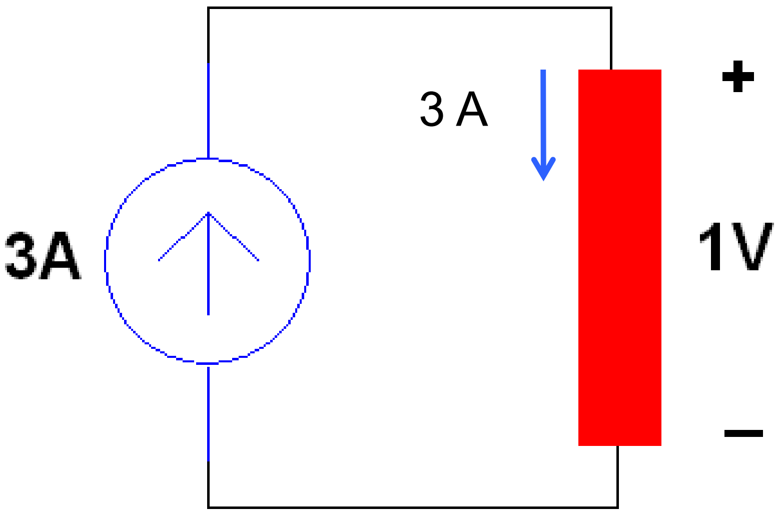


# Example 1

- This means that 1V is also dropped across the independent current source. Therefore, the current source is generated 1 V(3 A) = 3 W of power.
- Passive sign convention: When current leaves the + side of a voltage drop across the independent current source, the power associated with the current source is: $p = -3\text{ A}(1\text{ V}) = -3\text{ W}$



# Example 1




- Conservation of energy means that the other element in red must be dissipating 3 W of power.

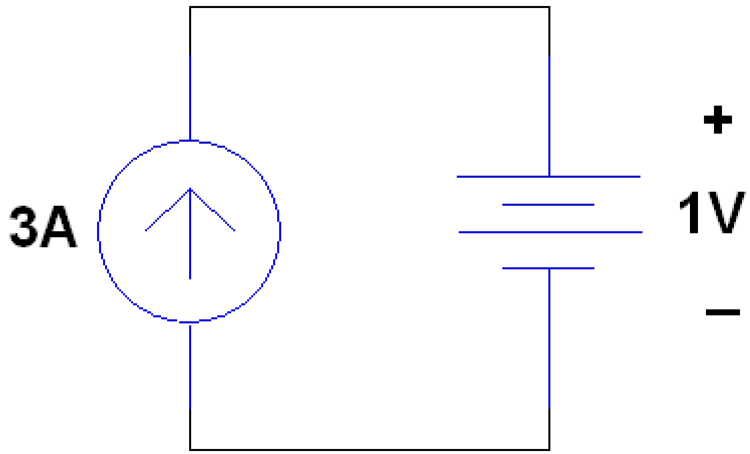
$$\sum p = p_{current\ source} + p_{red\ \mathrm{element}} = 0$$

$$p_{current\ source} = -3\ \mathrm{W;\ therefore,}\ p_{red\ \mathrm{element}} = 3\ \mathrm{W}$$

– Passive sign convention: When current enters the + side of a voltage drop across the element in red, the power associated with this element is:

$$p = 3\ \mathrm{A}(1\ \mathrm{V}) = 3\ \mathrm{W}$$

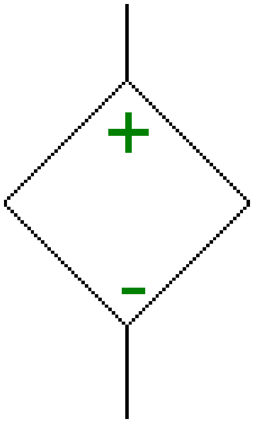
# Example 1



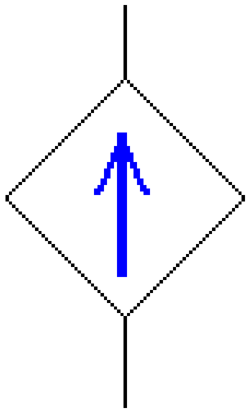

- Suppose the red element was an independent voltage source.
- This means is that the independent current source happens to be supplying power to the independent voltage source, which is dissipating power.
- This happens when you are charging a battery, which is considered to be an independent voltage source.

# Dependent Power Sources

- Voltage controlled voltage source
  - (VCVS)
- Current controlled voltage source
  - (CCVS)



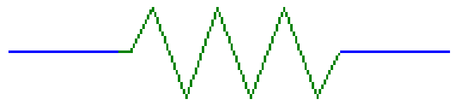
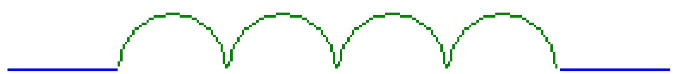
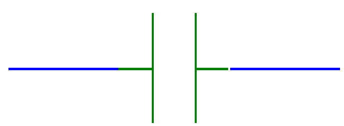

- Voltage controlled current source
  - (VCCS)
- Current controlled current source
  - (CCCS)



# Passive Elements

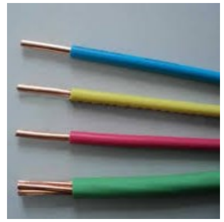
- The magnitude of the voltage drop and current flowing through passive devices depends on the voltage and current sources that are present and/or recently attached to the circuit.
  - These components can dissipate power immediately or store power temporarily and later release the stored power back into the circuit.

