E40M
Charge, Current, Voltage and Electrical Circuits
KCL, KVL, Power & Energy Flow

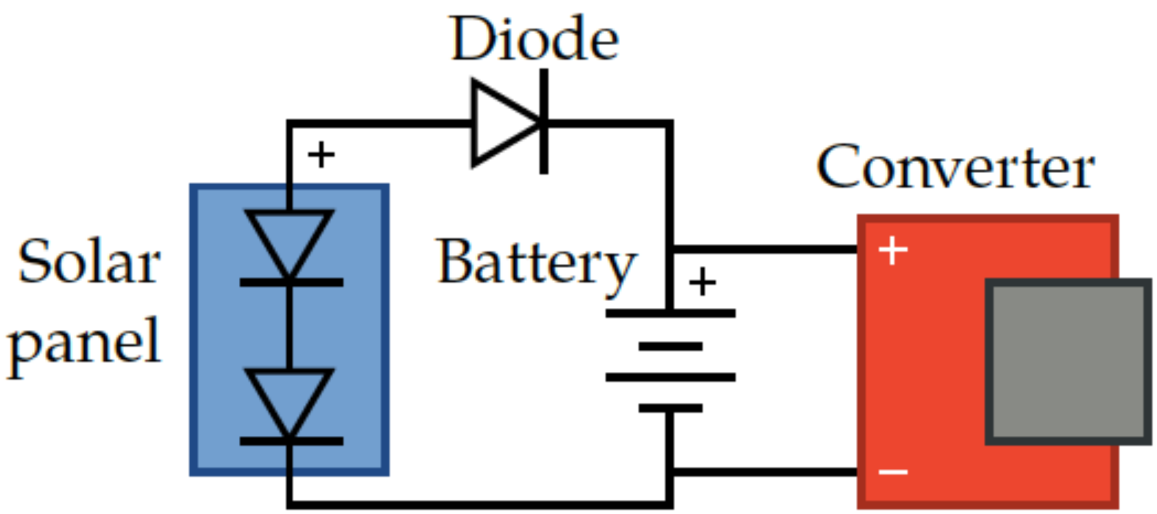
Reading For Topics In These Slides

- Chapter 1 in the course reader

OR

- A&L 1.6-1.7 - Two terminal elements
  - Voltage source; resistor; wires
- A&L 2.1-2.2 – Circuit Laws KCL & KVL

Understanding the Solar Charger – Lab Project #1



We need to understand how:

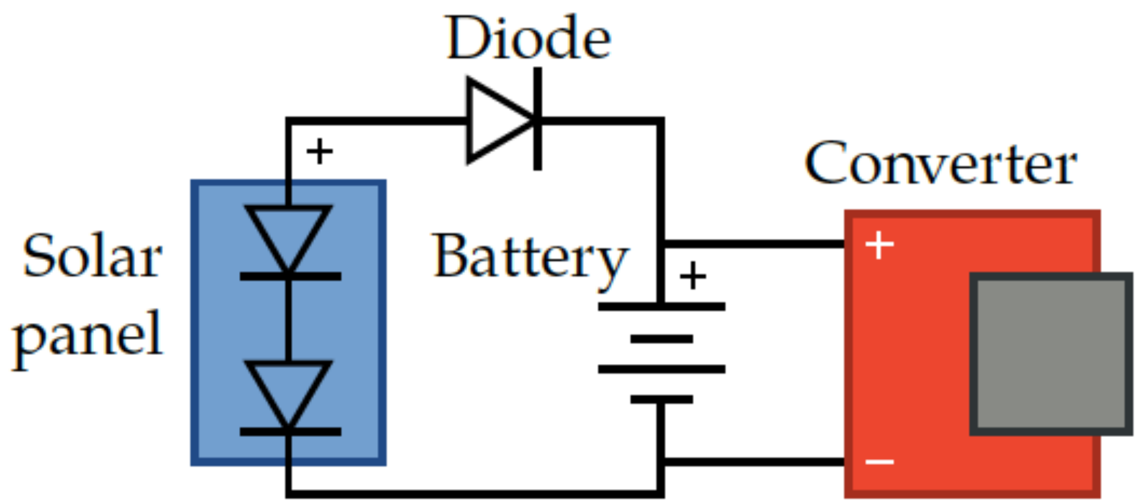
1. Current, voltage and power behave in circuits
2. Electrical devices constrain current and voltage
3. Diodes including solar cells work
4. Voltage converter works (later in the quarter).

What Does It Do?

- Takes energy from sun light
- Stores it
- Provides that energy later
  - To charge your cellphone
  - Create reading light, flashlight

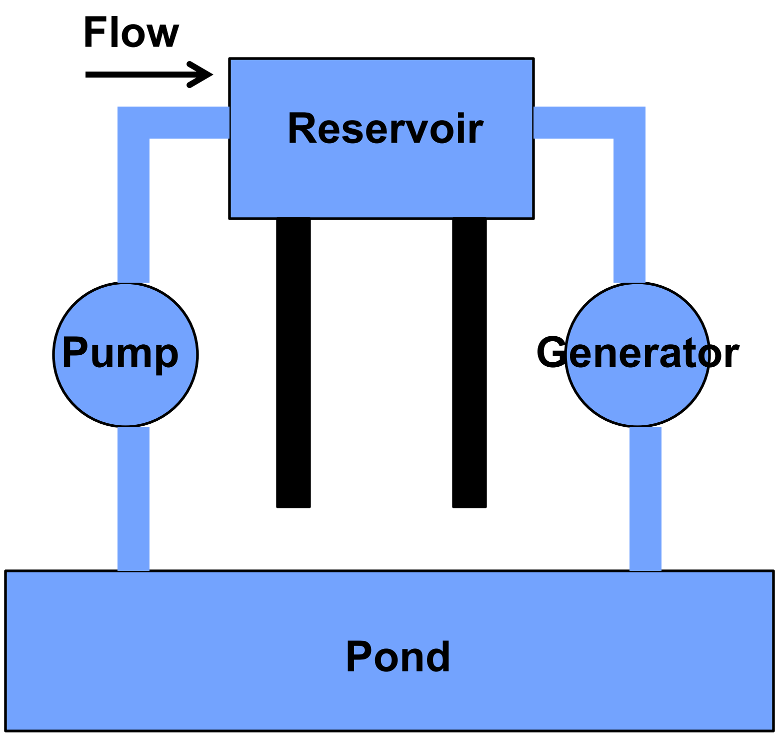
How does it do that?

