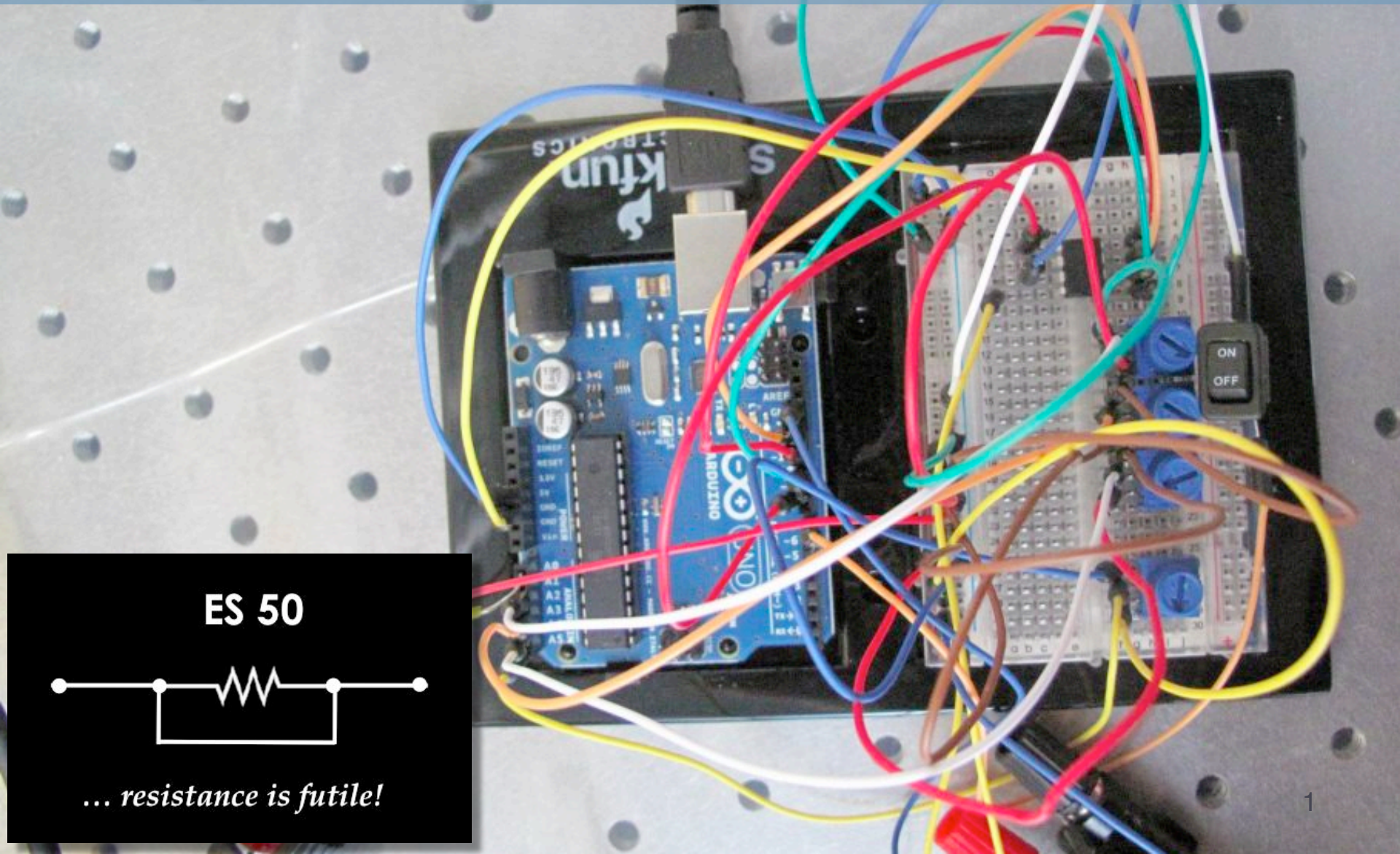
ES 50: Introduction to Electrical Eng.

Explore EE, satisfy a Gen Ed requirement & have fun



ES 50

… resistance is futile!

Lecture 2: Analog Electrical Circuits (Part 1)

ES 50: Introduction to Electrical Engineering

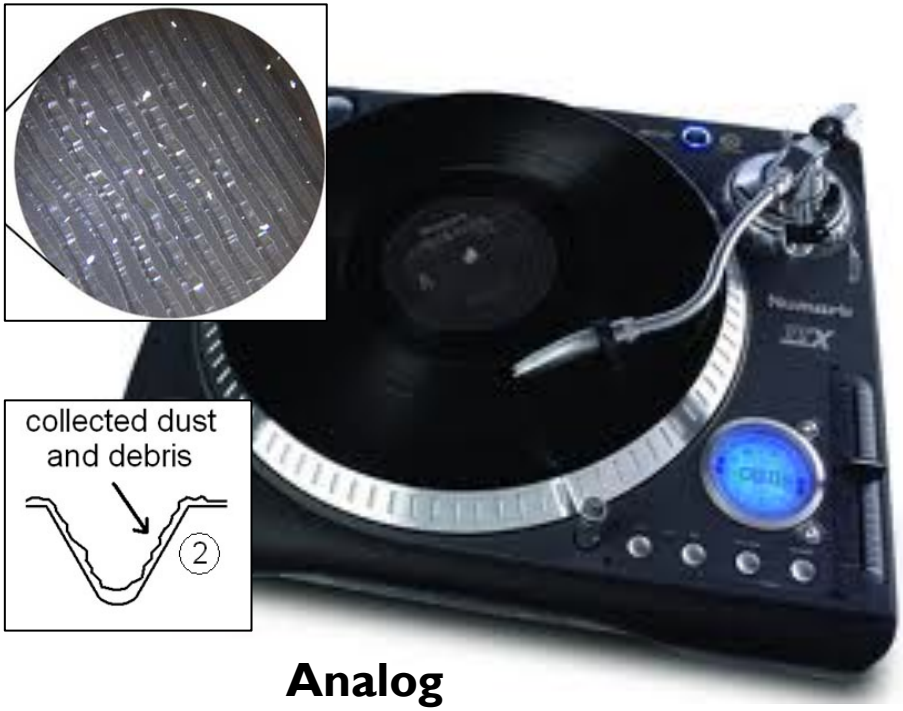
Announcements

- **Remember to check the course website frequently** for important updates & announcements
  - Printed syllabus is already out of date…
  - HW #1 will be posted on Sat 9/12 and due Sat 9/19
  - Lecture 2 PDF posted Tues 9/8
- **Office hours, review & problem solving sessions**
  - Gu (MD333): T/Th 1-2PM or by appointment
  - Chris (Pierce 287): T/Th 4-5PM or by appointment
  - **Review & problem solving sessions (Pierce 301): W/Th 7-9:30PM**
- **Sign up for lab sections by 12:01AM Sept 12, 2015**
  - Please sign up for 4-6 out of 9 available time slots
  - You will be notified of section assignments over the weekend.
  - If you cannot make any of the section times, please e-mail Jessica Lam (head TF) ASAP (also cc Gu and Chris).
- **Lab #1** starts next week!
  - Lab handouts are available on canvas. Please read them before going to lab.

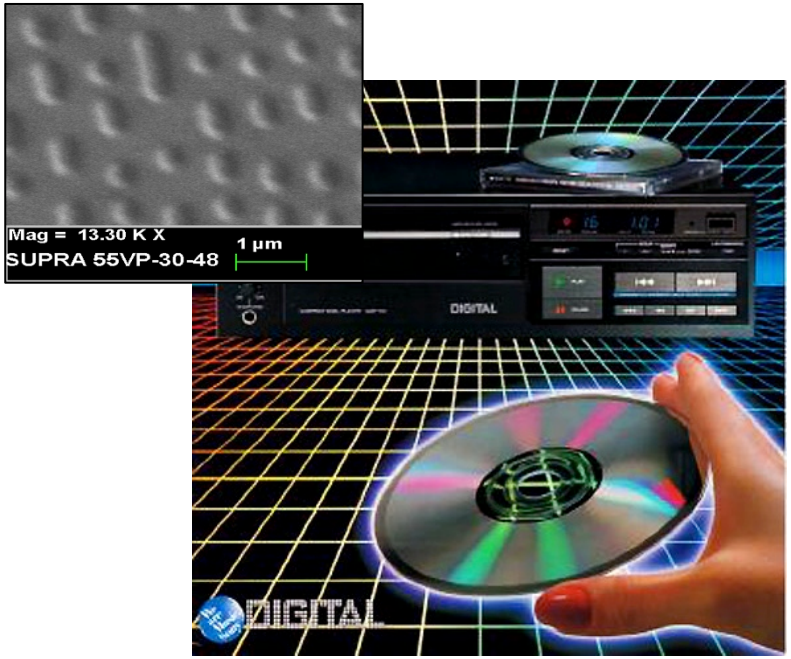
Today, we will cover…

- Analog *vs.* Digital signals: Pros and cons
- Voltage
- Current
- Resistance
- Ohm's Law
- The importance of reference direction in electrical circuits
- Ideal *vs.* realistic voltage and current sources

Analog vs. Digital Signals



Analog

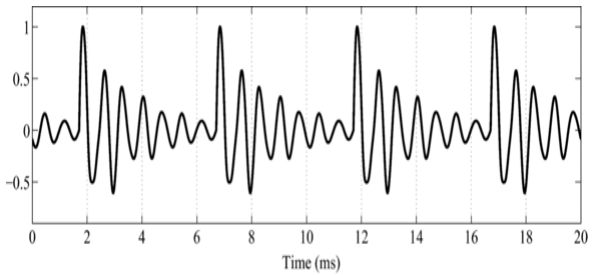


Digital

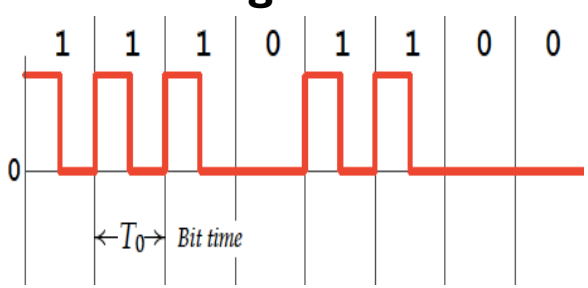
- Examples of analog and digital signals…
- What are advantages and disadvantages of analog and digital signals?
    - Storage? Fidelity? Susceptibility to noise? Information processing?
- How do we go from analog to digital, and back? Why would we want to?