# Passive Components

| Component | Symbol | Basic Measure (Unit) |
|---|---|---|
| Resistor  |  | Ohm (Ω) |
| Inductor  |  | Henry (H) |
| Capacitor  |  | Farad (F) |

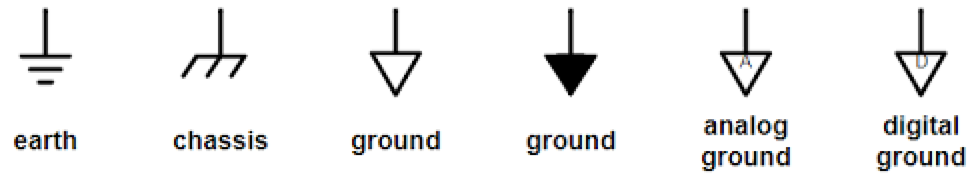
# Other Basic Circuit Elements

- Electric wire

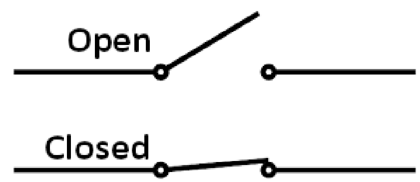


Symbol

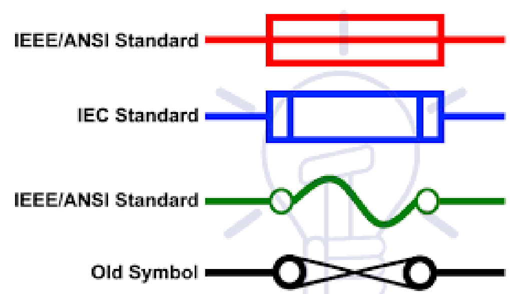
- Ground




- Switch




- Fuse



# Switches

- Switches are used to control whether a complete path is formed from an end of at least one power supply to the other end of the same power supply (closed circuit).
  - Current will only flow when there is a closed circuit.
- Switches can be mechanical, as are used on light switches in your home, or are electronic switches, which are semiconductor based.
- Electronic switches are used in TV sets, for example, to turn on the TV when an infrared optical signal from the remote control is detected.

# Protective Devices

- Circuits that have carry dangerous levels of current and voltages are required to include fuses, circuit breakers, or ground fault detectors by federal and state electrical safety codes.
  - These protective devices are designed to create an open circuit, or a break in the round trip path in the circuit, when a malfunction of a component or other abnormal condition occurs.
  - The speed of response of the protective device, fast-acting or time-delay (slow-blow) is determine by the engineer, based upon the expected type of malfunction.

# Wires

- Wires are assumed to have zero resistance; i.e., they are ideal conductors or short circuits.
  - The current carrying capability of a wire is determined by its diameter or cross-sectional area.
  - AWG, American wire gauge, is the standard followed in the US and is used to rate how much current a wire can safely carry.
  - The larger the gauge wire, the smaller its current carrying capability is.
    - The AWG standard includes copper, aluminum and other wire materials.
    - Typical household copper wiring is AWG number 12 or 14.
    - Telephone wire is usually 22, 24, or 26.
    - The higher the gauge number, the smaller the diameter and the thinner the wire.

# AWG to square mm cross sectional area

| American Wire Gauge *(#AWG)* | Diameter *(inches)* | Diameter *(mm)* | Cross Sectional Area *(mm²)* |
|---|---|---|---|
| 0000 (4/0) | 0.460 | 11.7 | 107 |
| 000 (3/0) | 0.410 | 10.4 | 85.0 |
| 00 (2/0) | 0.365 | 9.27 | 67.4 |
| 0 (1/0) | 0.325 | 8.25 | 53.5 |
| 1 | 0.289 | 7.35 | 42.4 |
| 2 | 0.258 | 6.54 | 33.6 |
| 3 | 0.229 | 5.83 | 26.7 |
| 4 | 0.204 | 5.19 | 21.1 |
| 5 | 0.182 | 4.62 | 16.8 |
| 6 | 0.162 | 4.11 | 13.3 |
| 7 | 0.144 | 3.67 | 10.6 |
| 8 | 0.129 | 3.26 | 8.36 |
| 9 | 0.114 | 2.91 | 6.63 |
| 10 | 0.102 | 2.59 | 5.26 |

| American Wire Gauge *(#AWG)* | Diameter *(inches)* | Diameter *(mm)* | Cross Sectional Area *(mm²)* |
|---|---|---|---|
| 11 | 0.0907 | 2.30 | 4.17 |
| 12 | 0.0808 | 2.05 | 3.31 |
| 13 | 0.0720 | 1.83 | 2.63 |
| 14 | 0.0641 | 1.63 | 2.08 |
| 15 | 0.0571 | 1.45 | 1.65 |
| 16 | 0.0508 | 1.29 | 1.31 |
| 17 | 0.0453 | 1.15 | 1.04 |
| 18 | 0.0403 | 1.02 | 0.82 |
| 19 | 0.0359 | 0.91 | 0.65 |
| 20 | 0.0320 | 0.81 | 0.52 |
| 21 | 0.0285 | 0.72 | 0.41 |
| 22 | 0.0254 | 0.65 | 0.33 |
| 23 | 0.0226 | 0.57 | 0.26 |
| 24 | 0.0201 | 0.51 | 0.20 |
| 25 | 0.0179 | 0.45 | 0.16 |
| 26 | 0.0159 | 0.40 | 0.13 |

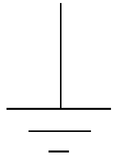
# AWG to ohm/meter

Approximate resistance of copper wire[6]:27

| AWG | mΩ/ft | mΩ/m | AWG | mΩ/ft | mΩ/m | AWG | mΩ/ft | mΩ/m | AWG | mΩ/ft | mΩ/m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.1 | 0.32 | 10 | 1 | 3.2 | 20 | 10 | 32 | 30 | 100 | 320 |
| 1 | 0.125 | 0.4 | 11 | 1.25 | 4 | 21 | 12.5 | 40 | 31 | 125 | 400 |
| 2 | 0.16 | 0.5 | 12 | 1.6 | 5 | 22 | 16 | 50 | 32 | 160 | 500 |
| 3 | 0.2 | 0.64 | 13 | 2 | 6.4 | 23 | 20 | 64 | 33 | 200 | 640 |
| 4 | 0.25 | 0.8 | 14 | 2.5 | 8 | 24 | 25 | 80 | 34 | 250 | 800 |
| 5 | 0.32 | 1 | 15 | 3.2 | 10 | 25 | 32 | 100 | 35 | 320 | 1000 |
| 6 | 0.4 | 1.25 | 16 | 4 | 12.5 | 26 | 40 | 125 | 36 | 400 | 1250 |
| 7 | 0.5 | 1.6 | 17 | 5 | 16 | 27 | 50 | 160 | 37 | 500 | 1600 |
| 8 | 0.64 | 2 | 18 | 6.4 | 20 | 28 | 64 | 200 | 38 | 640 | 2000 |
| 9 | 0.8 | 2.5 | 19 | 8 | 25 | 29 | 80 | 250 | 39 | 800 | 2500 |