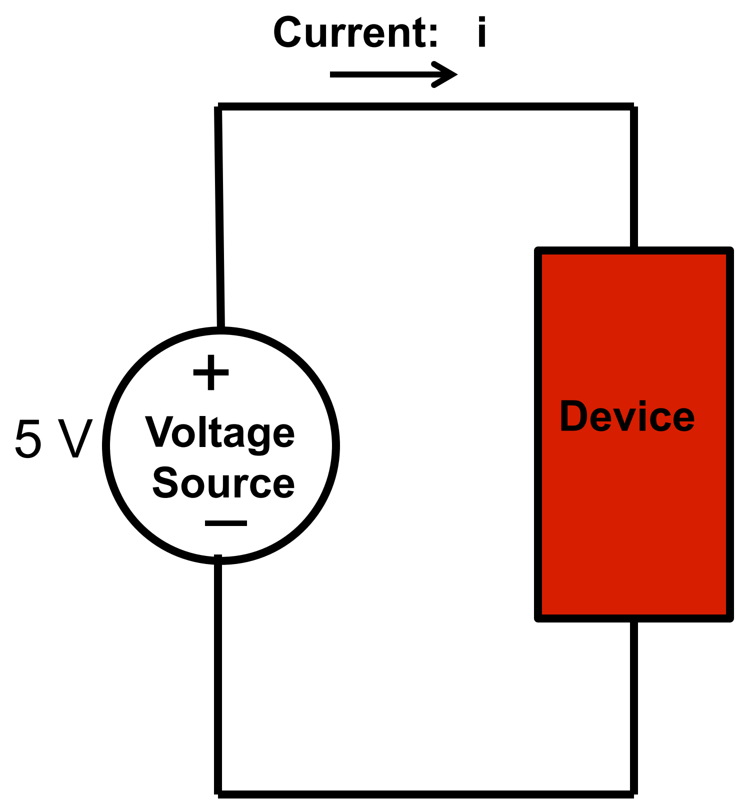
How Our Solar Charger Works



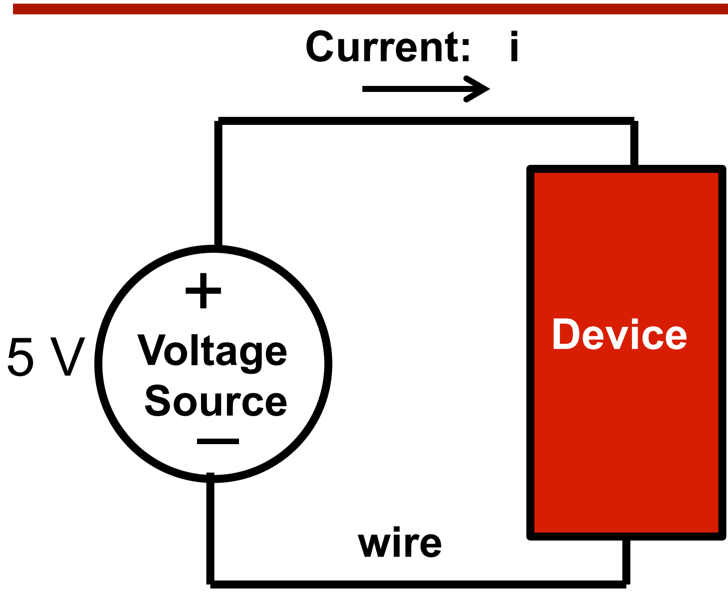
- Converts some energy from sunlight into an electrical signal
- That **electrical signal** connects to a rechargeable battery
  - So energy flows from solar cell to battery
- Another electrical signal connects the battery to the USB port
  - So energy can flow to the USB, and charge your phone
- So we need to understand electrical signals

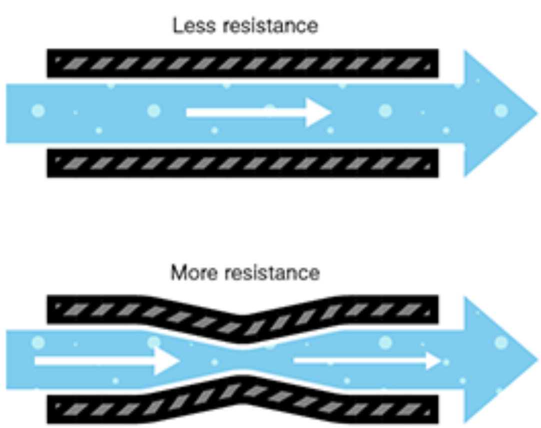
Fluidic “Circuits” ≅ Electrical Circuits





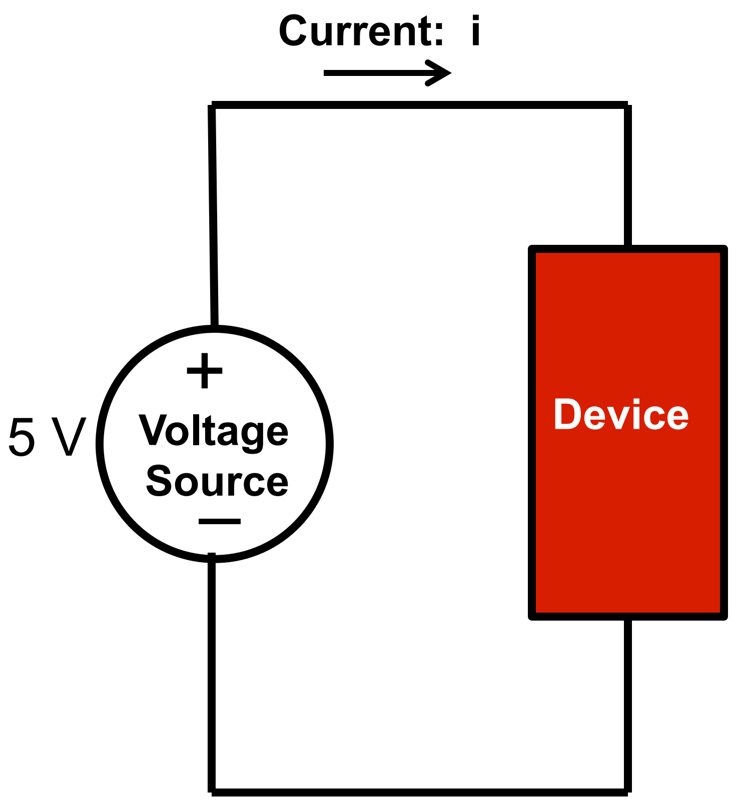
Electrical Charge





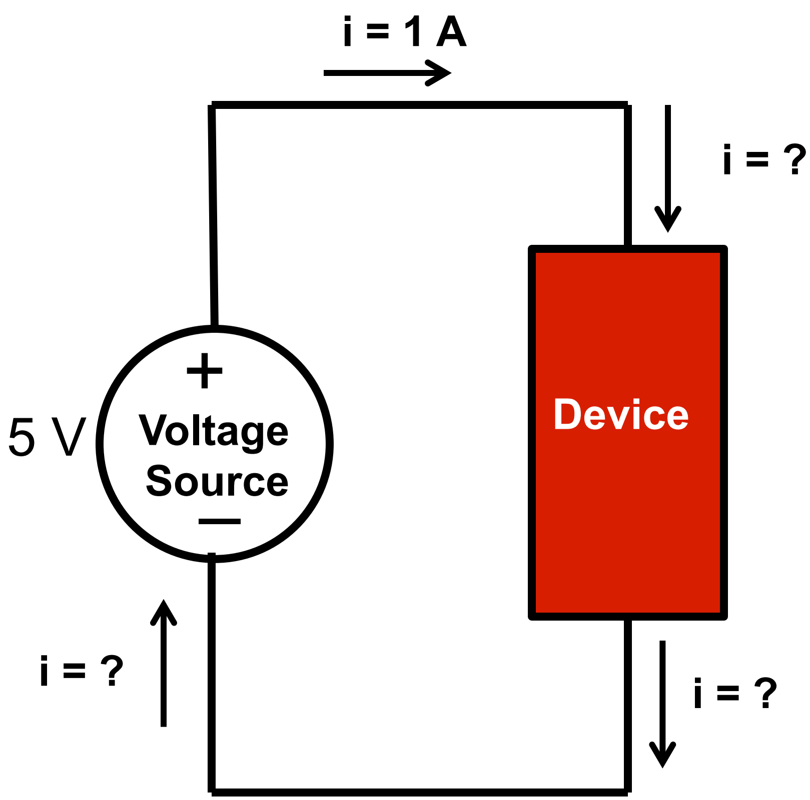
- In electrical systems current is carried by charges, usually electrons
- Charge is measured in **Coulombs**
  - 1 coulomb is a *lot* of charge
  - Each electron has a charge of -1.6×10^{-19} Coulombs
- Charge can flow (move) in a material that **conducts**
  - **wires**, **devices** (power is dissipated if they have resistance)
- Like magnets, opposite charges attract; like charges repel.