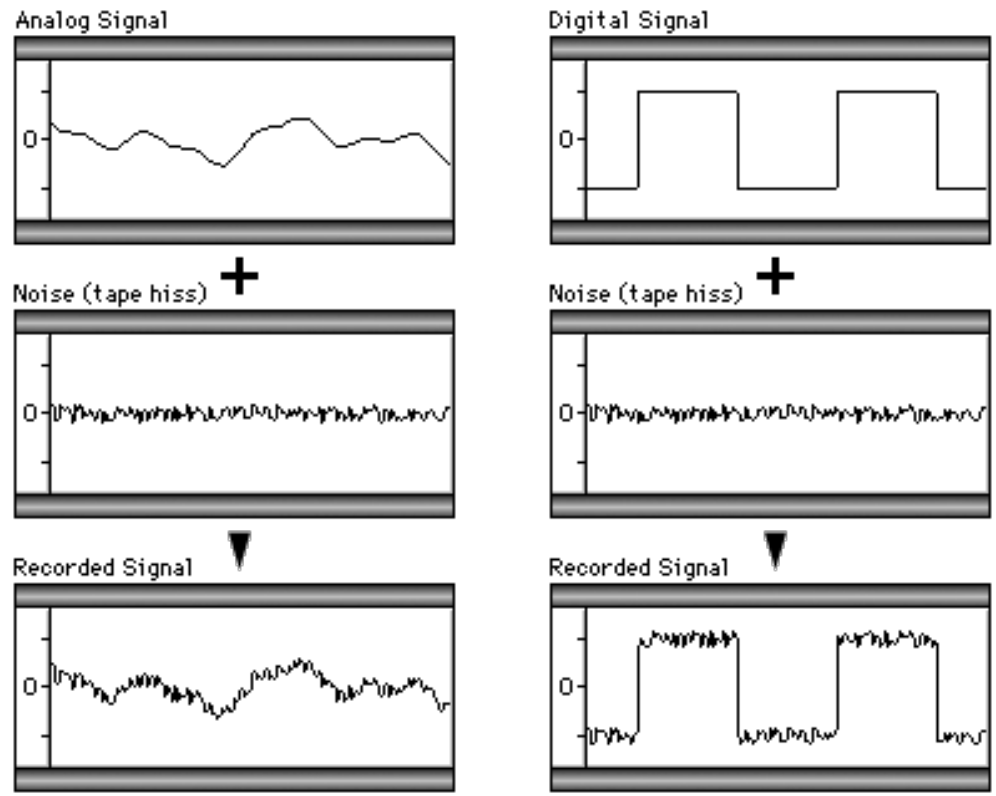
Analog vs. Digital Signals

Analog



Digital





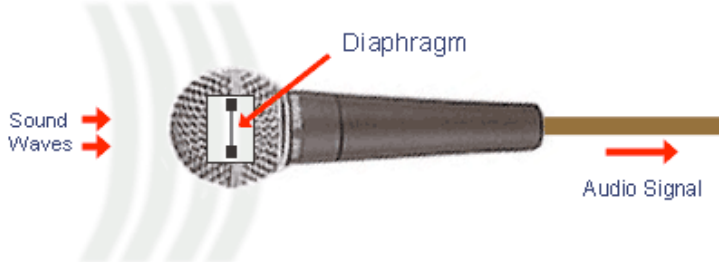
Analog: Continuous in time; **information is in the amplitude of the signal** (or frequency/phase) => **susceptible to noise**; difficult to process (need analog computer);

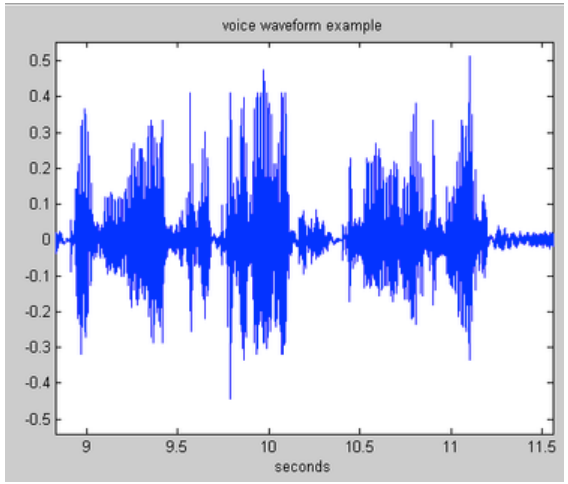
Digital: Discrete in time; in the simplest case only two values of the signal: 1 and 0; easy to store; **information is in the presence of the signal** => less susceptible to noise

Examples

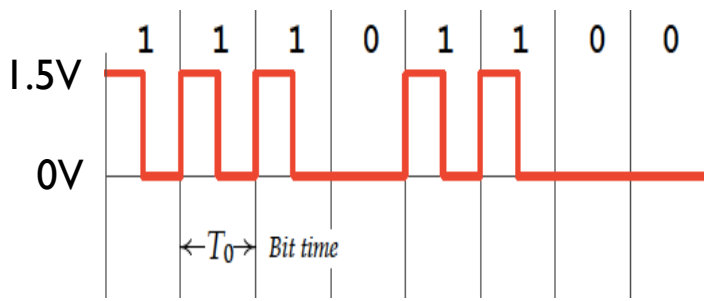
Voltage from microphone time domain

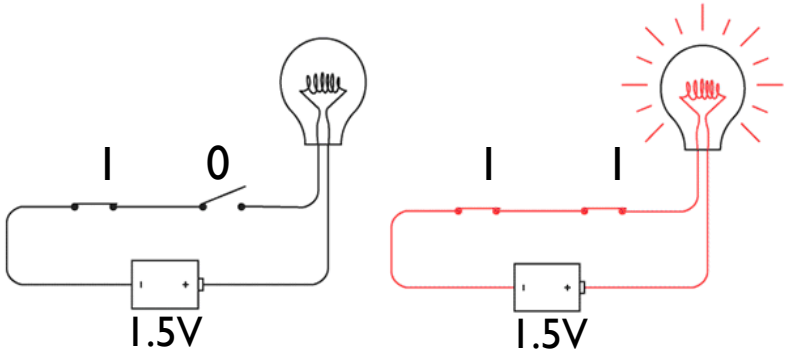
Analog





Digital

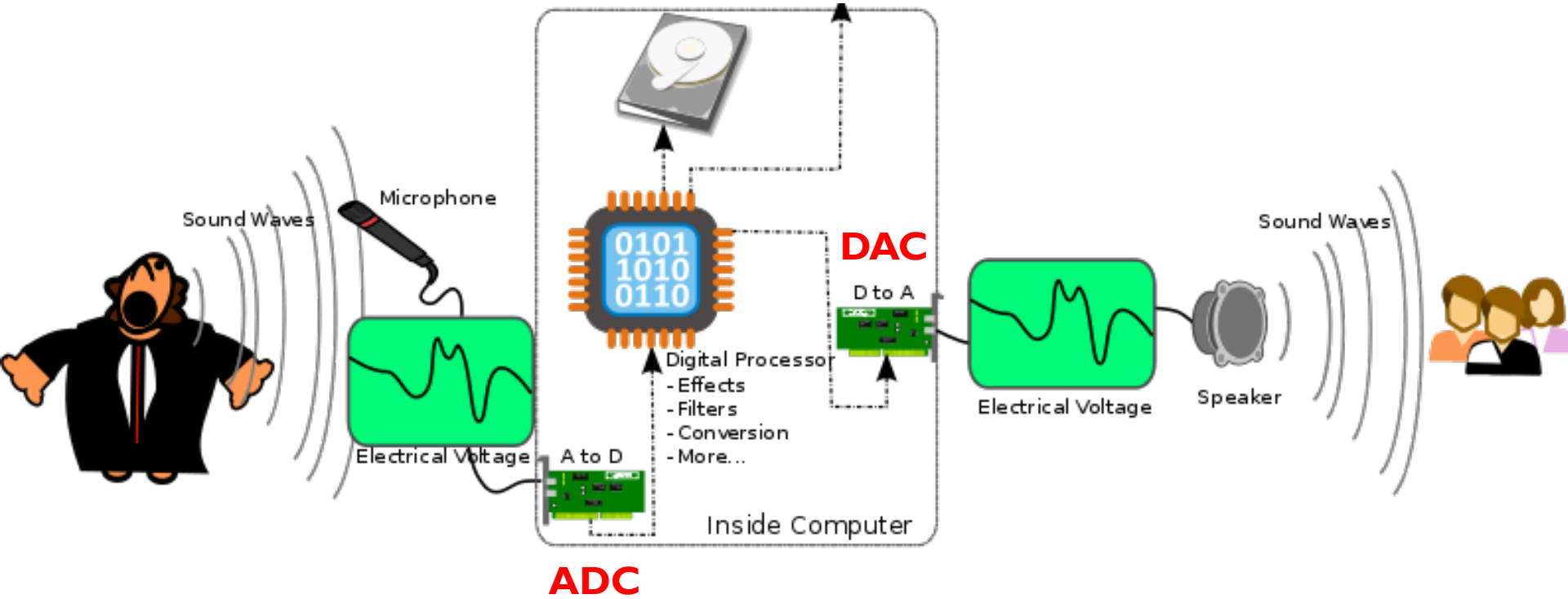




"0" ⇔ no signal, low voltage, switch off, "false"

"1" ⇔ there is a signal, high voltage, switch on, "true"

Both analog and digital signals are important!