# Ground

- Earth ground is a ground that is physically connected to the earth, itself.
  - All homes have an earth ground
    - a wire connected to a metal pipe that is driven into the ground immediately next to the house.
    - Wires that have a green jacket or are bare copper are connected to this pipe.
- Reference ground or common is used in a circuit to indicate a point where the voltage in the circuit is equal to zero.



# General Rules

- All points on a same electric wire have the same voltage.
- A voltage source always have voltage difference of its pins equal to its value.
- A current source always have current pass through it equal to its value.
- Ground always has zero voltage. (0 volts)

# Electric Flow Rule

- Electric current flows from high voltage to low voltage when there is a path.
- Electric current can freely pass through electric wire.
- Electric current can flow through a resistor with the amount according to Ohm's law.
- Electric current can flow through a voltage source with the amount depended on other components in the circuit.
- Electric current can flow pass a current source according to its value.

# Charge

- Electrical property of atomic particles
  - Electrons are negatively charged
  - Protons are positivity charged
- The absolute value of the charge on an electron is $1.6 \times 10^{-19}$ C
- The symbol used is $Q$ or $q$
  - Uppercase is used to denote a steady-state or constant value
  - Lowercase is used to denote an instantaneous value or time-varying quantity

# Current

- The flow of charge through a cross-sectional area as a function of time or the time rate of change of charge
- Symbol used is *I* or *i*

$$i = \frac{dq}{dt}$$

$$Q = \int_{t_1}^{t_2} i \, dt$$

# DC vs. AC

- DC (or dc) is the acronym for direct current.
  - The current remains constant with time.
    - Uppercase variables are used when calculating dc values.
- AC (or ac) is the acronym for alternating current.
  - Specifically, AC current varies sinusoidally with time and the average value of the current over one period of the sinusoid is zero.
    - Lowercase variables are used when calculating ac values.
  - Other time-varying currents exist, but there isn't an acronym defined for them.

# Voltage (Potential Difference)

- The electromotive force (emf) that causes charge to move.
- 1 Volt = 1 Joule/1 Coulomb

$$\text{v} = \frac{dw}{dq}$$

# Power

- The change in energy as a function of time is power, which is measured in watts (W).

$$p = \frac{dw}{dt} = \frac{dw}{dq}\frac{dq}{dt} = \mathrm{v}i$$

# Energy

- Energy is the capacity to do work.

$$w = \int_{t_1}^{t_2} p\, dt = \int_{t_1}^{t_2} \mathrm{v}\, i\, dt$$

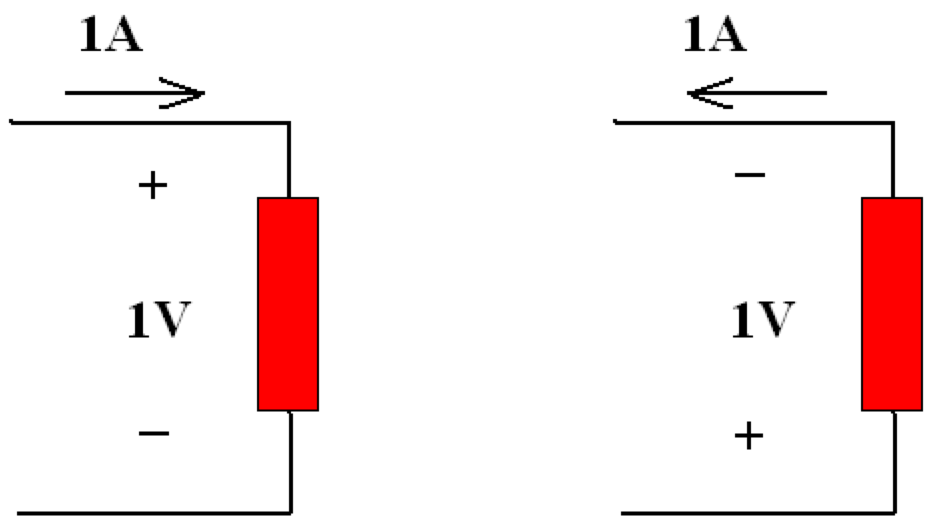
- Units for energy are kW-hr, which is what the electric company measures on your electric meter.

  1 kW-hr = 3.6 MJ.