Electrical Current



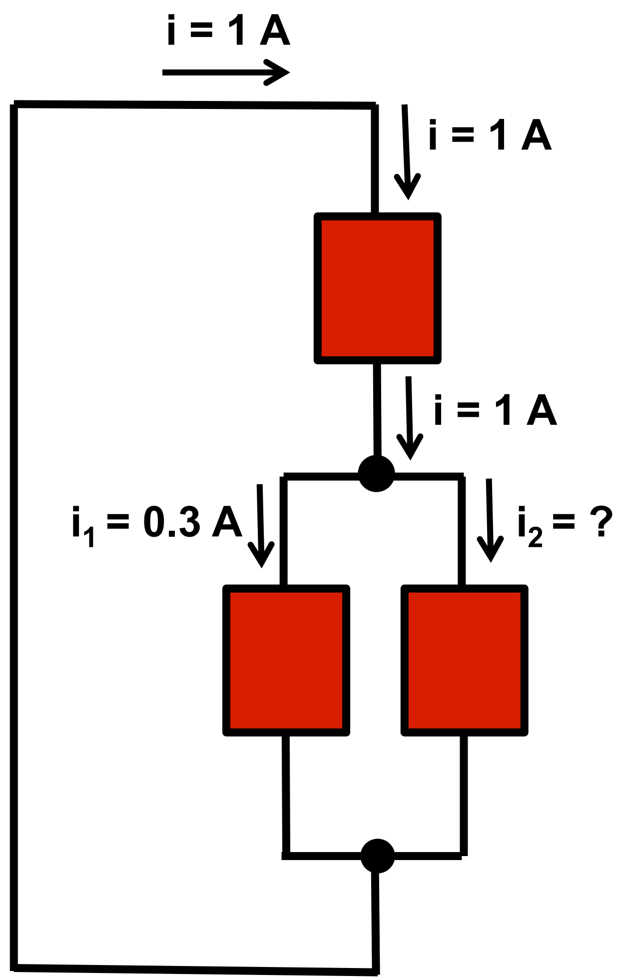
- Moving charge is called current
  - Current is the flow of charge per second
  - Past some measured point
- Its unit is the Ampere, usually called amps and abbreviated A
  - 1 A = 1 Coulomb/sec = 1 Cs^{-1}
- The symbol for current is usually i

Electrical Current is Continuous



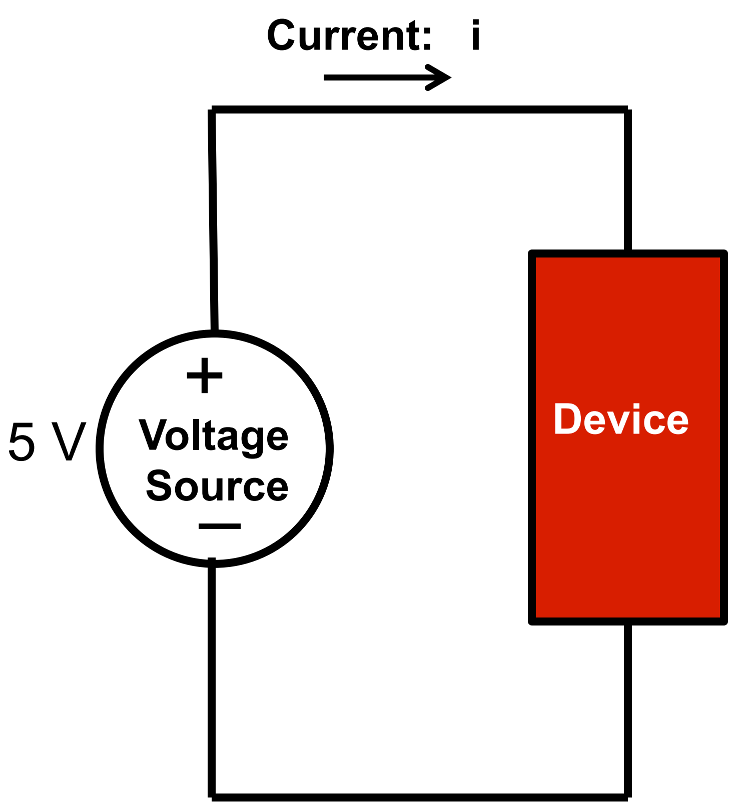
- The current flow in a wire remains the same along it, since there are no “leaks” of charge out of the wire
- The current flows in one terminal of the device and out the other
- The wires and the device are neutral (zero charge), even though current is flowing through them

Circuits with Branches: Constraints on Currents (KCL)



- The black dot is an electrical connection between the wires
- What is the value of the current i_2?

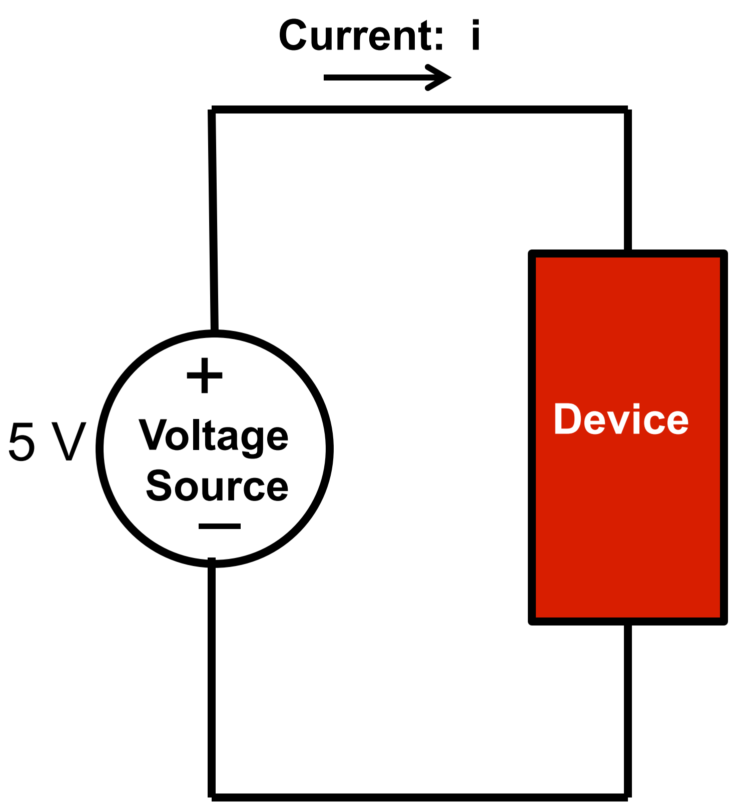
If You Think of Charge as a Fluid



- Current is then fluid flow
- Current constraints are then about fluid conservation
  – The fluid in any object is constant
- But we know that a fluid doesn't move unless it is pushed
  – What pushes charge to make it move?

A Voltage Source

Electrical Voltage



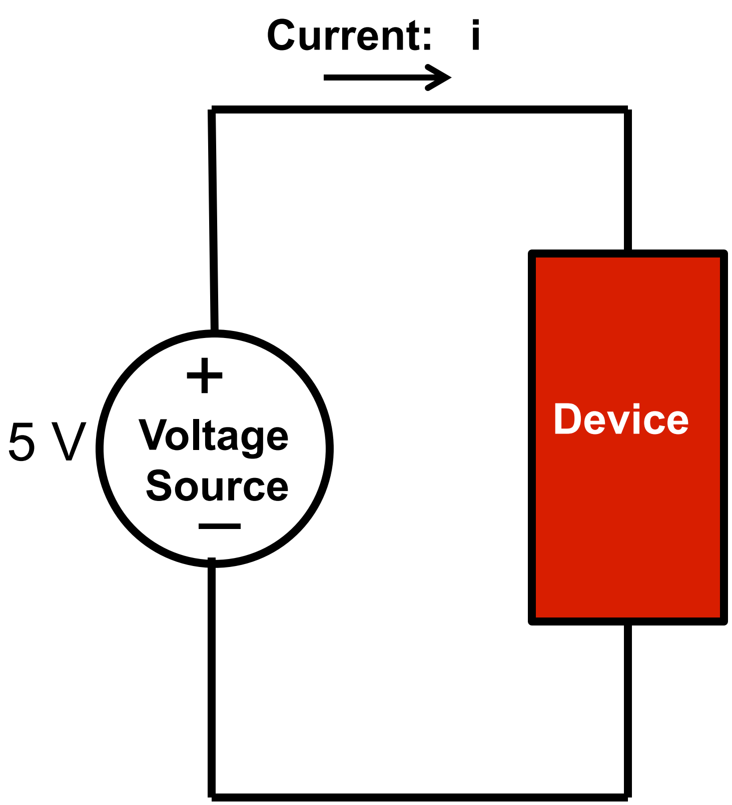
- **Voltage** is a measure of the potential energy per unit charge
  - It is measured in **Volts**
    - Which has the units of Joules per Coulomb.
- The charge on the higher energy side will move through an external path (a wire) to neutralize the negative charge on the other side of the device.
  - This causes the charge to flow in the wire, as well as through the device.

What is a Battery?

- It is a chemical pump for electrons!
  - There is a pair of chemical reactions that pump electrons from anode to cathode
    - Actually, a battery absorbs electrons at the anode and creates electrons at cathode (with ions moving through the middle), but it has exactly the same effect
  - The battery voltage is the potential energy given to electrons as a result of this pump.