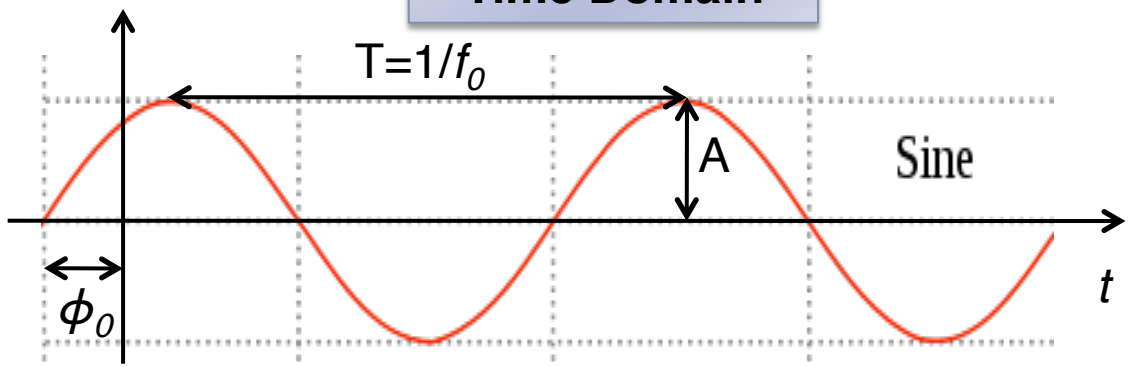


Analog Signals: Time and Frequency Domain

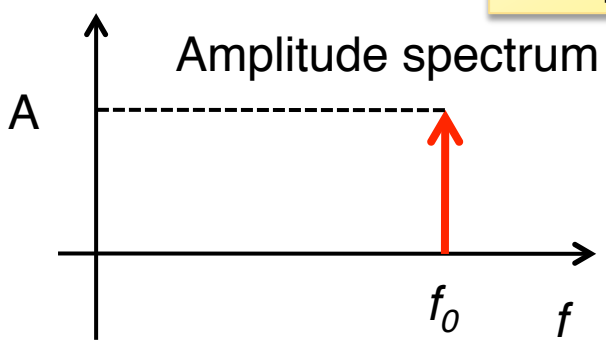
$$f(t) = A \cdot \sin(2 \cdot \pi \cdot f_0 \cdot t + \phi_0)$$

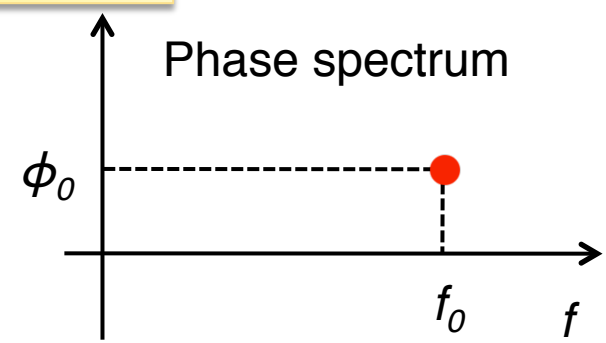
A – amplitude (A>0)
f_0 – frequency, $T=1/f_0$ = period
ϕ_0 – phase

Time Domain



Frequency Domain



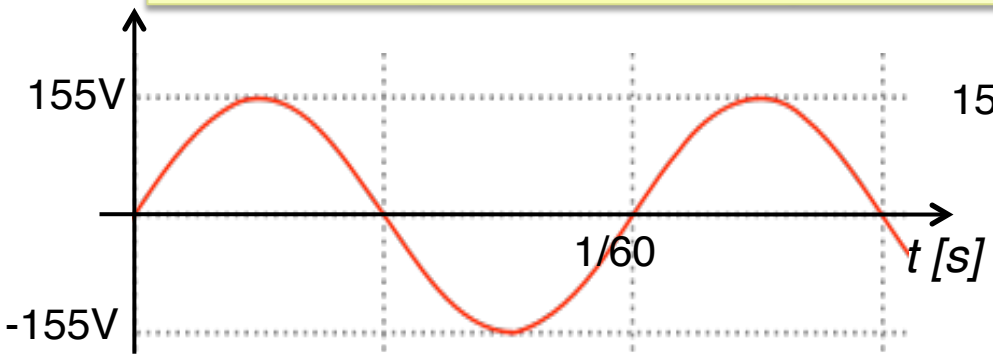


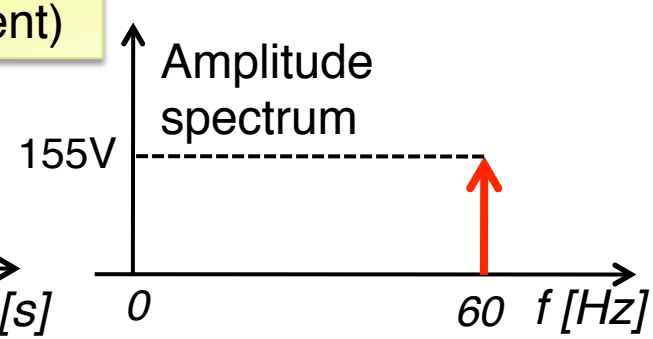
Both phase and amplitude are important!
But in ES 50, we will often "worry" about amplitude only.

Signals in electrical engineering: **voltages and currents**

$$v(t) = 155V \cdot \sin(2 \cdot \pi \cdot 60Hz \cdot t)$$

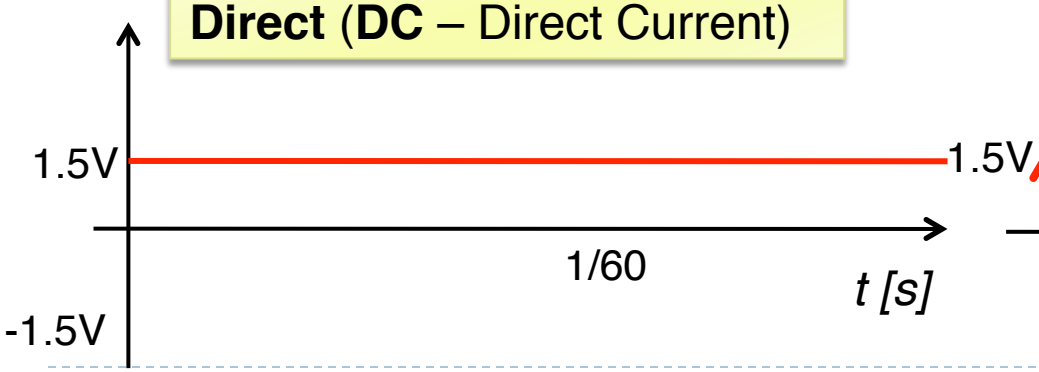
Alternating (AC - Alternating Current)

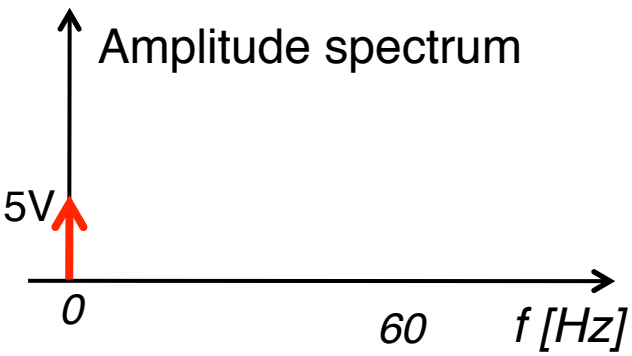




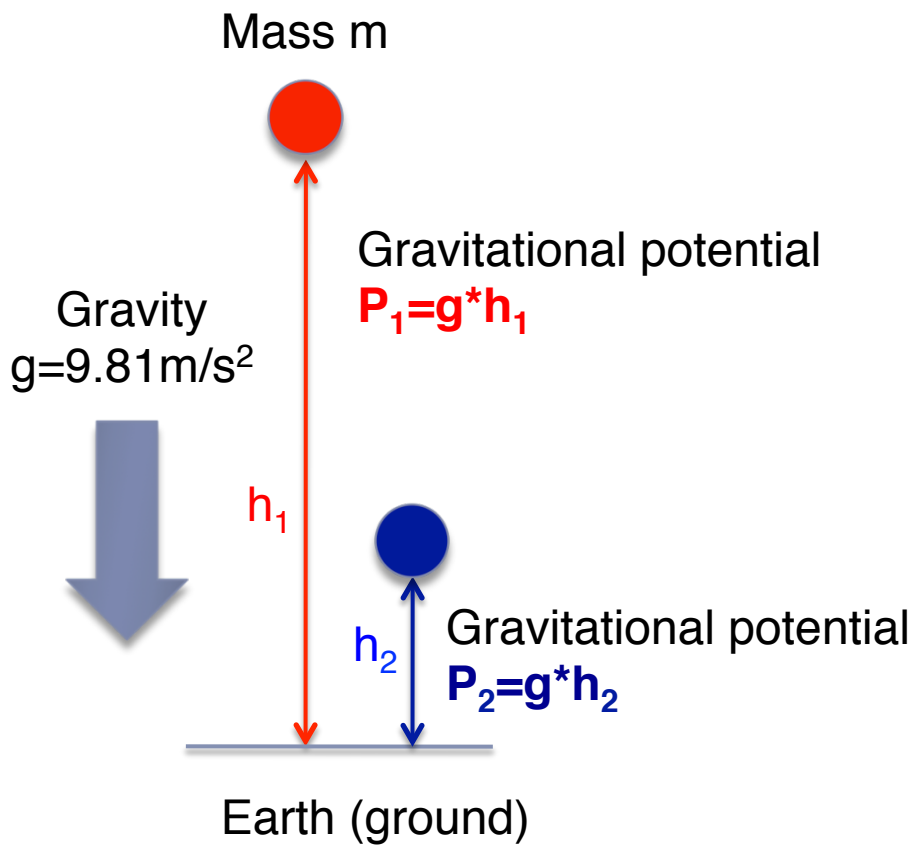
$$v(t) = 1.5V$$

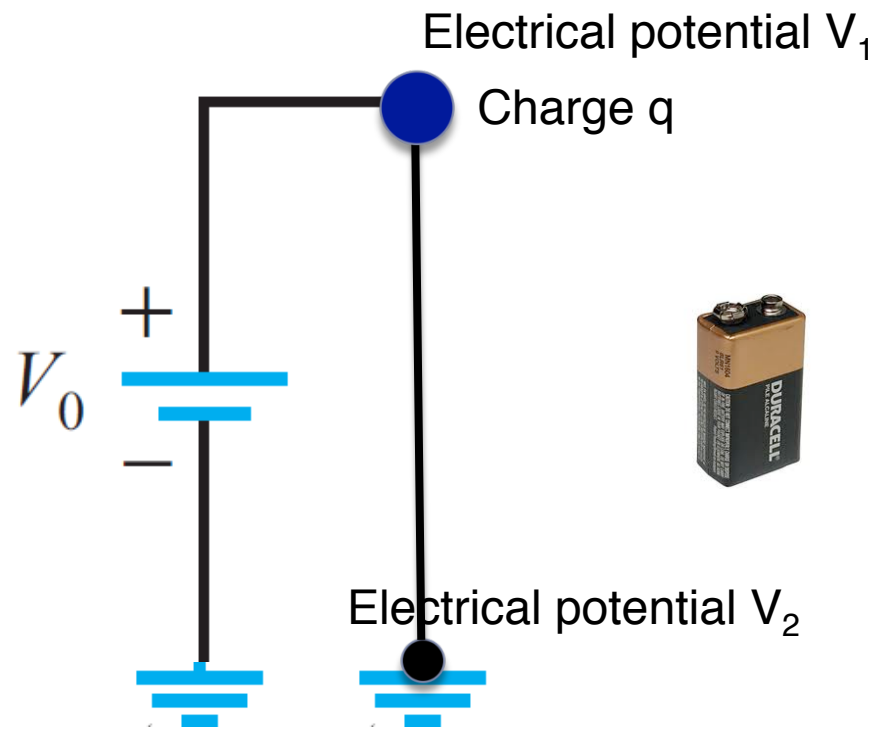
Direct (DC – Direct Current)