# Positive vs. Negative Power

- Power consumed/dissipated by a component is positive power

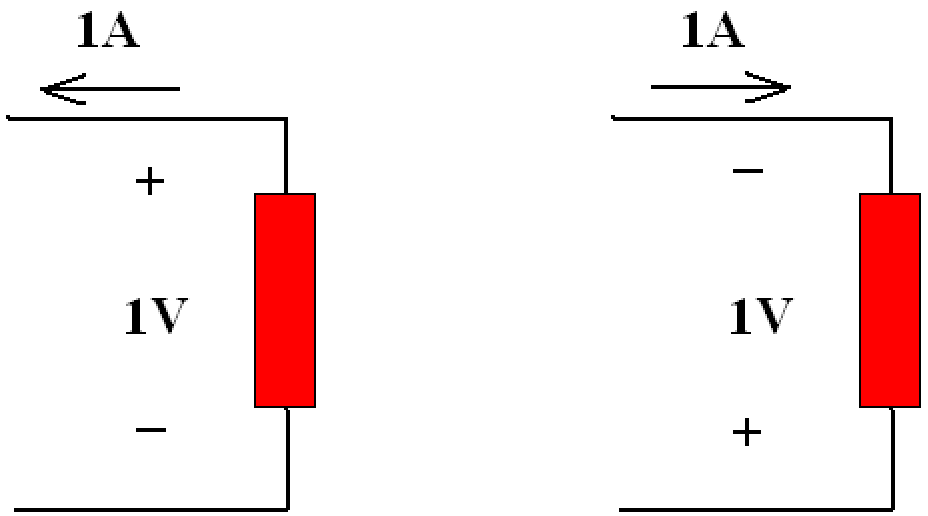
$$P = +1W$$



# Positive vs. Negative Power

- Generated power has a negative sign

P = -1W

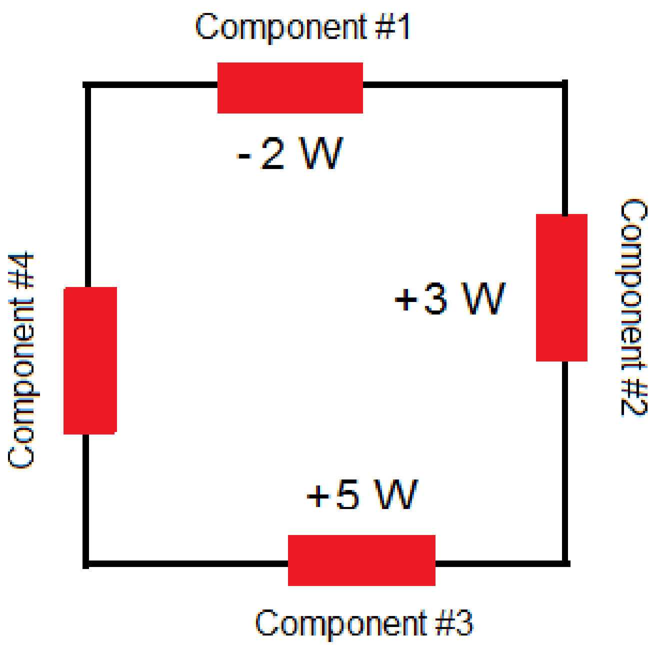


# Conservation of Energy

- All power instantaneously consumed by components must be instantly generated by other components within the circuit.

$$\sum p = 0$$

# Example

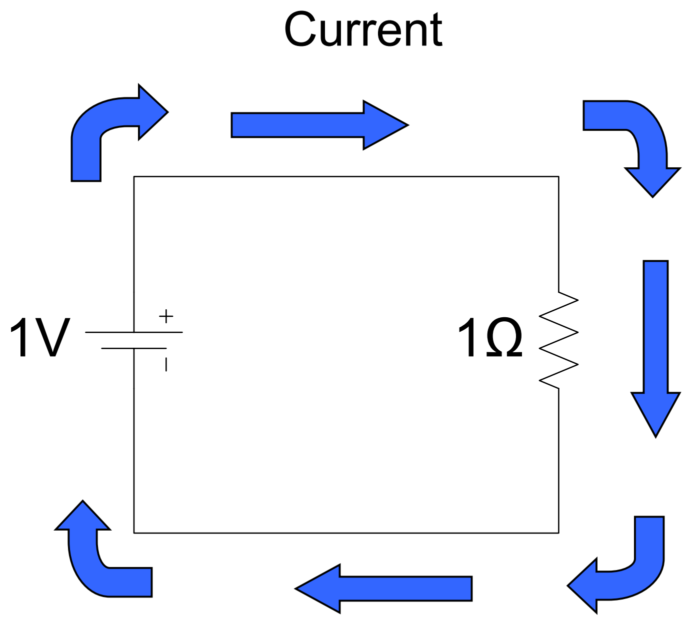



- There are 4 electrical components in the circuit shown to the right.
- Component #1 is generating 2 W of power and supplying this power to the circuit.
- Components #2 and #3 are consuming power.
- Component #2 is dissipating 3 W of power while Component #3 is dissipating 5 W of power.
- Component #4 must be generating 6 W of power in order to maintain the Conservation of Energy.

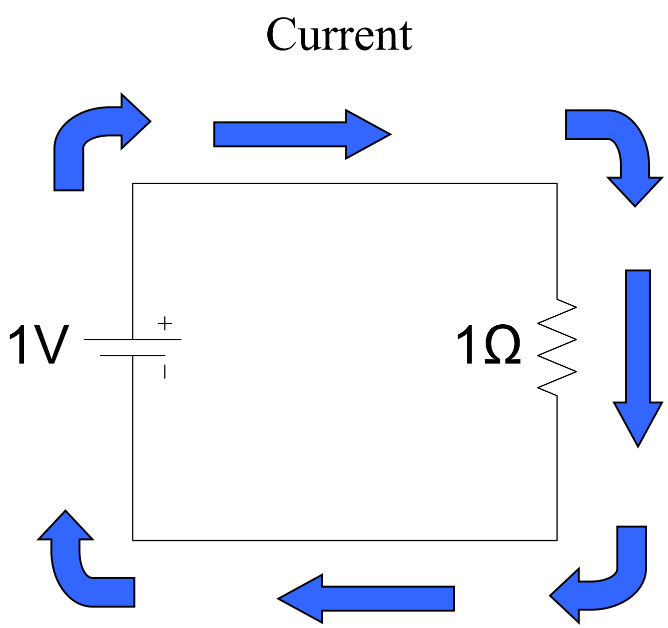
$$\sum p = p_{Component\#1} + p_{Component\#2} + p_{Component\#3} + p_{Component\#4} = 0$$