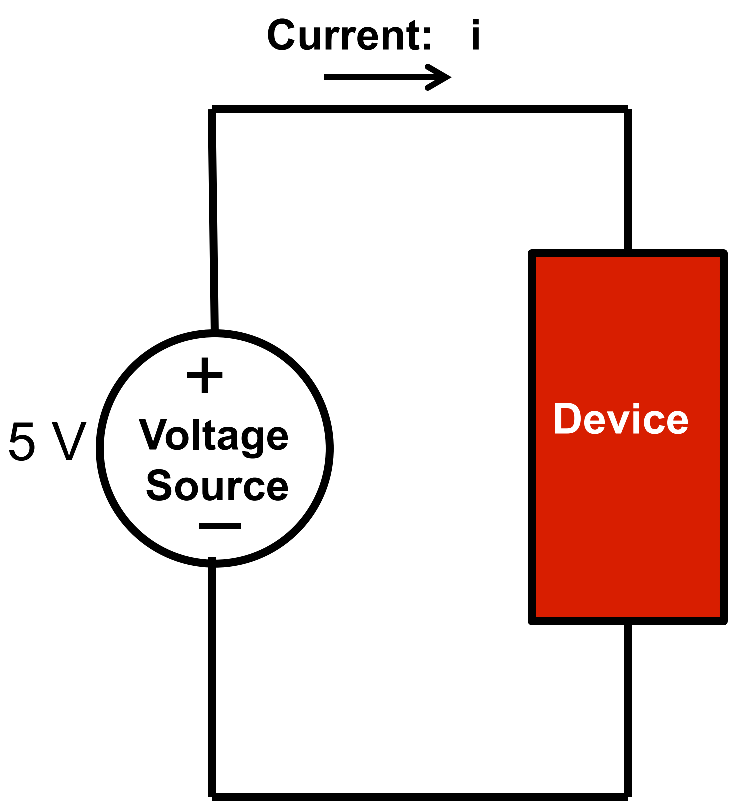
- The voltage of the battery depends on chemicals
  - Generally either 1.5 V, or multiples
  - Or around 3.5 V (lithium)

Energy and Power



- The battery or power supply provides power to the device. ($P = i \cdot V$)
- Since energy is conserved, the device does something with this power
  - Resistor turns it into heat
  - LED turns it into light
  - Logic circuit computes something
  - Motor turns it into mechanical energy
  - Pump turns it into potential energy by pumping water uphill
  - . . . .

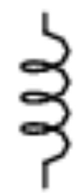
Electrical Devices



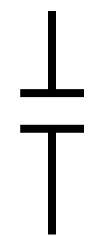
- We'll learn about many different electrical devices.