Potential: Ability of an object to do some work
Voltage: Difference between electrical potentials
Current: Motion of the free charges due to potential difference (voltage)



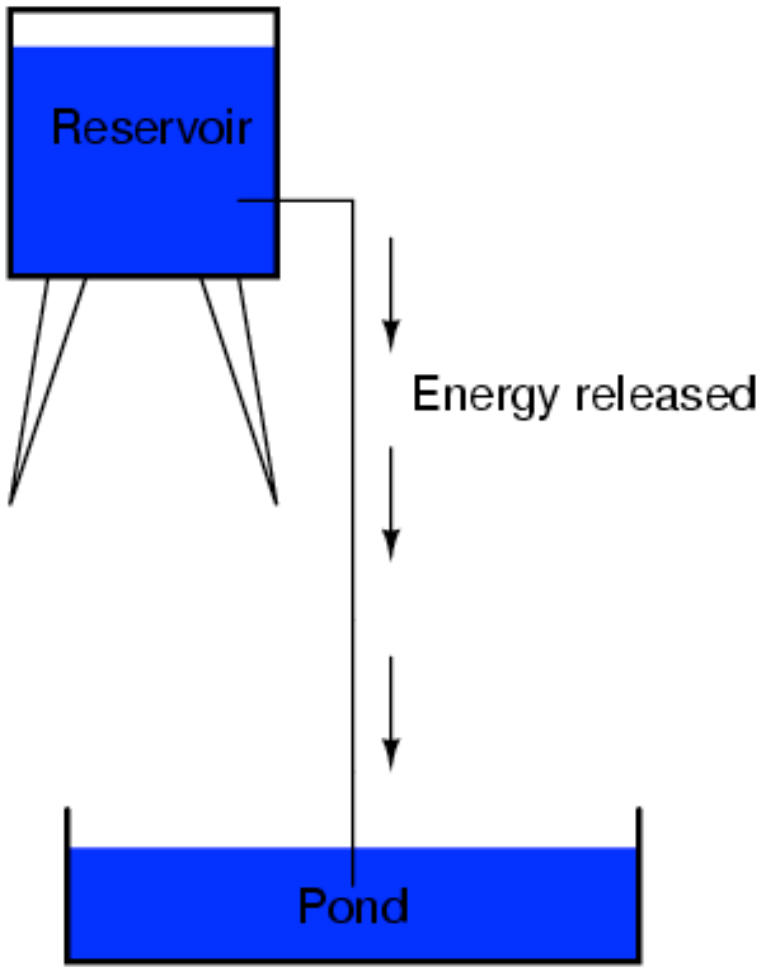


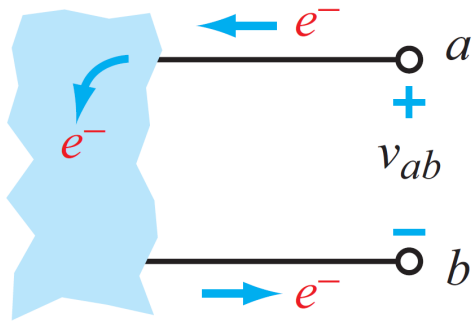
Potential difference: P_1-P_2

Voltage: $V_0= V_1-V_2$

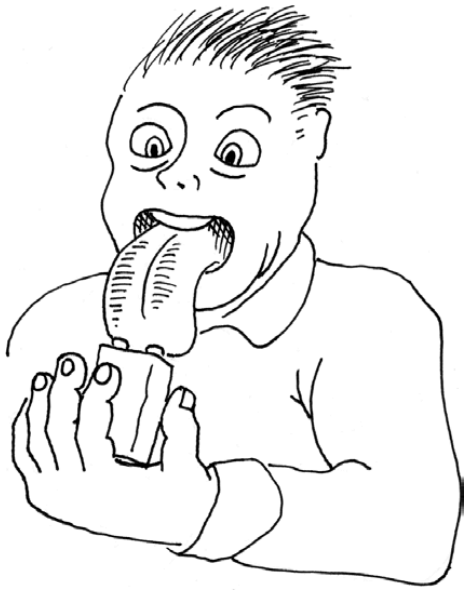
Current: $I=dq/dt$

Analogy: water ⇔ water pressure





Any material

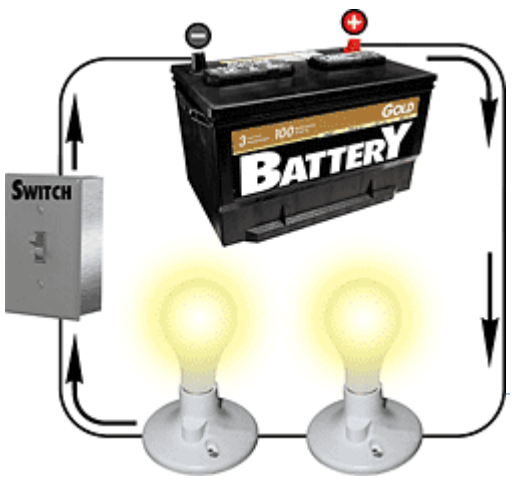


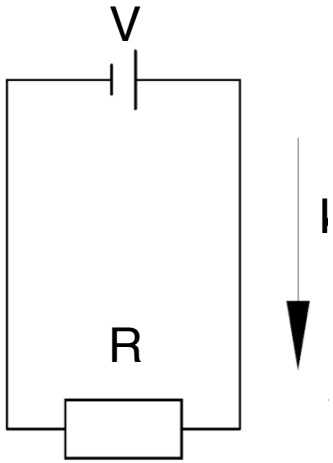
If you've never tried this, give it a shot… ☺

Voltages and Currents

- *Voltage refers to a difference in electrical potential between two parts of a* circuit.
  - A unit of voltage is a *volt (V),* after the inventor of the battery Alessandro Volta.
  - US AC sockets provide 110 volts and European AC sockets provide 220 volts.
  - *The Arduino microcontroller can be powered up* from a 5V USB connection, for example. Voltages inside computers are within a similar range (0 to 12V).

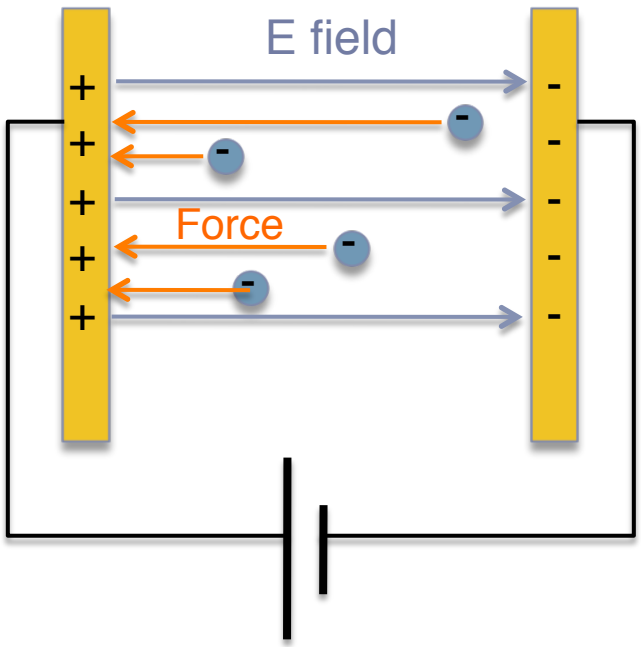
- If two parts of a circuit with different electrical charges are connected, voltage potential creates a current flow. A unit of current is an *ampere* (A). Often referred to as “amp”.
  - Larger voltage creates a larger current. If a component is used with a voltage higher than what it is rated for, it will usually burn out.
  - A lamp will be brighter with a 9V battery than with a smaller 4.5V battery.



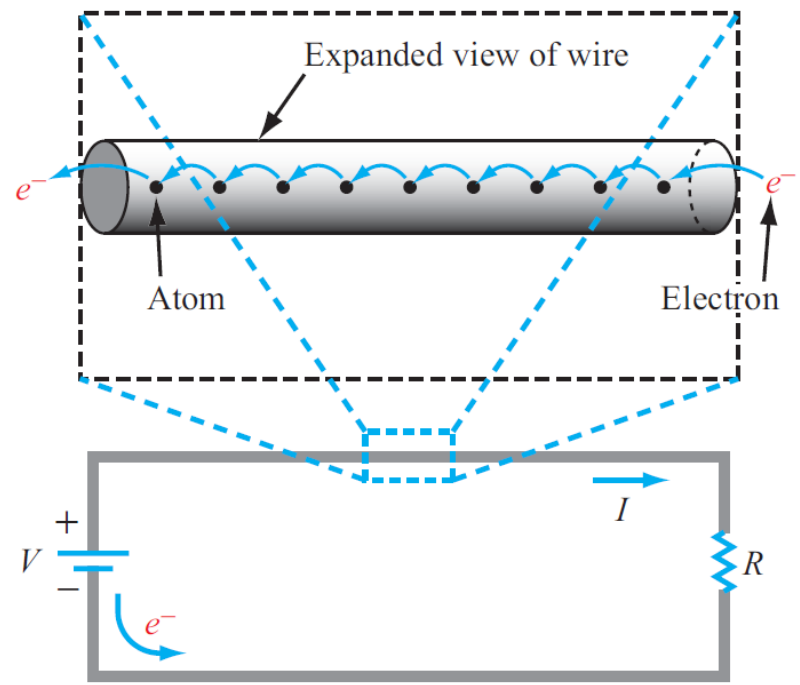


V - Voltage aka potential difference (provided by battery)
I - Amperage aka current
R - Resistance (e.g., light bulbs)

Physics behind this….