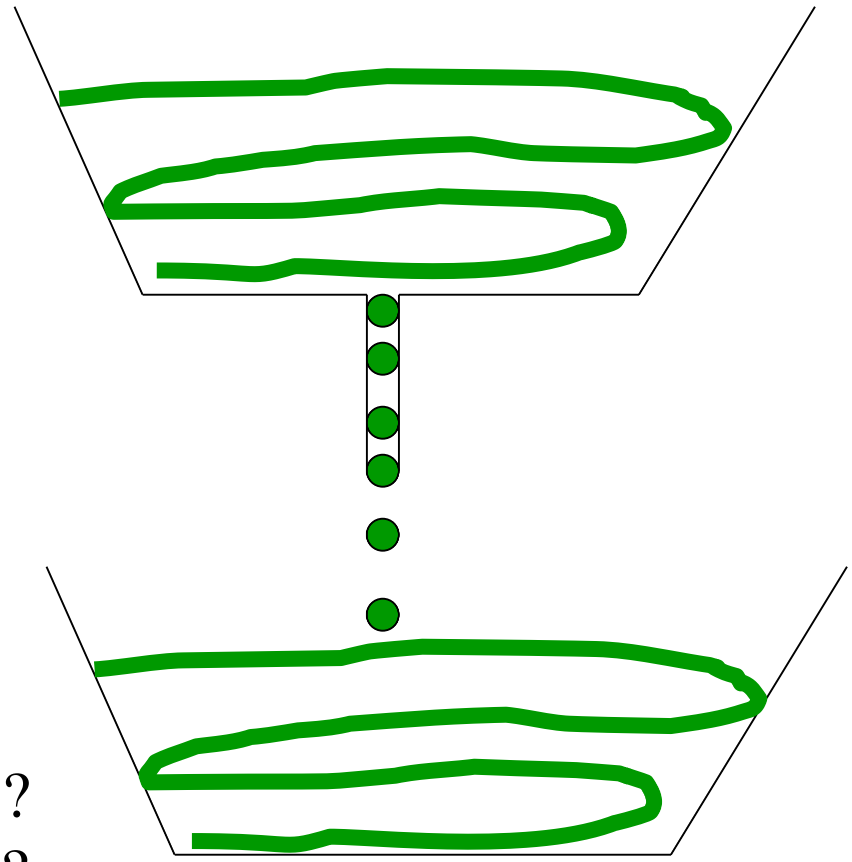
$$p_{Component\#4} = -(p_{Component\#1} + p_{Component\#2} + p_{Component\#3}) = -(-2\text{ W} + 3\text{ W} + 5\text{ W}) = -6\text{ W}$$

# Simple DC Circuit



# Metaphor



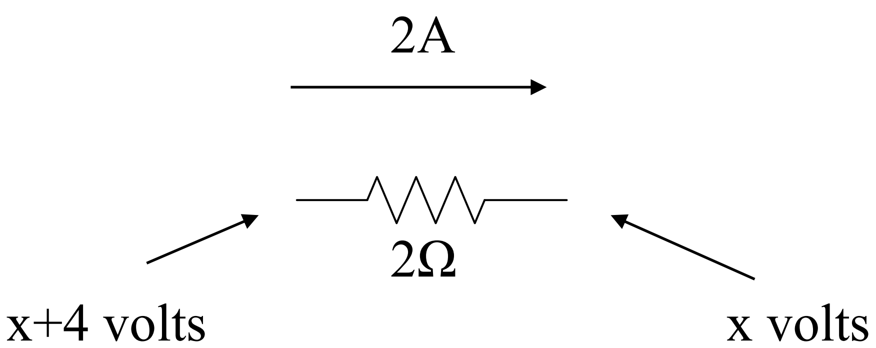
- Increasing V is compared to ?
- Increasing R is compared to ?

# Ohm's Law

$V = IR$

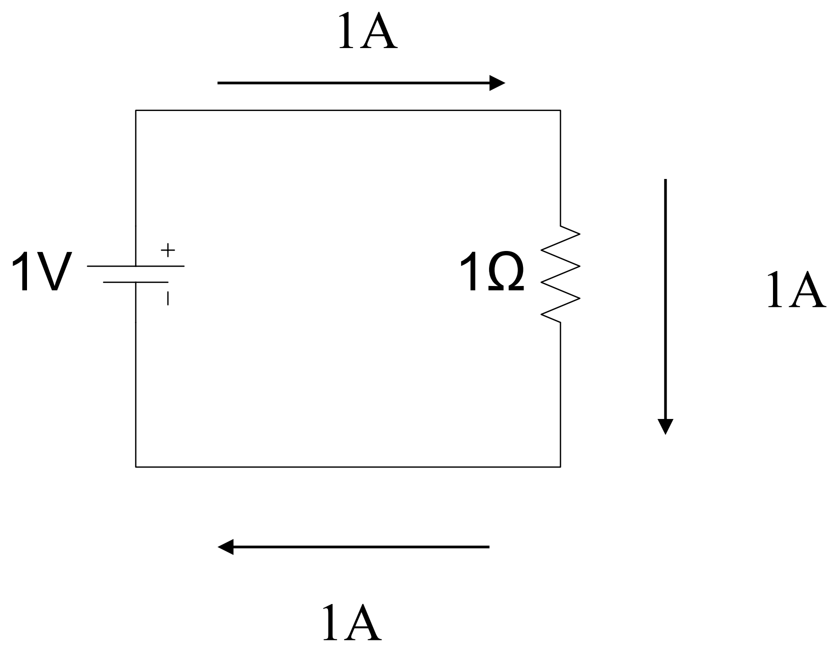
for using with a resistor only

Voltage (Volts) =
current (Amperes) x resistance (Ohms)