Resistors

Diodes

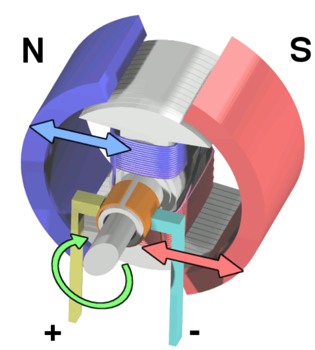


Inductors

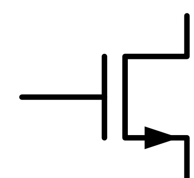


Capacitors

Light Emitting Diodes

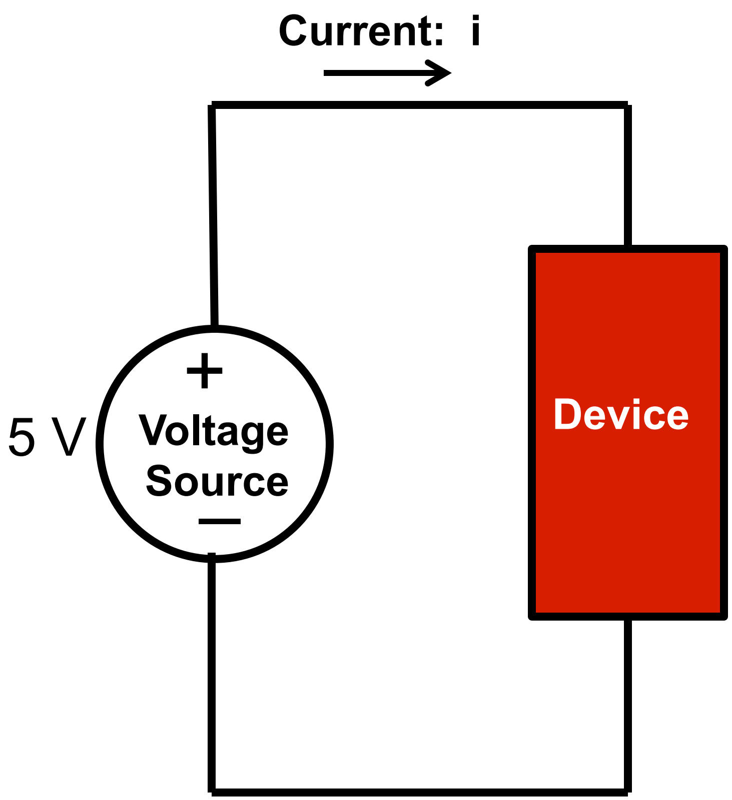


Motors



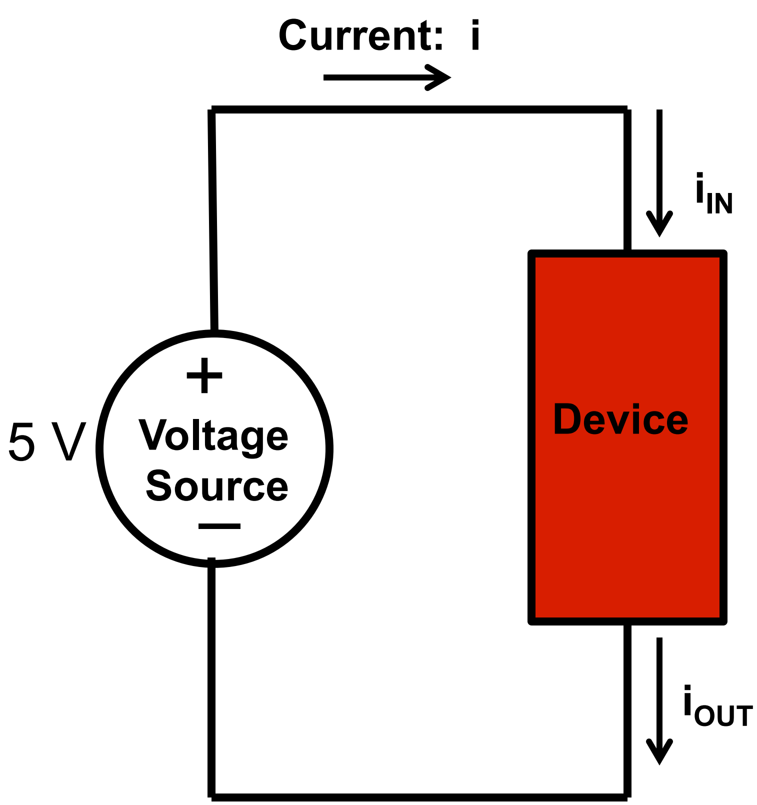
Transistors

Electrical Devices



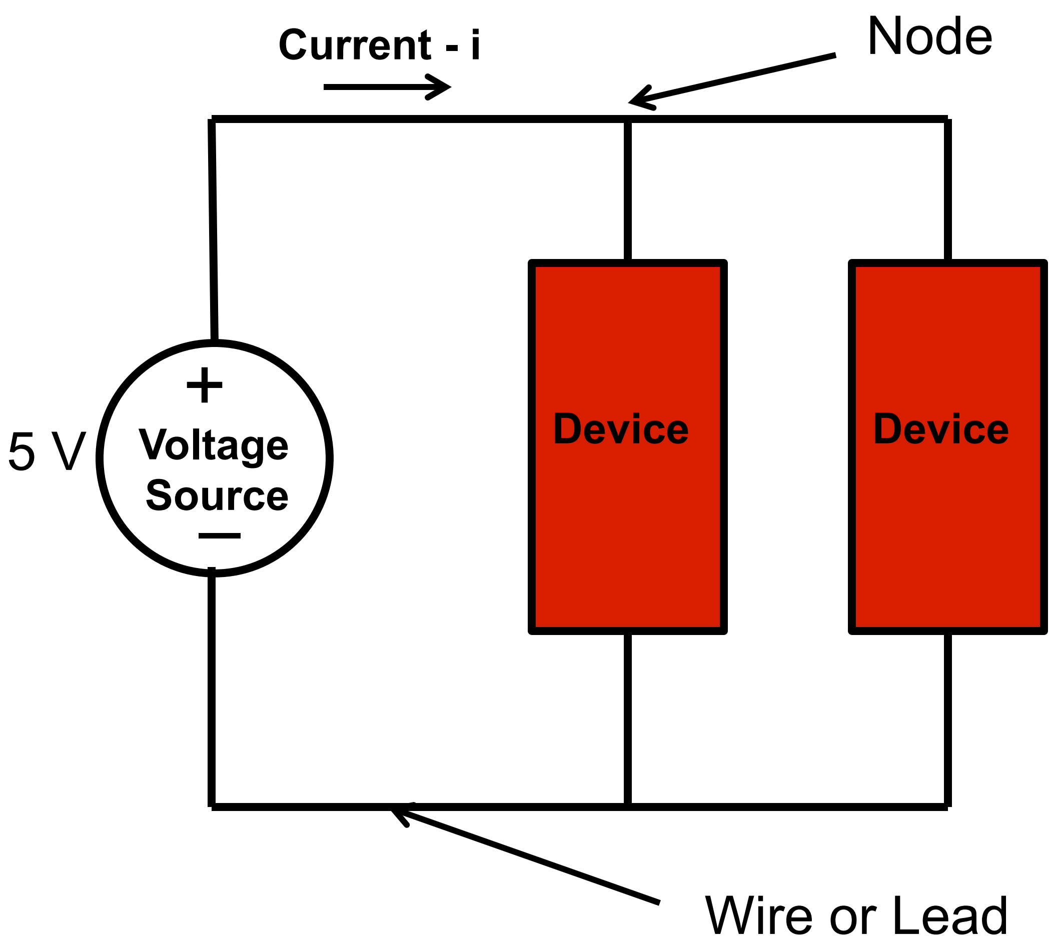
- Each electrical device responds differently to the voltage and current provided to it.
- Electrical engineers combine these devices to do interesting and useful things.
- You'll build and demonstrate several interesting examples in E40M.

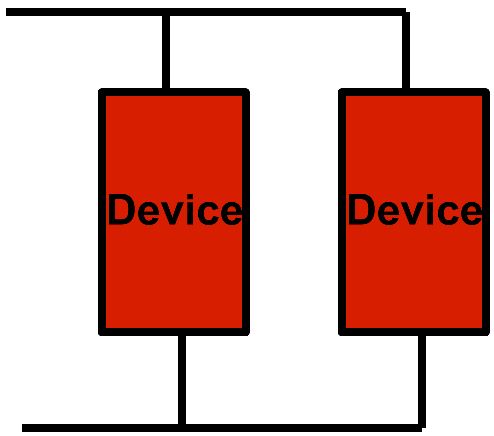
Electrical Devices – Some Properties



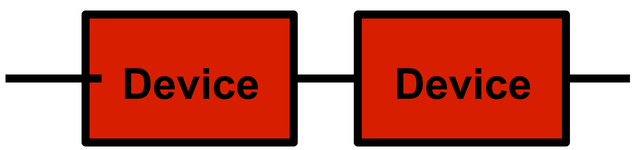
- Charge neutral; *i.e.*, charge entering = charge leaving
  - Batteries or power supplies separate charge but the overall device is still charge neutral
- The net current into any device is **always zero**, so $i_{IN} = i_{OUT}$
  - Current that flows into one end of a wire must flow out the other
  - Often called KCL (Kirchhoff's Current Law)
- Dissipate power ($P = i \cdot V$)

