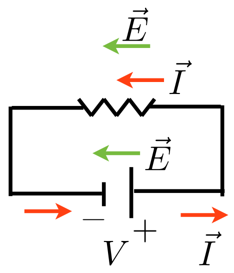
- Consider the following circuit:

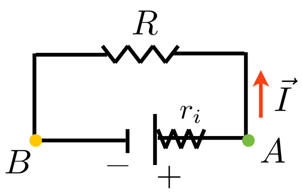


- Lets follow the current around and draw the E-field across the circuit elements
- The E-field points in the opposite direction from the current inside the voltage source!
- Something must supply energy so that the (+) charges can go from low -> high potential
- Like gravity: “A ball cannot go uphill without some push”

- Work must be done on the charges, the energy must come from somewhere.
  - In a battery, the work comes from chemical reactions
  - In a power plant, the work comes from the mechanical energy generated from steam.

<u>EMF:</u>

- Suppose $R = \infty$, and thus $I = 0$



$$\Rightarrow \quad V_A - V_B = V_b = \mathcal{E}$$

“EMF”

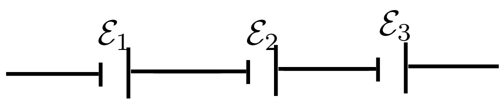
- EMF is the potential across a <u>fixed voltage source</u> when no current is flowing

- Suppose $R \neq 0$, therefore $I > 0$
  - The voltage source always has some small internal resistance r_i

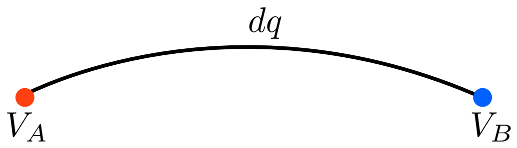
$$\Rightarrow \quad \mathcal{E} = I\left(R + r_i\right) \qquad V_b = IR = \mathcal{E} - Ir_i$$

-If R=0 then you get maximum current in circuit: $I_{\max} = \dfrac{\mathcal{E}}{r_i} \rightarrow V_b = 0$

-For batteries in series: $\mathcal{E}_{\text{total}} = \mathcal{E}_1 + \mathcal{E}_2 + \mathcal{E}_3$



Power:



- Suppose: $V_A > V_B$

- Let me move a charge dq from VA to VB -> requires me to do work:

$$dW = dq\,(V_A - V_B)$$

- divide both sides by dt: $\dfrac{dW}{dt} = \underbrace{\dfrac{dq}{dt}}_{I}(V_A - V_B)$

- Now have work/unit time = “**Power**” : $\boxed{P = IV}$ $\left[\dfrac{J}{s} = W\right]$ (always holds)

- If Ohm’s Law holds then $V = IR$:

$$\boxed{P = I^2R = V^2/R}$$ **(ONLY WHEN OHM’S LAW IS VALID)**

- Assuming an Ohmic resistor: $P = I^2R$

$$I = 1\ \text{A},\quad \text{R} = 100\ \Omega\quad \rightarrow \text{P} = 100\ \text{W}$$

$$I = 2\ \text{A},\quad \text{R} = 100\ \Omega\quad \rightarrow \text{P} = 400\ \text{W}$$

- This energy is dissipated as heat
    - If the resistor gets hot enough, you can get light (i.e. a lightbulb)
    - Tungsten filament in a lightbulb $\approx 2500\ \text{K}$

ex light blub:

-Assume: $P = 100\ \text{W}$ $V = 220\ \text{V}$

- Using $P = IV$: $I = 0.45\ \text{A}$

- Using $V = IR$: $R = 489\ \Omega$

- If V=110V then I=0.9A. This is why we use 220V in Korea; less current = smaller wires.