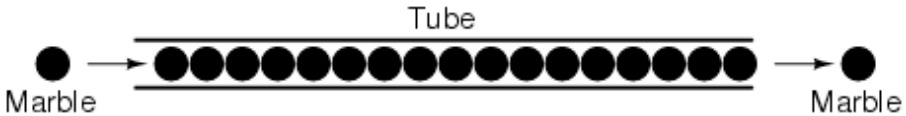
In wires, in the presence of atoms, this works slightly differently than in the free space:



- Electric field acting on a charged results in a force
  F = q * E
- Electrons move due to this force
- E field also results in potential energy of the particle

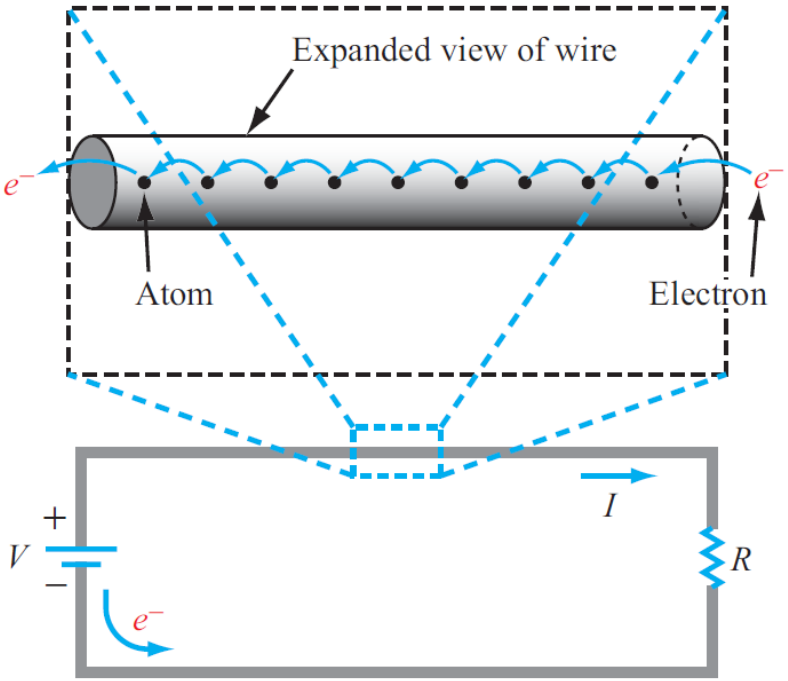
Physics behind this….

- As each electron moves through a conductor, it pushes on the one ahead of it, such that all the electrons move together as a group.
- The starting and stopping of electron flow through the length of a conductive path is **virtually instantaneous** (happens at the speed of light: $3*10^8$ m/s) from one end of a conductor to the other, even though the motion of each electron may be very slow (~1m/hour!). An approximate analogy is that of a tube filled end-to-end with marbles:

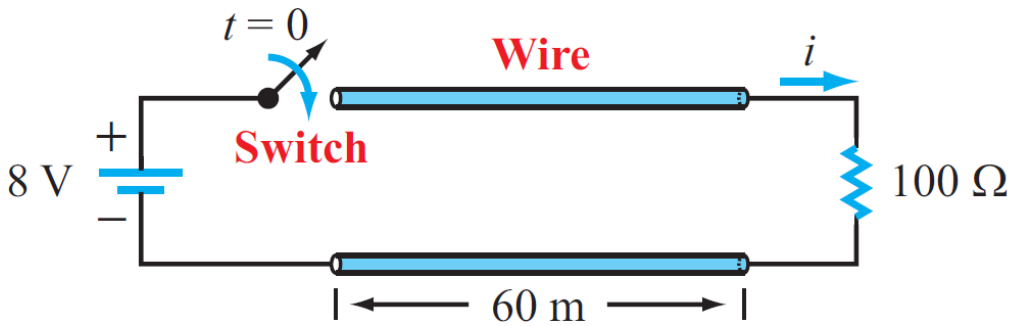


- When a single marble is inserted on the left-hand side, another marble will immediately exit the tube on the right. Even though each marble only traveled a short distance, the transfer of motion (marble flow) is virtually instantaneous!

In wires, in the presence of atoms, this works slightly differently than in the free space:



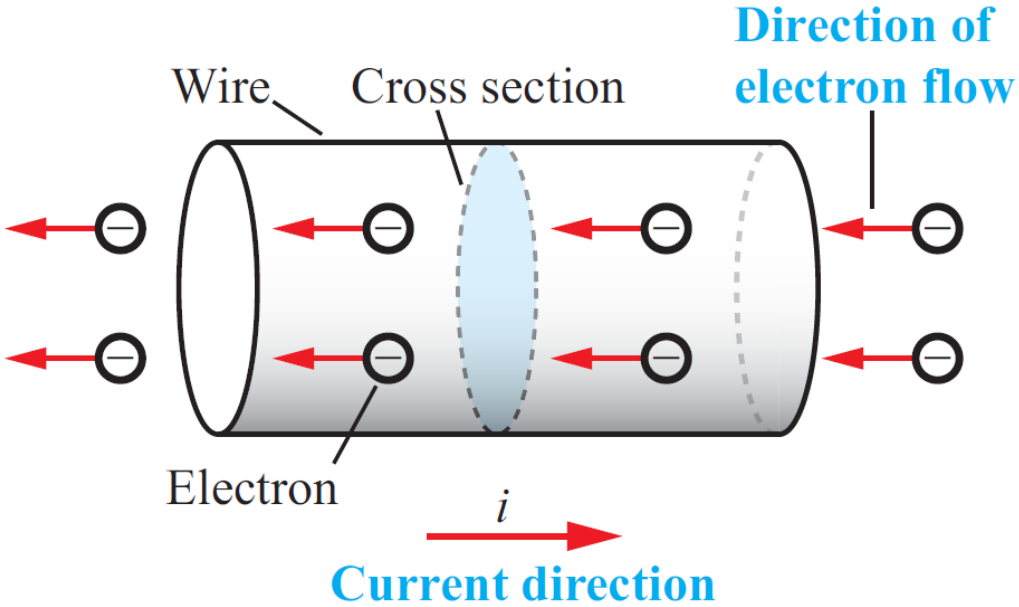
Electron Drift



$$i = \frac{dq}{dt} \qquad \text{(A)},$$

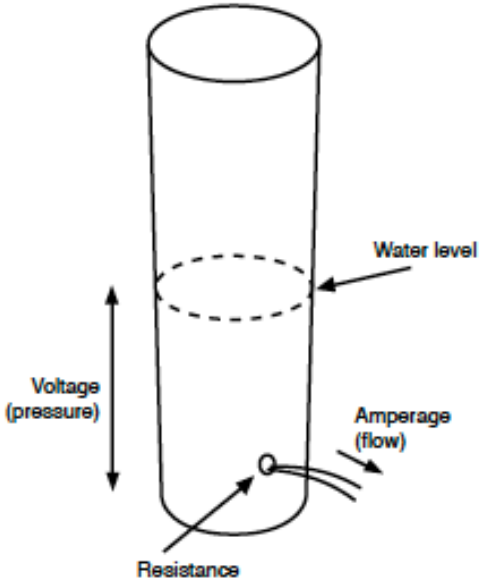
Response time = 0.2 microsecond

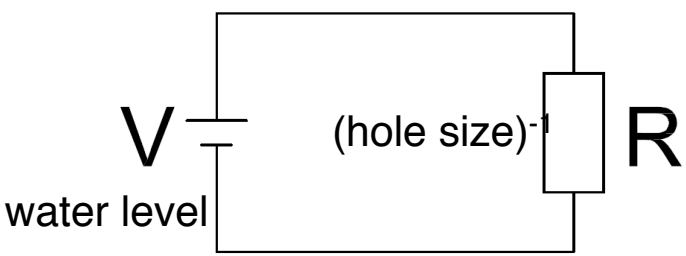
Actual travel time = 10 days!!



Analogy:
Voltage / Current ⇔ Water Height (pressure) / Water Flow

- Water tank ⇔ battery.
- The height of the water ⇔ voltage.
- Water flow through the hole, per second ⇔ amperage.
- The size of the hole is comparable to resistance.



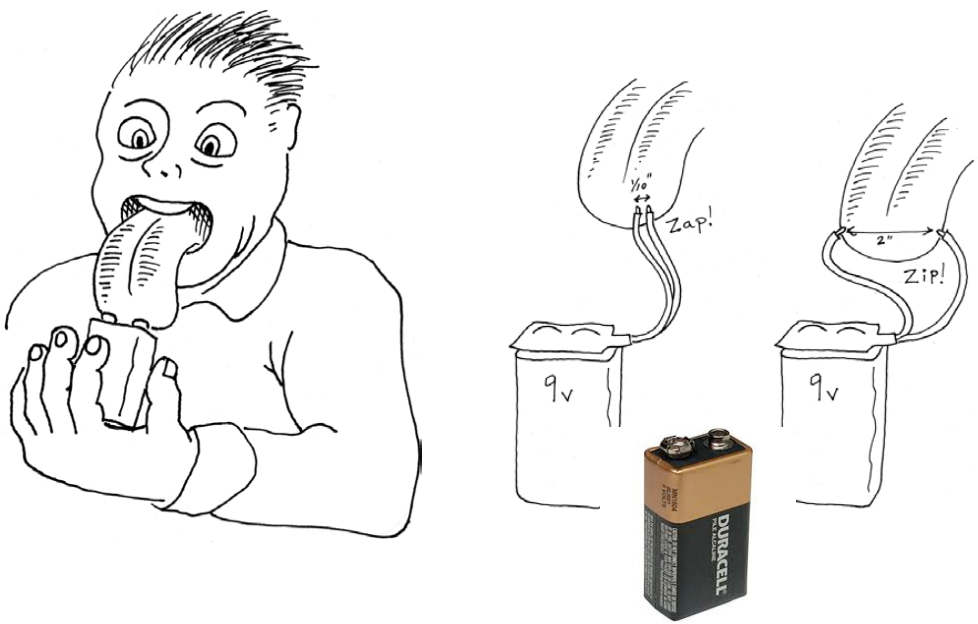


Ohm's Law: V = I * R

Larger resistance results in smaller current, for the same voltage

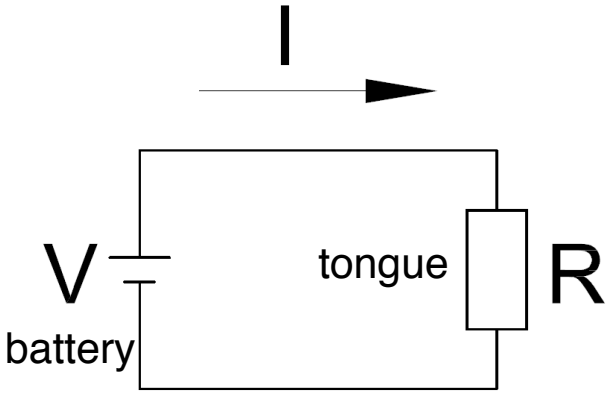
Learning by discovery

- If you've never tried this – give it a shot.



A shorter distance, i.e., lower resistance, allows greater flow of electricity, and a bigger zap.

Schematic of this experiment:



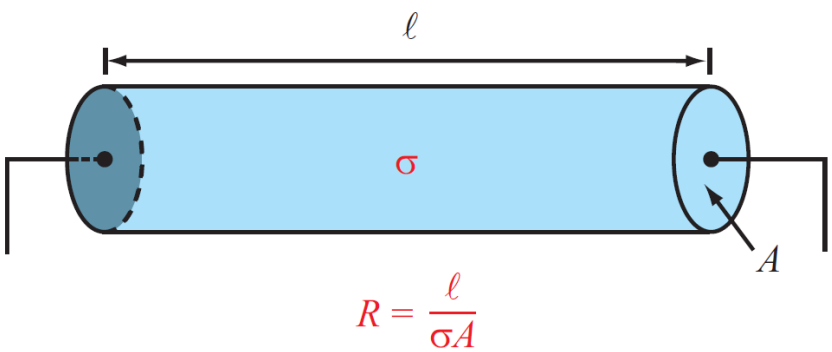
V - Voltage aka potential difference (provided by battery)
I - Amperage aka current
R - Resistance (provided by tongue)

Ohm's Law: V = I * R

Larger resistance results in smaller current, for the same voltage.