Electrical Circuit Terminology



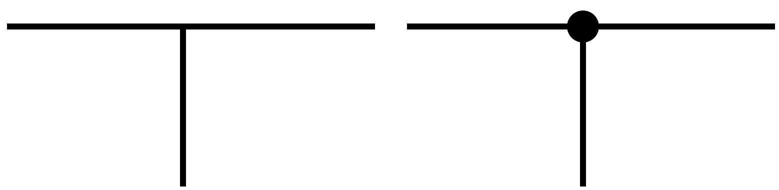


Devices in Parallel

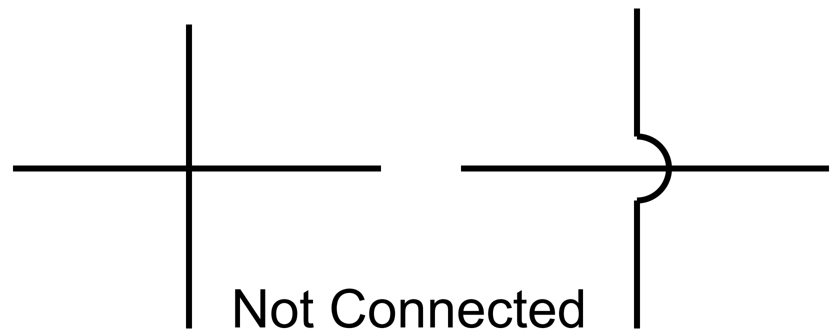


Devices in Series

Electrical Circuit Terminology

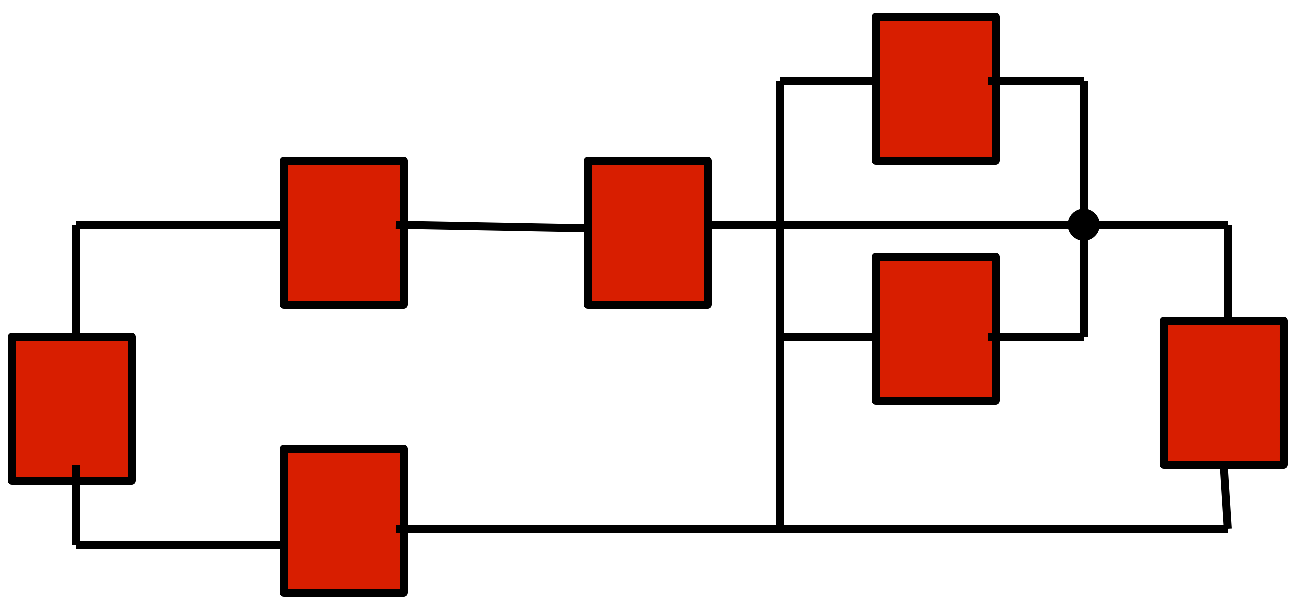


Connected

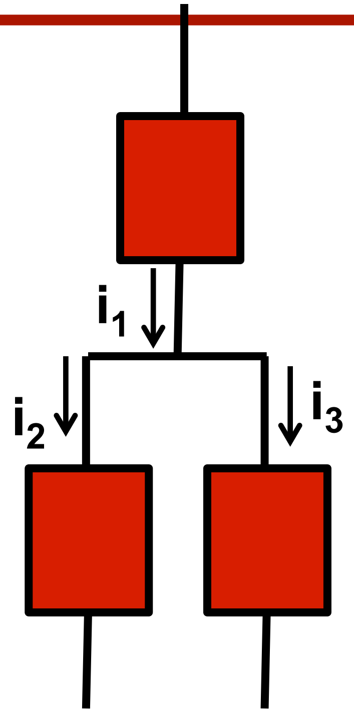


Not Connected

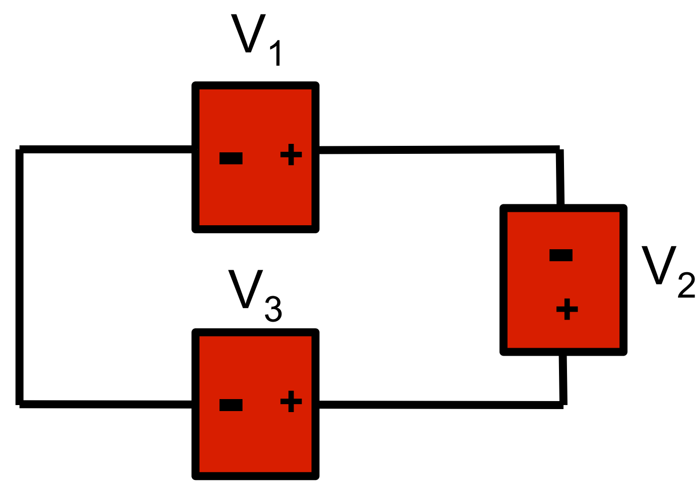
Example:



Kirchhoff's Current and Voltage Laws (KCL & KVL)



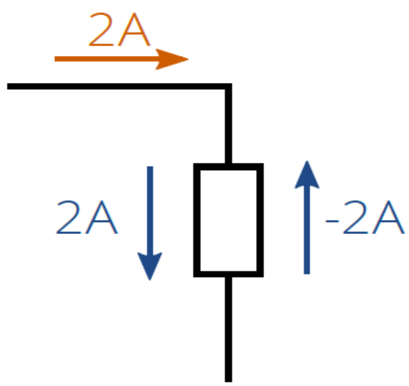
Kirchhoff's Current Law (KCL) states that the current flowing out of any node must equal the current flowing in. So, for example, $\boxed{i_1 = i_2 + i_3}$

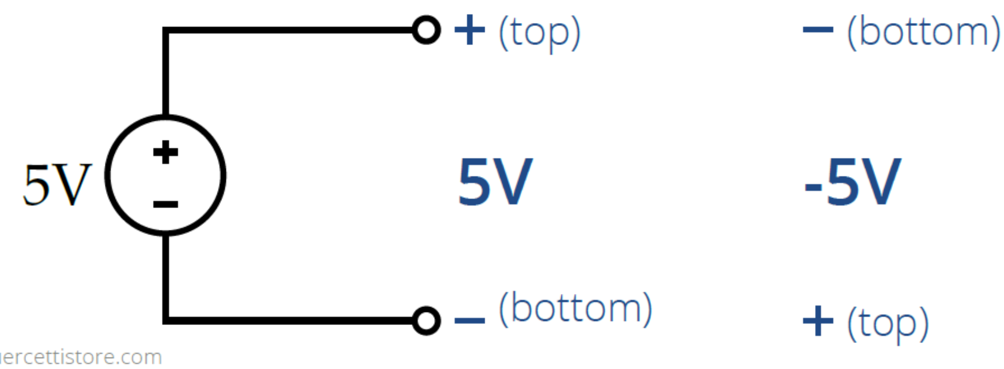


Kirchhoff's Voltage Law (KVL) states that the algebraic sum of the voltages around any closed path must be zero. So, for example, $\boxed{V_1 + V_2 - V_3 = 0}$

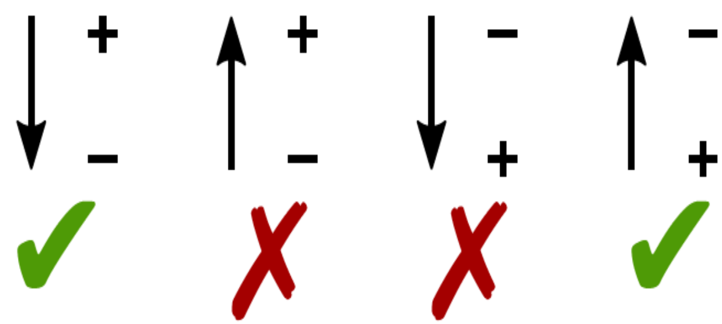
Labeling (Measuring) Voltage and Current

- Labels alone don't indicate current direction. It is a combination of the label and the sign

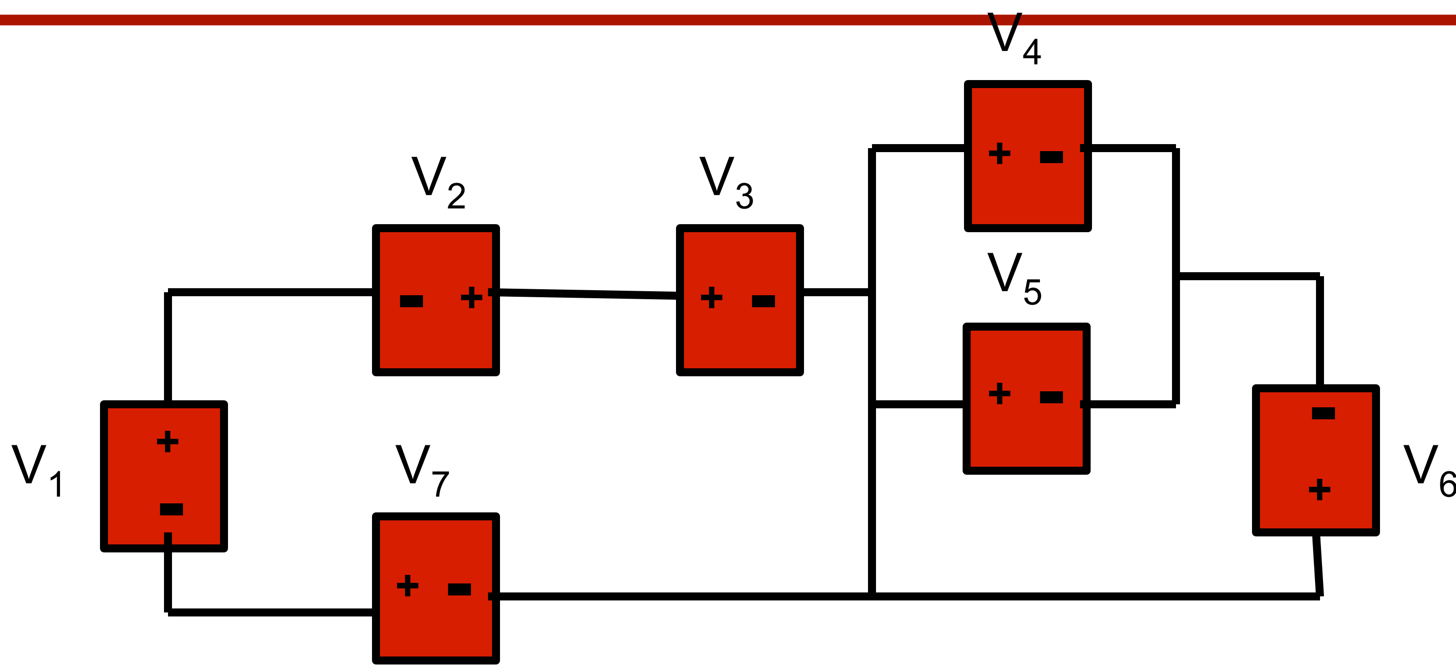




- You can pick any polarity and direction you want (you'll get the right answer), but convention is the green choices.
- Answers may be positive or negative.