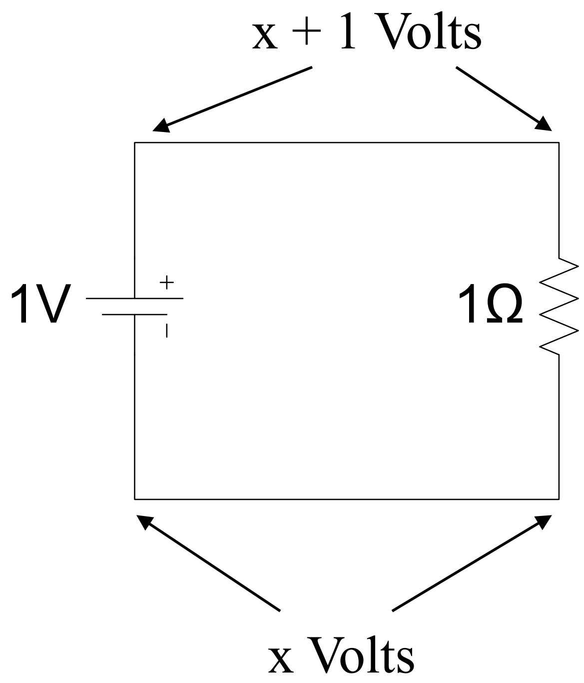

Note: (Theoretically) Electric wire has a resistance of 0 ohms

# Electric Current



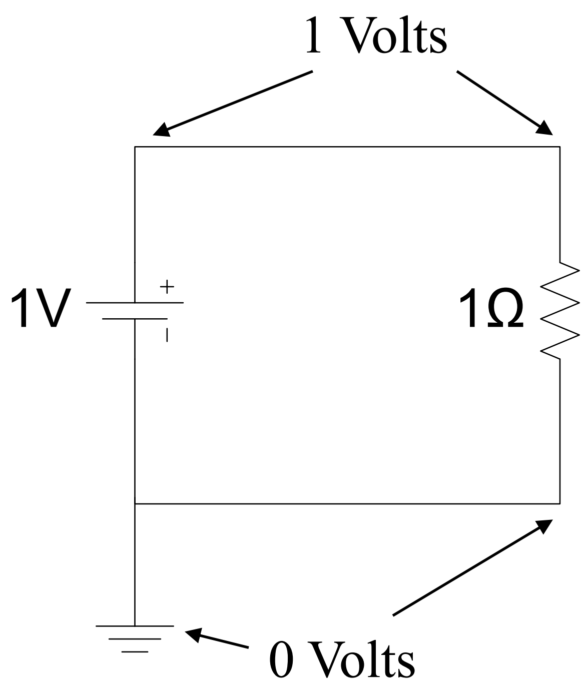

Every point in the circuit has current = 1A