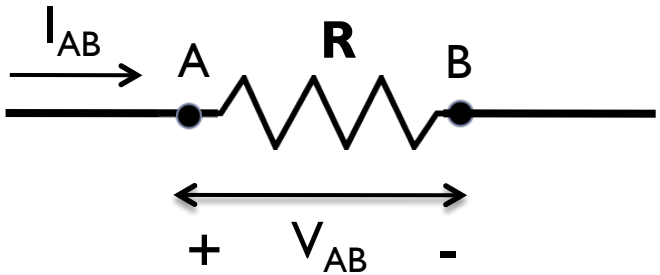
Resistors

Resistance: ability to resist flow of electric current



$$R = \frac{\ell}{\sigma A} = \rho \frac{\ell}{A} \qquad (\Omega),$$

ρ = resistivity: property of a material that resistor is made of

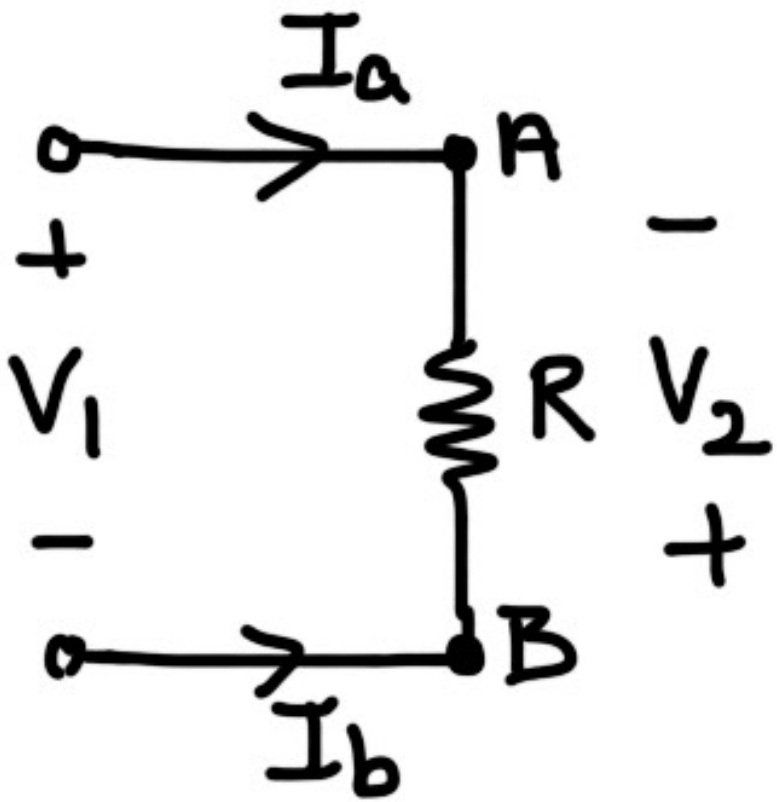


<u>Resistive load – or simply Resistor:</u> Current and voltage are related via Ohm's Law

$$V_{AB} = R \cdot I_{AB}$$

NOTE: Reference directions and sign convention for current and voltages are extremely important!
If we change the reference direction, we need to add some "-" signs

Reference Direction Example: Fill in the correct +/- sign



$V_1 = +\ I_a \bullet R$

$V_1 = -\ I_b \bullet R$

$V_2 = -\ I_a \bullet R$

$V_2 = +\ I_b \bullet R$

$I_a = -\ I_b$

$V_{AB} = +\ V_1$

$V_{AB} = -\ V_2$

$V_1 = -\ V_2$

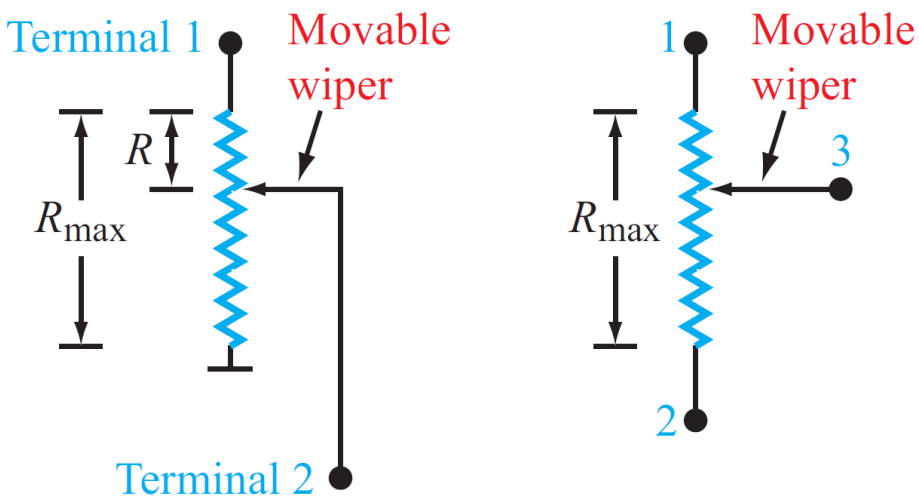
Conductivity

Table 2-1: Conductivity and resistivity of some common materials at 20°C.

Material	Conductivity σ (S/m)	Resistivity ρ (Ω-m)
Conductors		
Silver	6.17×10^{7}	1.62×10^{-8}
Copper	5.81×10^{7}	1.72×10^{-8}
Gold	4.10×10^{7}	2.44×10^{-8}
Aluminum	3.82×10^{7}	2.62×10^{-8}
Iron	1.03×10^{7}	9.71×10^{-8}
Mercury (liquid)	1.04×10^{6}	9.58×10^{-8}
Semiconductors		
Carbon (graphite)	7.14×10^{4}	1.40×10^{-5}
Pure germanium	2.13	0.47
Pure silicon	4.35×10^{-4}	2.30×10^{3}
Insulators		
Paper	$\sim 10^{-10}$	$\sim 10^{10}$
Glass	$\sim 10^{-12}$	$\sim 10^{12}$
Teflon	$\sim 3.3 \times 10^{-13}$	$\sim 3 \times 10^{12}$
Porcelain	$\sim 10^{-14}$	$\sim 10^{14}$
Mica	$\sim 10^{-15}$	$\sim 10^{15}$
Polystyrene	$\sim 10^{-16}$	$\sim 10^{16}$
Fused quartz	$\sim 10^{-17}$	$\sim 10^{17}$

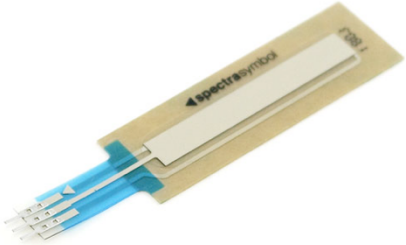
Table 2-3: Common resistor terminology.

Thermistor	R sensitive to temperature
Piezoresistor	R sensitive to pressure
Rheostat	2-terminal variable resistor
Potentiometer	3-terminal variable resistor



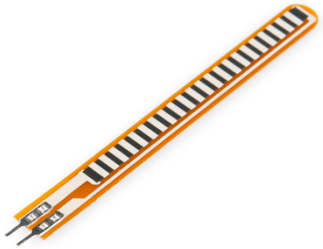
(a) Rheostat (b) Potentiometer

Applications: Resistors as Sensors



Pressure-sensitive variable resistor: By pressing down on various parts of the strip, the resistance linearly changes from 100Ohms to 10,000Ohms allowing the user to very accurately calculate the relative position on the strip.
Can be used as an accurate positional indicator, variable user input (volume level input for example), straight user input, etc.

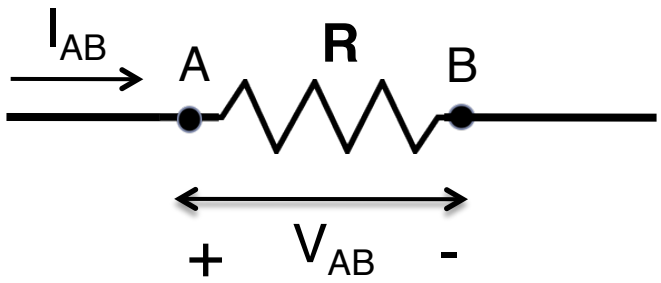
Photocell light sensor: Changes its resistance depending on the amount of light it is exposed to. These little sensors make great ambient light triggers (when light in the room turns on, do something).



Flex sensor: As the sensor is bent, the resistance across the sensor increases.

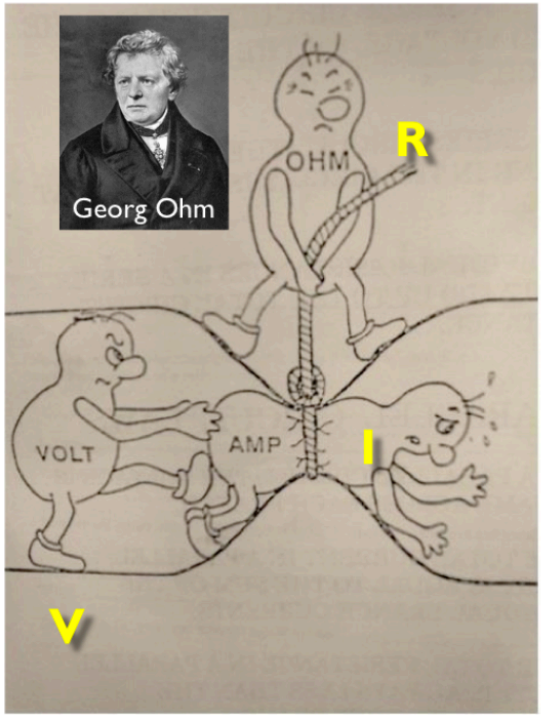
Lab #1 will connect a variable resistor sensor to an Arduino pin

Summary:
Ohm's Law & Importance of the Reference



$$V_{AB} = R \bullet I_{AB}$$

Alessandro Volta



Adnre Marie-Ampere

NOTE:
Reference directions & sign convention for current and voltages are extremely important!