Example #1: Kirchhoff's Voltage Law (KVL)



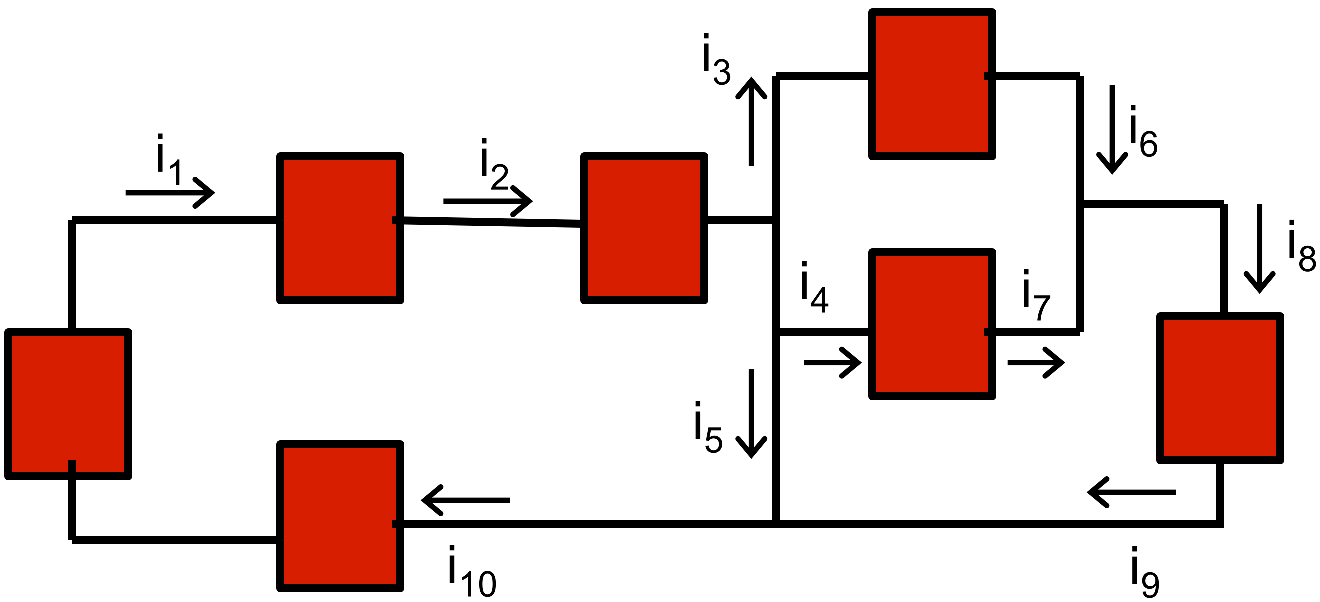
$$V_1 + V_2 - V_3 - V_4 + V_6 + V_7 = 0$$

$$V_1 + V_2 - V_3 + V_7 = 0$$

$$\therefore -V_4 + V_6 = 0 \quad \text{(Check for consistency)}$$

Quiz: What can you say about V_4 and V_5?

Example #2: Kirchhoff's Current Law (KCL)



$i_1 = i_2 = i_{10}$

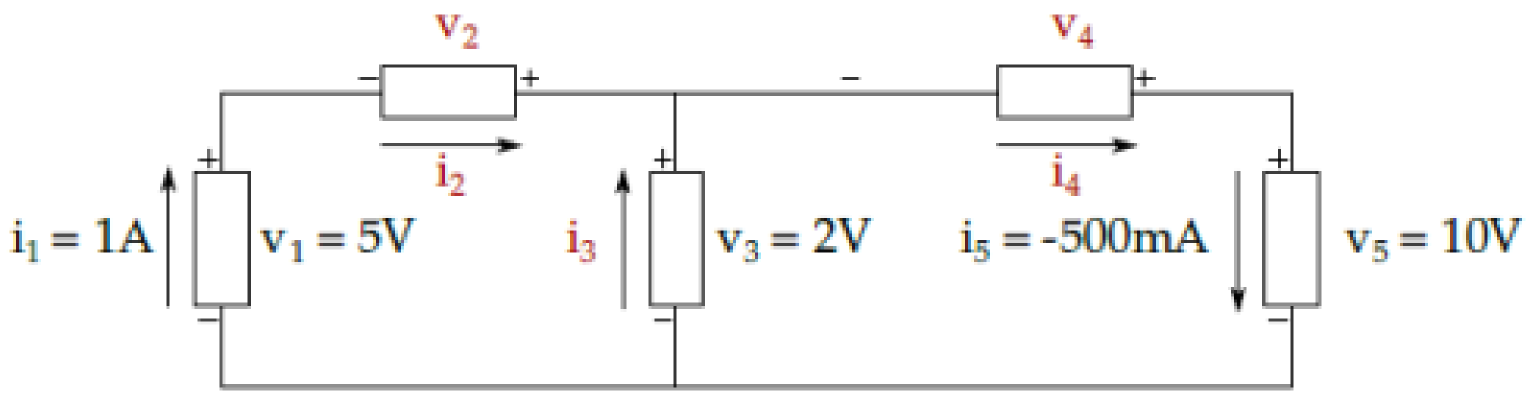
$i_2 = i_3 + i_4 + i_5$

$i_3 = i_6$ and $i_4 = i_7$

$i_8 = i_9 = i_{10} - i_5$

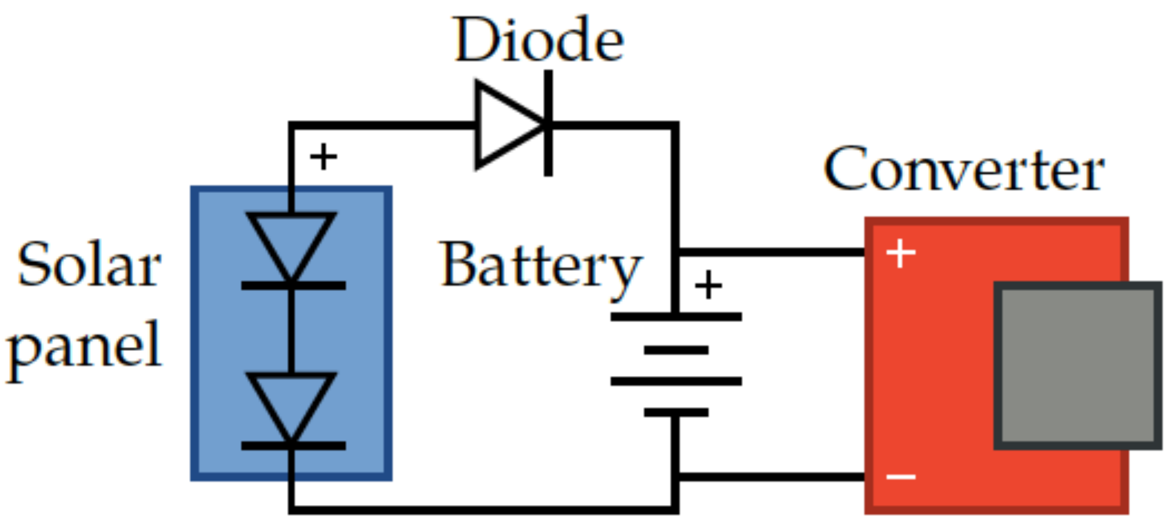
Using KCL and KVL

- Find the current, and voltages for the circuit below



Getting Back to the Solar Charger: Energy and Power

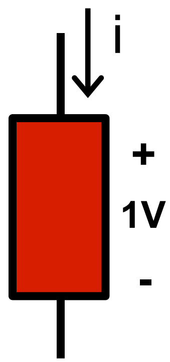
- Look inside:
  - See a number of different devices wired together in a circuit:



- Need to move energy around
  - And that is done with voltage and current

Electrical Power and Energy

- Voltage is electrical potential energy
  - Volt = Joule/Coulomb
  - Means moving 1 Coulomb of charge up 1V requires 1J



- Remember definition of an amp?
  - Coulomb/sec
- Power "consumed/provided" in the electrical component
  - (i)*(V) = 1A * 1V = 1 Joule/sec = 1 Watt of power
  - Often the lost energy is converted to heat
- Power is the rate of energy transfer i.e. Power = Energy/sec or Energy transferred = (Power)(time)

Getting a Feeling for a Watt

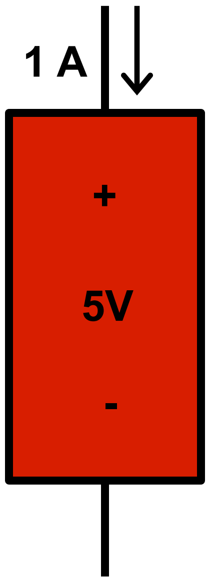
- Quick physics review
  - Unit of energy   Joule = Coulomb · Volt
  - Unit of power   Watt = Joule/sec = A·V