# Electric Voltage

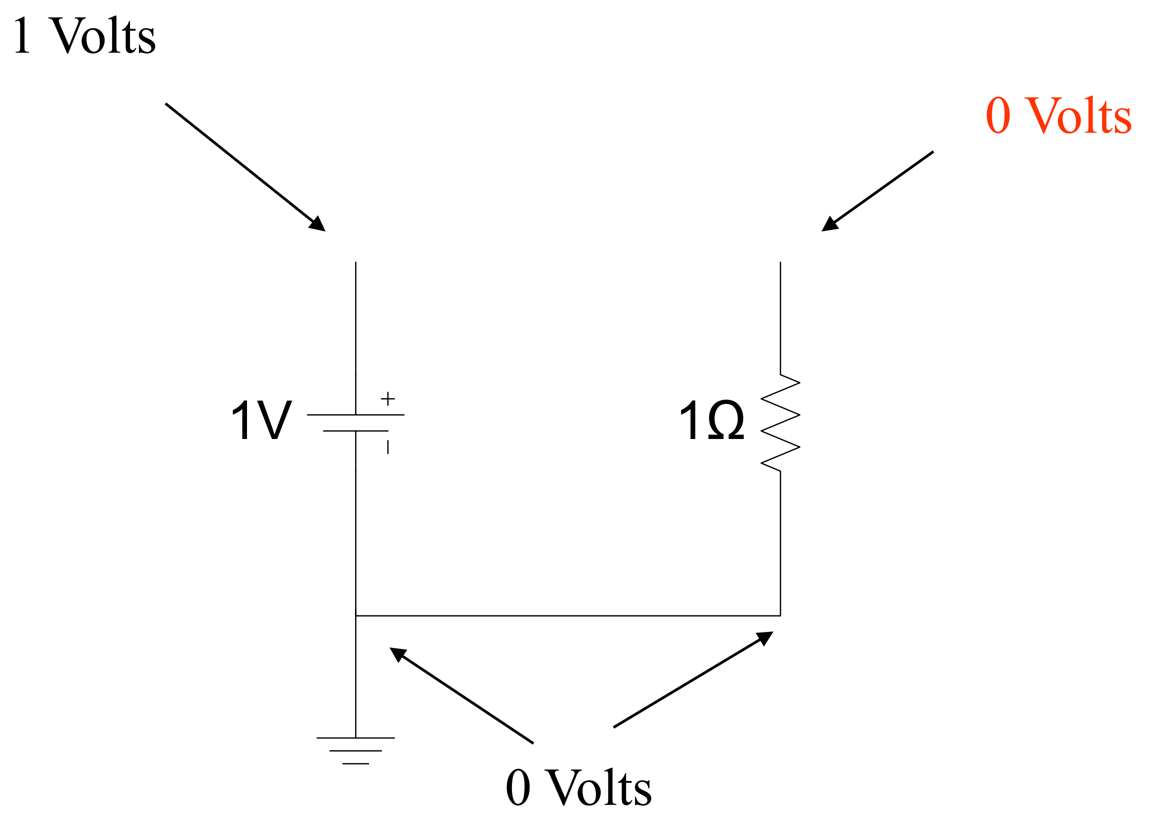


# Ground

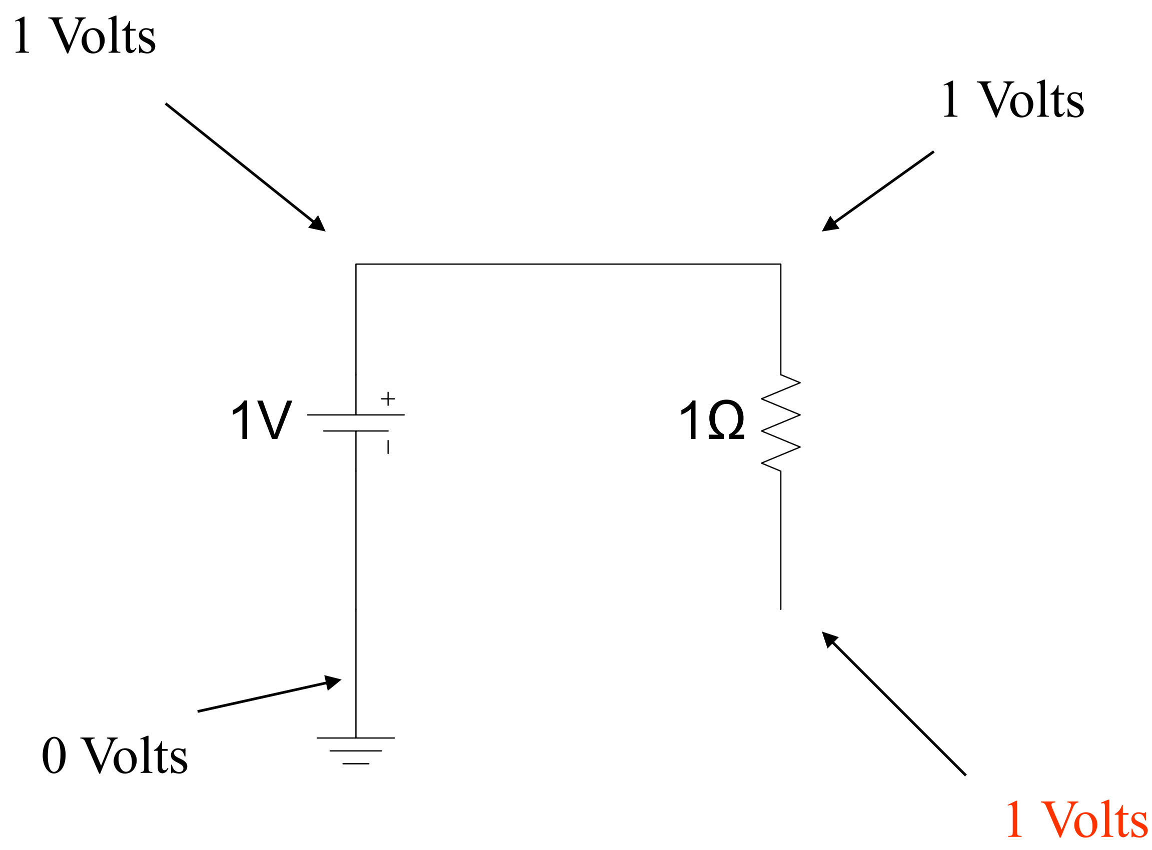
Ground = reference point always have voltage = 0 volts



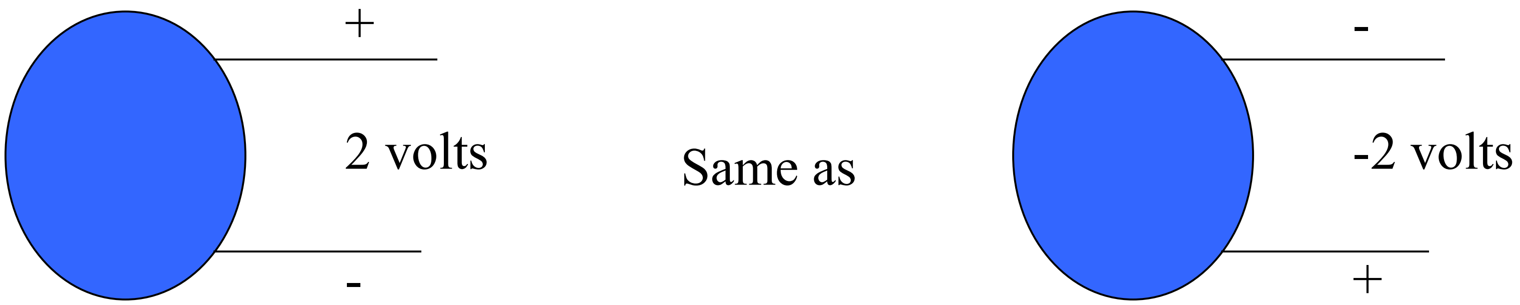
# Electric Voltage (2)