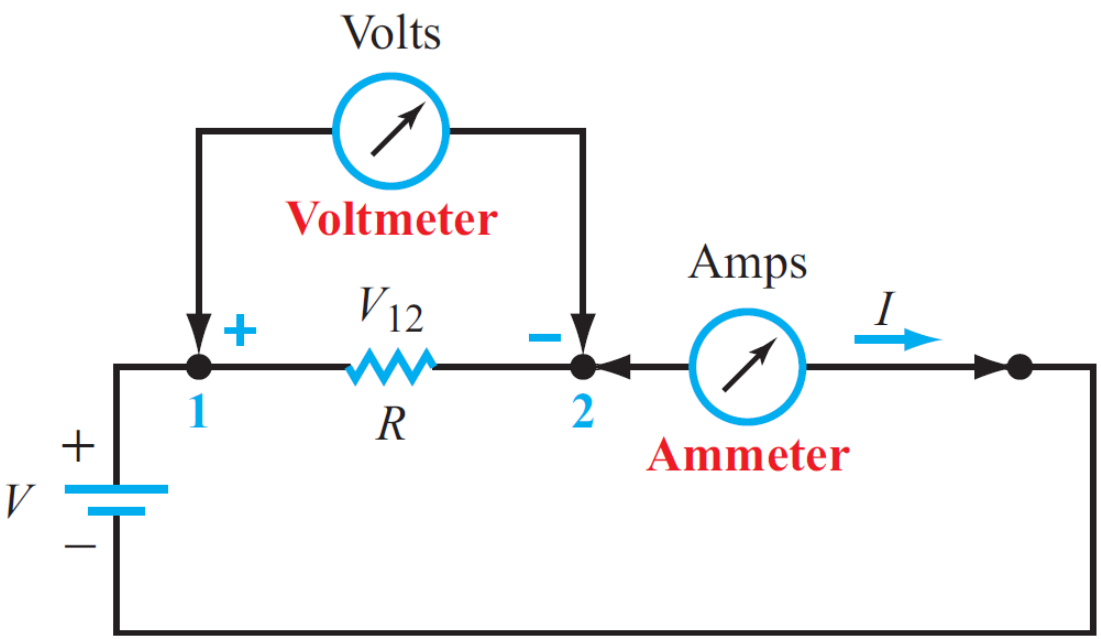
If we change the reference direction, we need to add some "-" signs

A historical aside on Mr. Volta, Mr. Ampere and Mr. Ohm

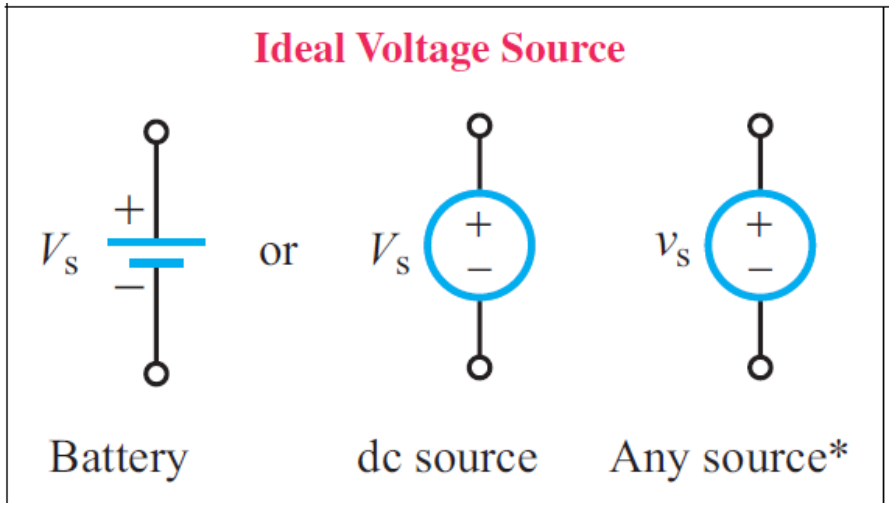
- **Alessandro Volta** (born in Italy in 1745)
  - Studied chemistry (discovered methane in 1776) and then became a professor of physics;
  - Became interested in the so called galvanic response
    Galvanic response of a frog leg & Neuro-bridge (final project idea ☺)
  - First battery: A wine glass full of salt water with copper and zinc electrodes
  - Refined his battery in 1800 by stacking plates of copper and zinc, separated by cardboard soaked in salt and water. This became known as "voltaic pile".
- **Andre-Marie Ampere** (born in France in 1775)
  - A mathematical prodigy who became a science teacher (though, self-educated)
  - Derived a theory of electromagnetism in1820, describing the way that an electric current generates a magnetic field.
  - Found that an electric current running through a wire creates a magnetic field around it, also known as Ampere's Law. He used this principle to make the first reliable measurements of what came to be known as amperage.
- **Georg Simon Ohm (**born in Bavaria in 1787)
  - Worked in obscurity for much of his life, studying the nature of electricity using metal wire that he had to make for himself
  - Demonstrated in 1827 that the electrical resistance of a conductor such as copper varied in inverse proportion with its area of cross-section, and the current flowing through it is proportional to the voltage applied to it, as long as temperature is held constant.
  - Today, this important discovery is known as **Ohm's Law.**

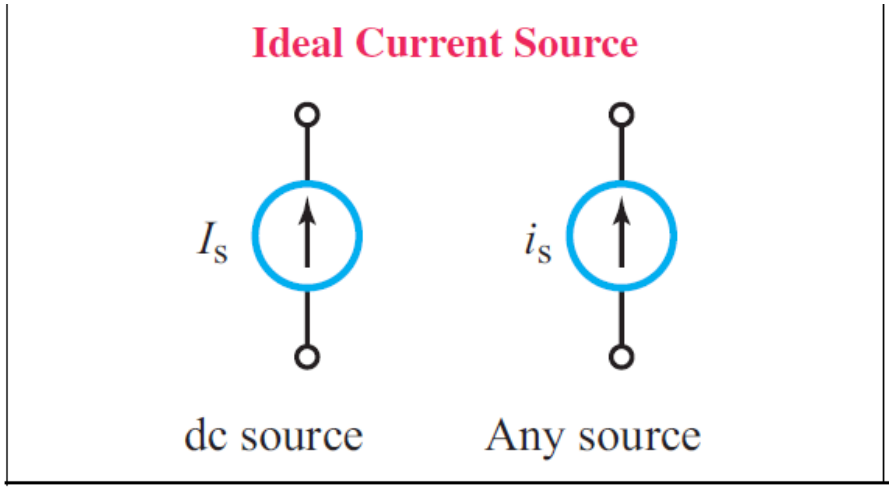
Lab: Measuring Voltage & Current

- Voltmeter: measures voltage without drawing current
  - Is introduced in **PARALLEL** with the element whose voltage you wish to measure
- Ammeter: measures current without dropping voltage
  - Is introduced in **SERIES** with the element whose current you wish to measure



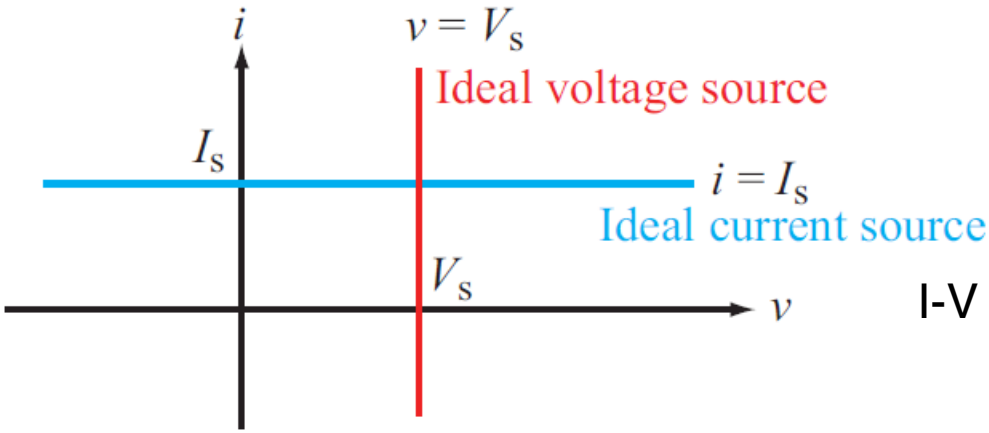
Voltage and Current Sources





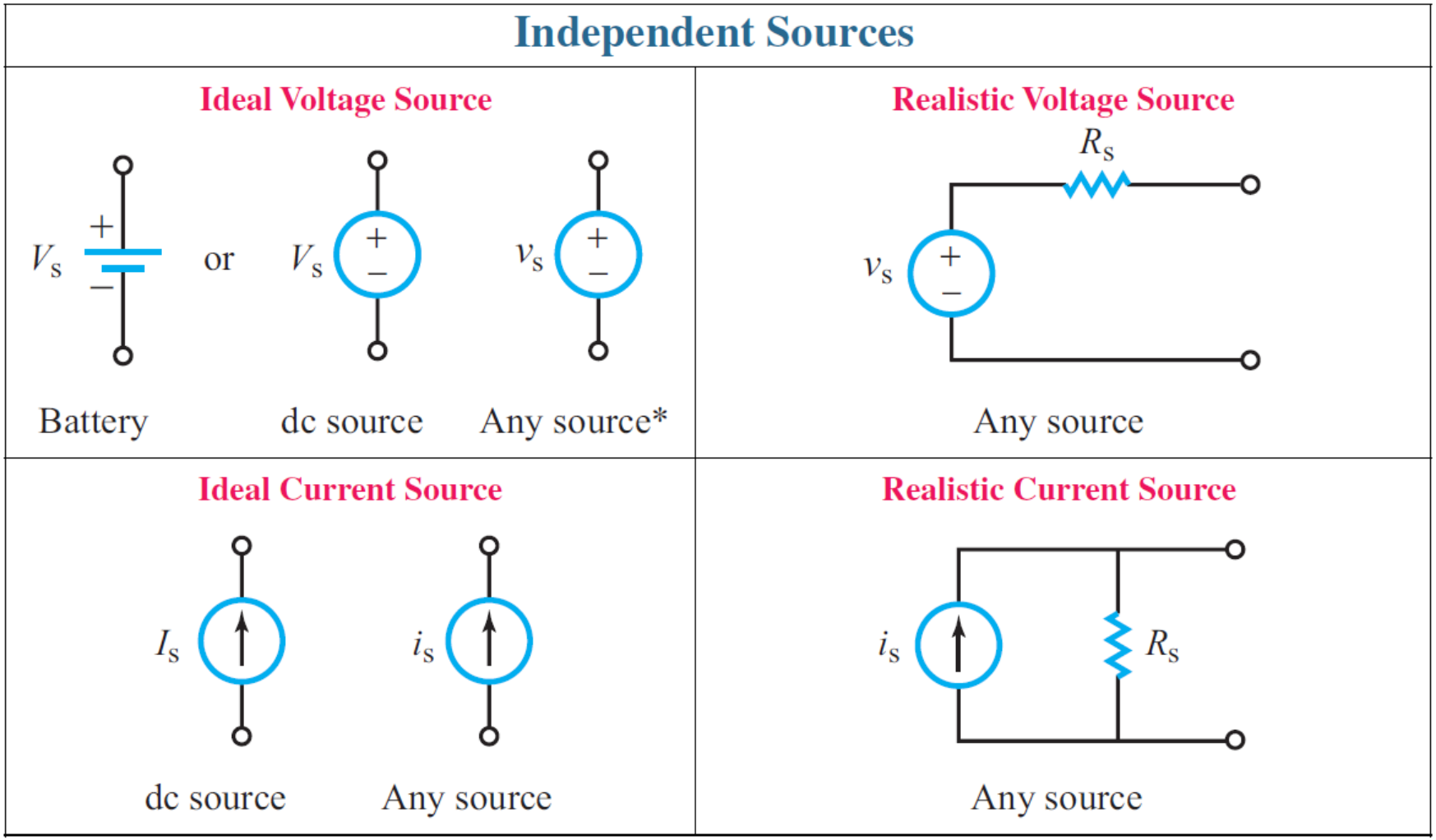
<u>Ideal Voltage Source:</u> outputs "prescribed" voltage, regardless of the load;

