Apply a voltage $E$ to a resistor $R_j$ current $I$ flows.

Ohm's Law: $V = IR$

- $V =$ voltage across resistor ($E$ above)
- $R =$ resistance (const if "Ohmic")
- $I =$ current that flows

$I = \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$

Easy to have $I = 1.00 \ A$
But having $Q = 1.00 \ C$ is crazy.
Charges are balanced.
Current is the flow of one (or the other) type of charge.
+ charges form current in the same direction they flow.
- charges form current opposite to their flow.

\[+ \rightarrow - \rightarrow - \rightarrow - \rightarrow I\]
Measuring w/o Disturbing

Voltage: Working Circuit

\[ V = I_m R_m \]

Voltmeter has huge \( R_m \).

Current: Must break the circuit

\[ V = I R \]

Ammeter is part of the current path.

To measure \( I \), the meter uses no \( V \).

\[ V = I R_m \]

The Ammeter must have a tiny \( R_m \).

Wrong! Current cannot flow! Wrong! Lots of current flows!
4. Power is the flow of energy

\[ P = \frac{\text{Energy}}{\Delta t} = \frac{\text{change in energy}}{\text{change in time}} \]

\[ P = IV \]

\[ V = IR \]

\[ P = IV = I^2R = \frac{V^2}{R} \]

Out of 4 variables, we have 2 non-redundant equations. Need 2 values.

Ex: 60 W light bulb designed for 120 V electrical outlet.

\[ P = 60 \text{ W} \]

\[ V = 120 \text{ V} \]

\[ \frac{60W}{120V} = \frac{120V}{0.5A} \]

\[ I = 0.5 \text{ A} \]

\[ R = 240 \Omega \]

\[ P = I^2R \text{ is power lost in a wire} \]

\[ P = I \times E \]

\[ P_R = I^2R = IV_R \]

\[ P_w = I^2R_w \]
Physics of Flow

Consider the water in a pipe

\[ \text{Vol} = A \ell = A v \Delta t \]

Area = A \quad \ell = v \Delta t

Vol Flow Rate = \frac{\text{Vol}}{\Delta t} = Av

Mass Flow Rate = \rho Av

\rho = \text{density} = \text{mass/Vol}

Particle Flow Rate = \frac{\text{Count}}{\Delta t} = \eta Av

\eta = \text{particle density} = \text{count/Vol}

Charge Flow Rate = I = e \eta Av

Ex: \eta = 10^{28} \text{ m}^{-3} \quad \text{“carrier density”}

e = 1.6 \times 10^{-19} \text{ C}

A = \pi (0.001 \text{ m})^2

I = 1.0 \text{ A}

v = 0.0002 \text{ m/s} = 0.2 \text{ mm/s} = 12 \text{ mm/min}

This is the “Drift Velocity”.
People Flow Rate = \frac{\text{People}}{s} = \rho \cdot \frac{V}{W \cdot A}

\rho = \text{Density in people/m}^2

V = \text{walking speed}

W \cdot A = \text{width of doorway}

\text{Resistivity: } R = \rho \frac{L}{A}

\text{Resistivity in (}\Omega \cdot \text{m})

\text{Thermal Coefficient}

R = R_0 \left(1 + \alpha (T-T_0)\right)

\frac{R}{R_0} = 1 + \alpha (T-T_0)

\frac{R-R_0}{R_0} = \alpha (T-T_0)

\frac{R-R_0}{R_0} = \alpha (T-T_0)

\Delta R = \alpha BT

\alpha = 0.01 \text{ }^\circ \text{F}^{-1} \text{ means 1\% per } ^\circ \text{F}
$V + \frac{1}{R} \equiv R \quad I = \frac{V}{R}$

$P = IV = \frac{V^2}{R}$

Power heats the resistor.

If $\alpha$ is $0$: $\Delta R \leq \frac{\alpha R}{R_0}$

$\Delta R$ is $0$

$R$ increases

$P$ decreases

System finds equilibrium

If $\alpha$ is $\Theta$: $\Delta R$ is $\Theta$

$R$ decreases

$P$ increases

System heats more!

Thermal Runaway