- If those mean nothing to you
  - You probably know about calories
    - Another unit of energy
    - Calorie = 4 kJ   (a little c-calorie is only 4 J)
    - 2000 Calories = 10 MJoules
  - 10 MJ/day = $10^7/(24 \cdot 60 \cdot 60)$ ~ 100W (power you put out)
    - 30% is your brain, so your brain uses around 30W

Energy Flow

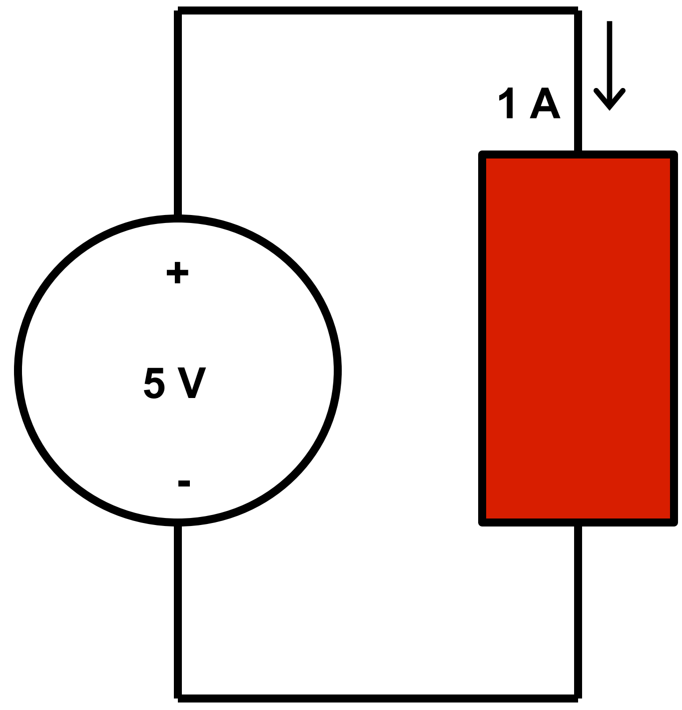
- The power associated with the red box is:
  - 1A · 5V = 5 W

- Is the box generating or consuming this power?
  - Every charge that enters, also leaves
    - Charge neutral
  - **Does the charge leave with more or less potential energy**?
    - More is higher voltage, less is lower voltage
  - If it leaves from the
    - Lower voltage lead – energy was lost;
      - The box consumed some energy
    - Higher voltage lead – energy was gained;
      - The box supplied energy



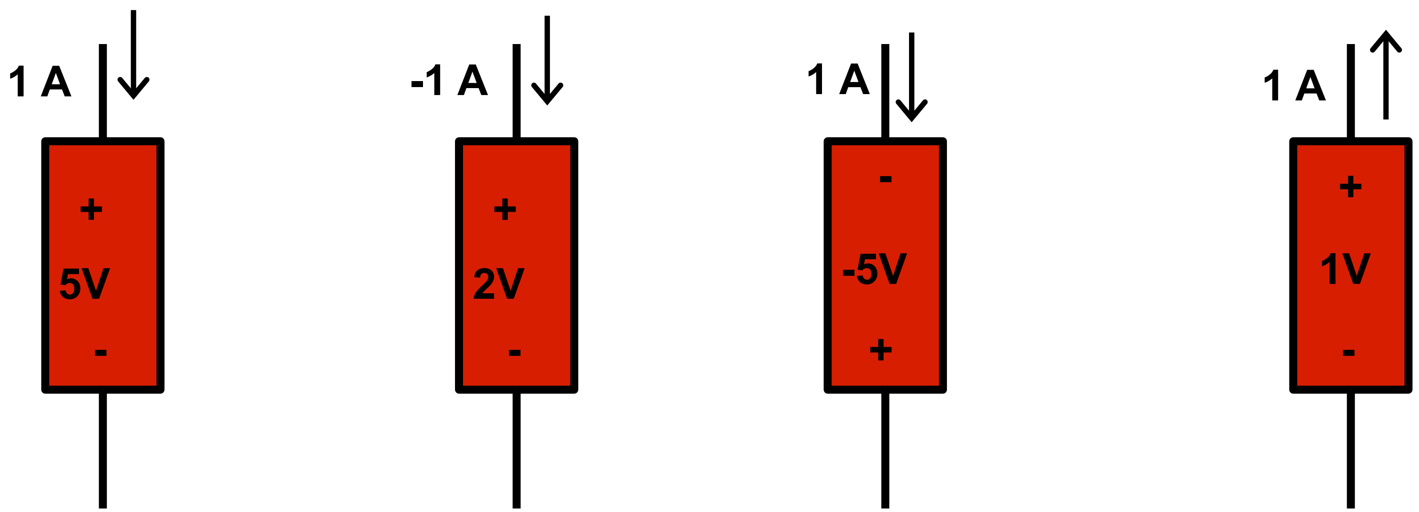
Energy Flow

- What generate/dissipates energy
  - The 5 V voltage supply
  - The red box



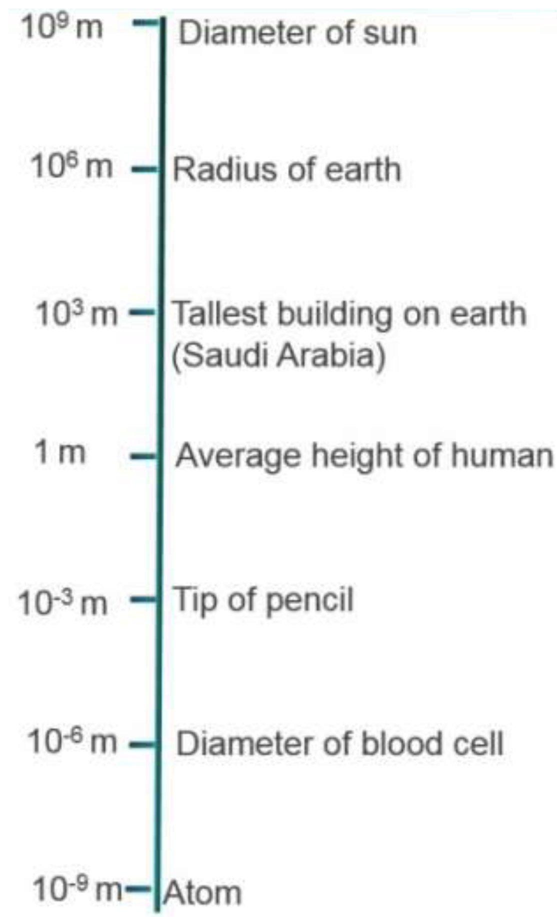
Find the Power Dissipated In Each Device

- First figure out which lead has the higher voltage
  - Then figure out whether current flows into or out of that lead



Standard Prefixes for SI Units

Factor	Prefix	Symbol
$1{,}000{,}000{,}000 = 10^9$	giga	G
$1{,}000{,}000 = 10^6$	mega	M
$1{,}000 = 10^3$	kilo	k
$100 = 10^2$	hecto	h
$10 = 10^1$	deka	da
$0.1 = 10^{-1}$	deci	d
$0.01 = 10^{-2}$	centi	c
$0.001 = 10^{-3}$	milli	m
$0.000\,001 = 10^{-6}$	micro	μ
$0.000\,000\,001 = 10^{-9}$	nano	n
$0.000\,000\,000\,001 = 10^{-12}$	pico	p



Example, if the unit is a meter

Learning Objectives – Charge, Current, Voltage, Electrical Circuits

- Understand that **charge** is what makes components electrical
  - Moving charge is called **current**, and often represented by “**i**”
    - Measured in **Amps** = Coulombs/sec
- Understand that all components and wires are **charge neutral**
  - This means that the net charge flowing into an object is 0
  - KCL - The sum of the currents into an device or wire = 0
- The energy that causes the charge to move is called **Voltage**
  - Measured in **Volts** = Joules/Coulomb
  - Voltage is a potential energy difference
    - Measured between two nodes

Learning Objectives – KCL, KVL, Energy Flow

- Sum of voltage drop around any loop of devices is always 0 (KVL); sum of currents into any node is always 0 (KCL).
- The power consumed by a device is always:
  - The current flowing into the + terminal multiplied by
  - The voltage across the device.
- A voltage source is an electrical device where $V = V_{source}$ and the current is determined by the rest of the circuit
- Learn SI prefixes