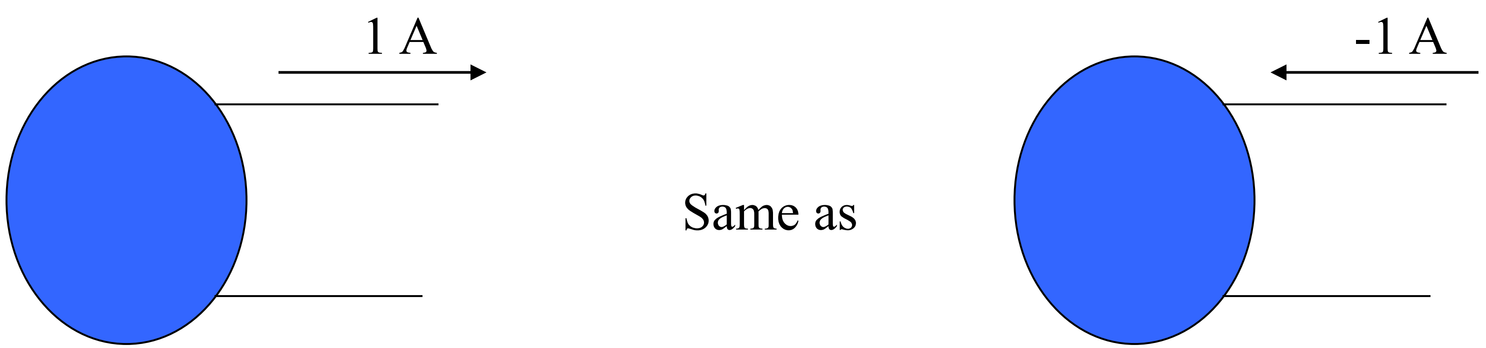


# Electric Voltage (3)



# Negative Voltage and Current

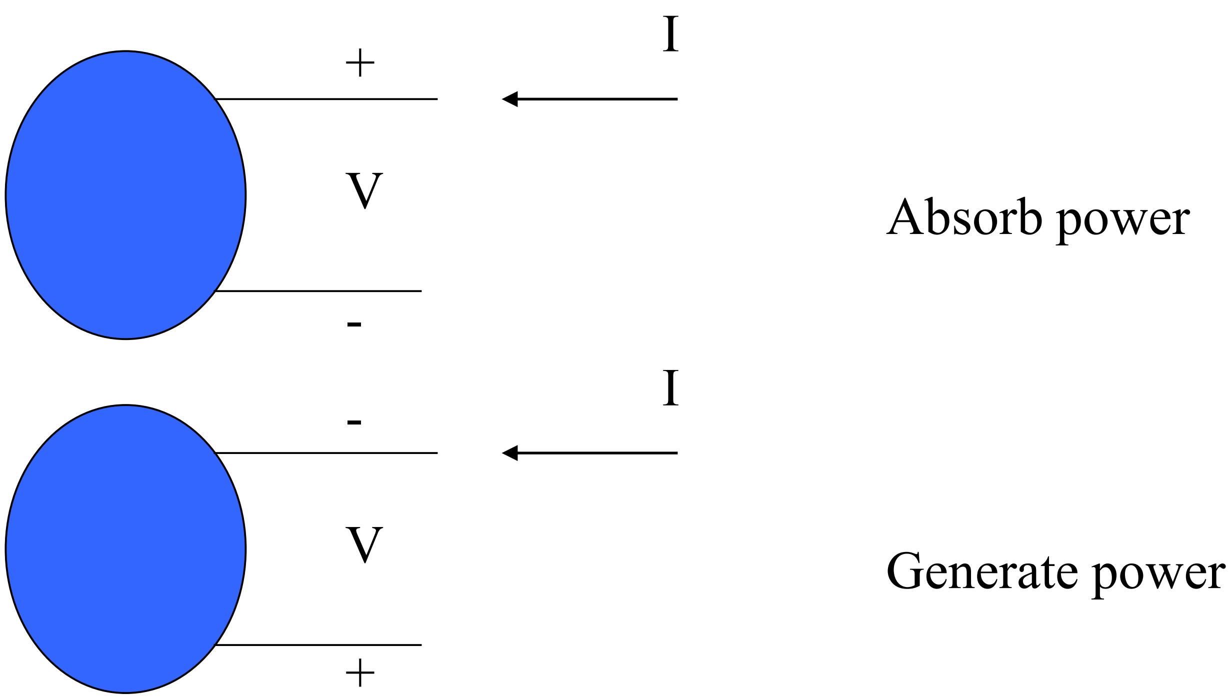


# Power

Symbol P has a unit of Watt

$$P = VI$$

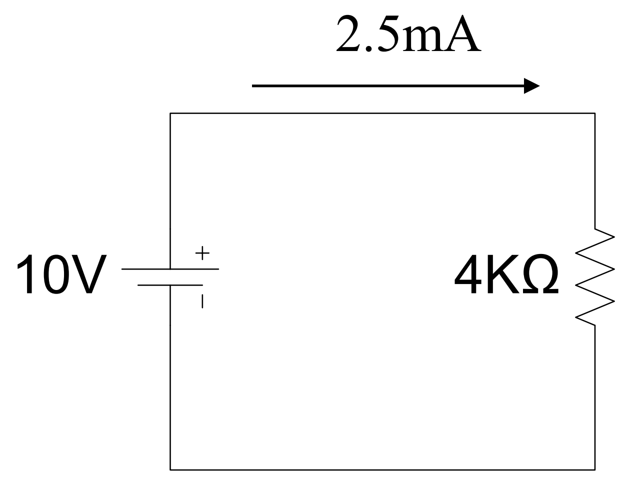


# Passive Sign Convention

Absorb power:  Power has a sign +

Generate power: Power has a sign -

# Example

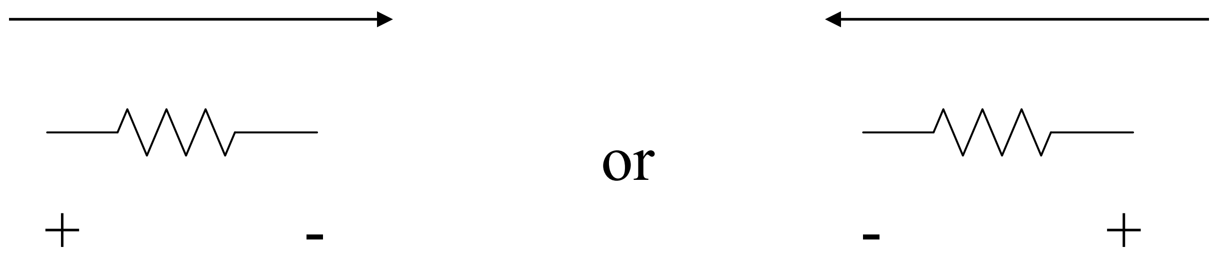



DC source generates power = 10V * -2.5mA = - 25mW

Resistor absorbs power = 10V * 2.5mA = 25mW

Note: Resistors always absorb power but DC source can either generate or absorb power

# Direction of Voltage & Current on Resistors




- Resistor always absorb power.
- Therefore, it always have current flow through it from high voltage pin to low voltage pin.