<u>Ideal Current Source:</u> outputs "prescribed" current, regardless of the load;

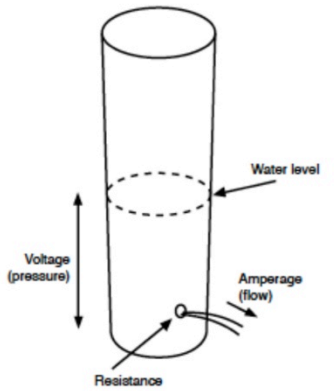


I-V characteristics (current *vs.* voltage) for ideal sources

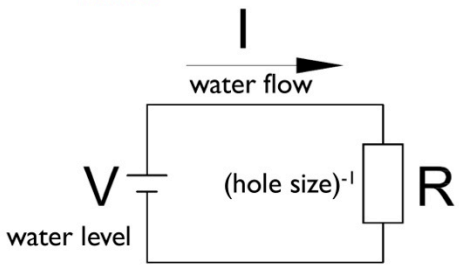
Sources: Ideal and Non-Ideal/Realistic



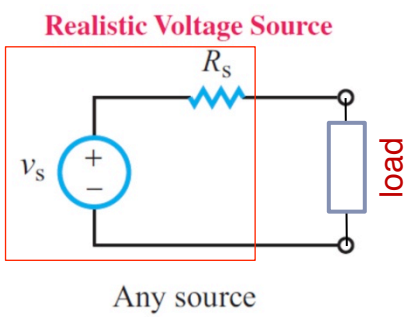
Constant Current, Constant Voltage…



Recall: Analogy of *height* of water as VOLTAGE
Diameter of hole as RESISTANCE



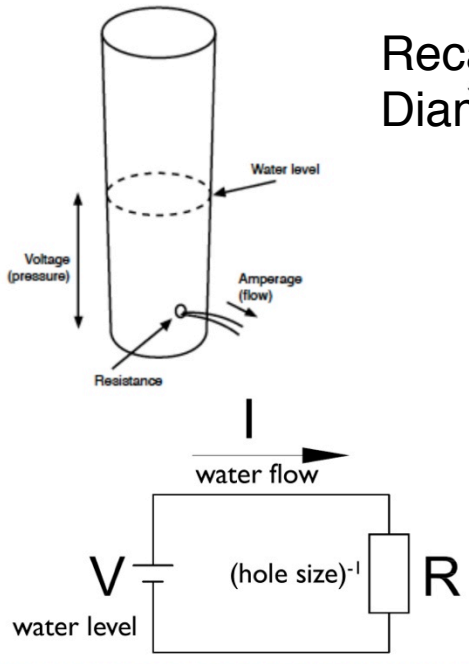
An *ideal* constant voltage source, maintains its voltage (height) no matter what the load: imagine if the hole had a tremendously large diameter



How do we model a 'realistic' voltage source?

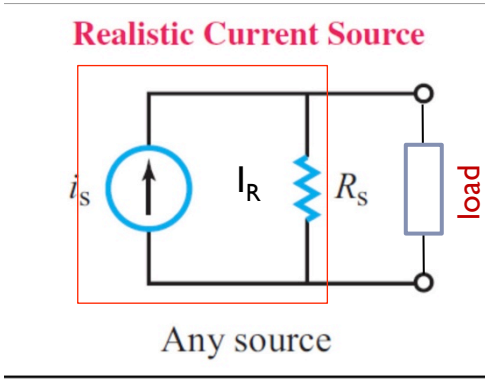
As soon as the source begins delivering voltage to a 'load', current will flow across R_s, resulting in I_sR_s = voltage drop across the (internal, parasitic) resistor.
$V_{load} = V_s - I_sR_s$.

Constant Current, Constant Voltage…



Recall: Analogy of *height* of water as VOLTAGE
Diameter of hole as RESISTANCE

An *ideal* constant voltage source, maintains its voltage (height) no matter what the load: imagine if the hole had a tremendously large diameter

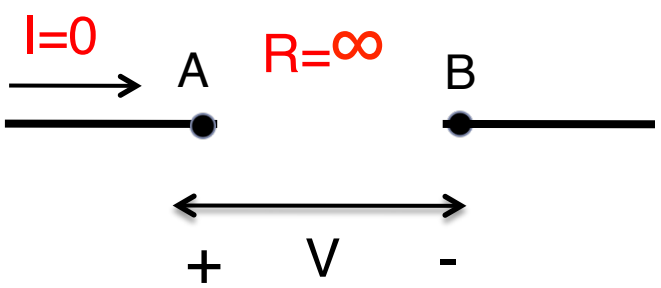


How do we model a 'realistic' current source?

As soon as the source begins delivering current to a 'load', current will *also* flow across R_s, resulting in $i_s - I_R$ delivered to the load.

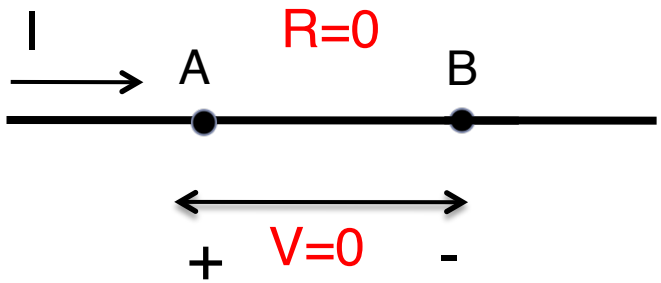
Open and Short Circuits

<u>Open Circuit:</u>
current through open is ZERO!
(no path for current to flow)

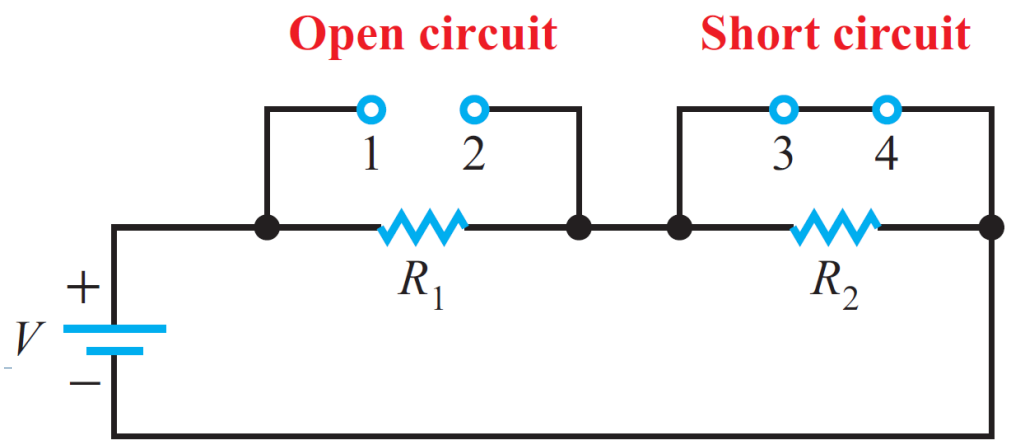


An *open circuit means that electricity cannot flow through a device.* For example, a device that is shut down by its power switch is an open circuit. Electricity can't flow when the circuit is "opened" by the switch.

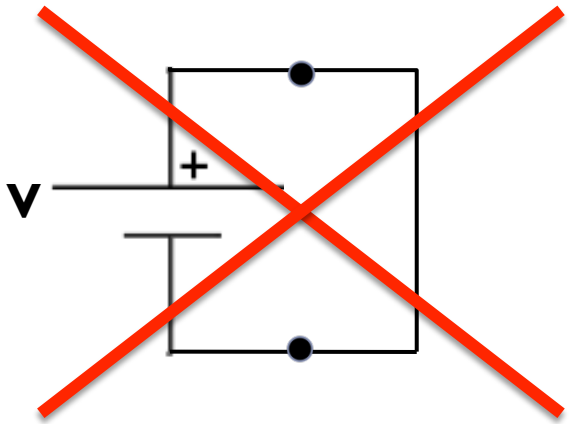
<u>Short Circuit:</u>
voltage across short is ZERO!
(voltage drop is zero)



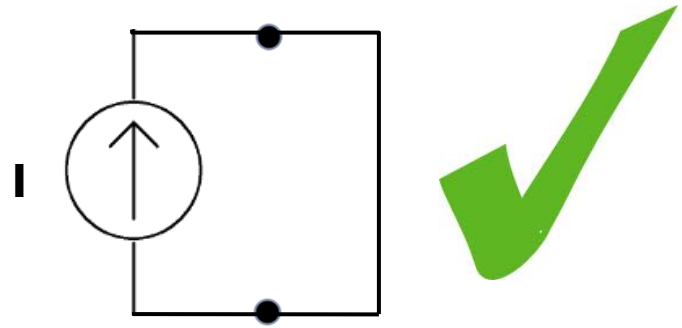
A *short circuit means that electricity can flow without any resistance.* Device that is "short circuited" or "shorted" will have zero voltage drop across its terminals



Also, important to remember….



DO NOT short a voltage source!
Q: Why?



It is OKAY to short a current source!
Q: Why?

Power

Rate of expending or absorbing energy

$$P = \frac{dw}{dt} = \frac{dw}{dq}\frac{dq}{dt} = vi$$

$$\sum P = 0$$ Energy conservation

Units: Watts

One watt = Power rate of doing one joule of work per second. 1W = 1A x 1V