- The human body generated ~100W. We do not get too hot since we have large surface area.

ex shorted battery:

- If I look at the total power generated in a resistor + the battery then:

$$P = I\mathcal{E} = I^2\left(R + r_i\right)$$

- If R=0 (by shorting the battery):

$$I_{\max} = \frac{\mathcal{E}}{r_i} \quad \Rightarrow \quad P_{\max} = \frac{\mathcal{E}^2}{r_i} = I^2_{\max} r_i$$

- Consider a shorted 9V battery:

$$\mathcal{E} = 9\ V \quad r_i = 2\ \Omega \quad \rightarrow \quad I_{\max} \approx 4.5\ \text{A}$$

$$\Rightarrow \quad P_{\max} = 40\ \text{W}$$

- All 40W will turn into heat -> battery will get hot.

- For 9V battery not so bad, but car battery this is very dangerous: $P_{\max} = 7000\ \text{W}$

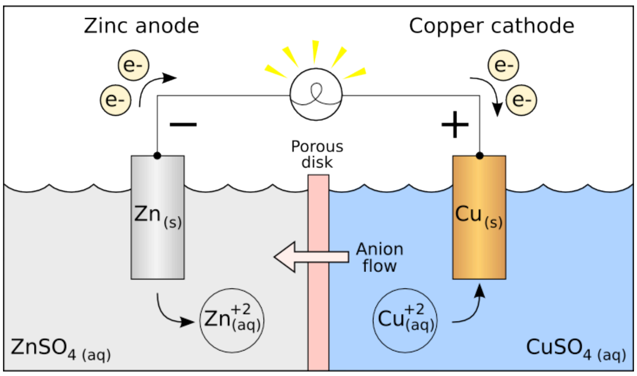
- So far we have only talked about electrons moving as current

- However, currents can also be formed by ions; atoms with extra, or missing, electrons

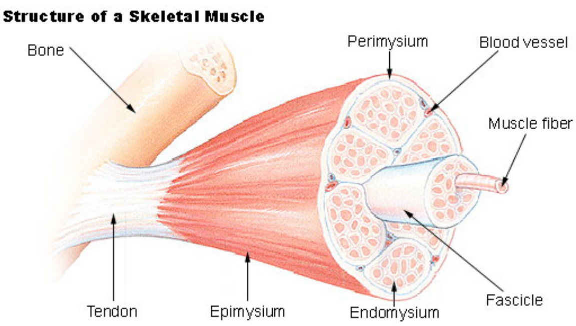
- This is how every battery works

- Electric currents in the human body are also generated by moving ions:

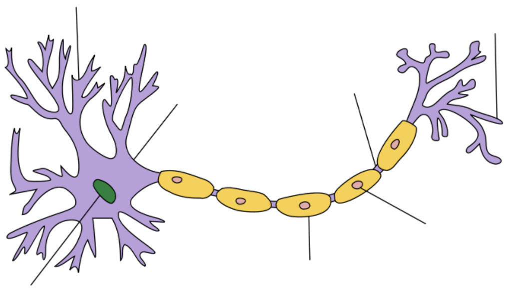
$$\text{Na}^+, \quad \text{Ca}^{++}, \quad \text{K}^+$$



Zinc-Copper Battery



Muscle Cells



Neuron

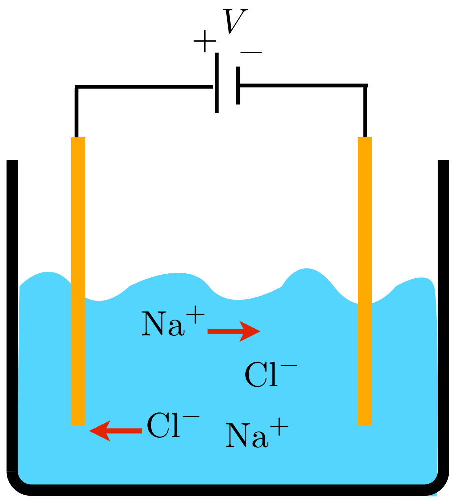
- Salt water is a very good source of ions:

- In water, salt breaks into ions:

$$\mathrm{Na}^{+}\ \mathrm{Cl}^{-}$$

- These ions increase the conductivity of water by 1 million times

- If I apply a voltage between two metal plates in slat water, the ions will move generating a current



Pickle Demo