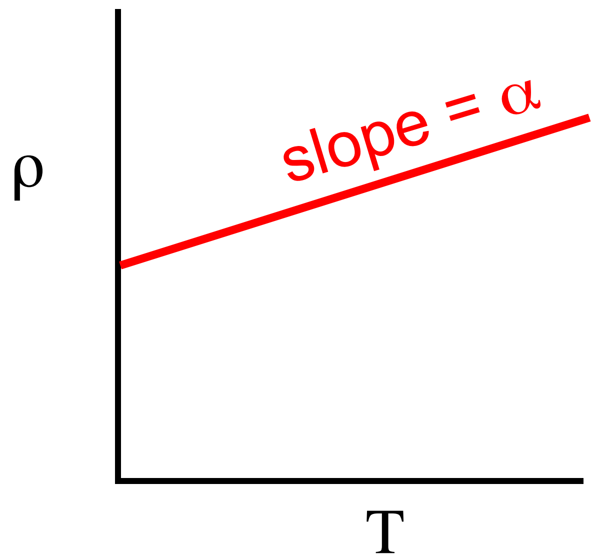
Temperature coefficient of resistivity



$$\rho = \rho_o[1 + \alpha(T - T_o)]$$

$$R = R_o[1 + \alpha(T - T_o)]$$

T_0 = reference temperature

α = temperature coefficient of resistivity, units of $(^{o}C)^{-1}$

For Ag, Cu, Au, Al, W, Fe, Pt, Pb: values of α are ~ $3\text{-}5\times10^{-3}$ $(^{o}C)^{-1}$

Example: A platinum resistance thermometer uses the change in R to measure temperature. Suppose R_0 = 50 Ω at T_0=20 ºC.

α for Pt is 3.92×10^{-3} $(ºC)^{-1}$ in this temperature range.

What is R when T = 50.0 ºC?

$$R = R_o[1 + \alpha(T - T_o)]$$

$$R = 50\Omega\ [1 + 3.92 \times10^{-3}\ (ºC)^{-1}\ (30.0\ ºC)] = 55.9\ \Omega$$

Temperature coefficient of resistivity

Example: A platinum resistance thermometer has a resistance R_0 = 50.0 Ω at T_0=20 ºC. α for Pt is 3.92×10^{-3} $(ºC)^{-1}$. The thermometer is immersed in a vessel containing melting tin, at which point R increases to 91.6Ω. What is the melting point of tin?

$$R = R_o[1+\alpha(T-T_o)]$$

$$91.6\Omega = 50\Omega\ [1 + 3.92\times10^{-3}\ (ºC)^{-1}(T-20ºC)]$$

$$1.83 = [1 + 3.92\times10^{-3}\ (ºC)^{-1}(T-20ºC)]$$

$$0.83 = 3.92\times10^{-3}\ (ºC)^{-1}(T-20ºC)$$

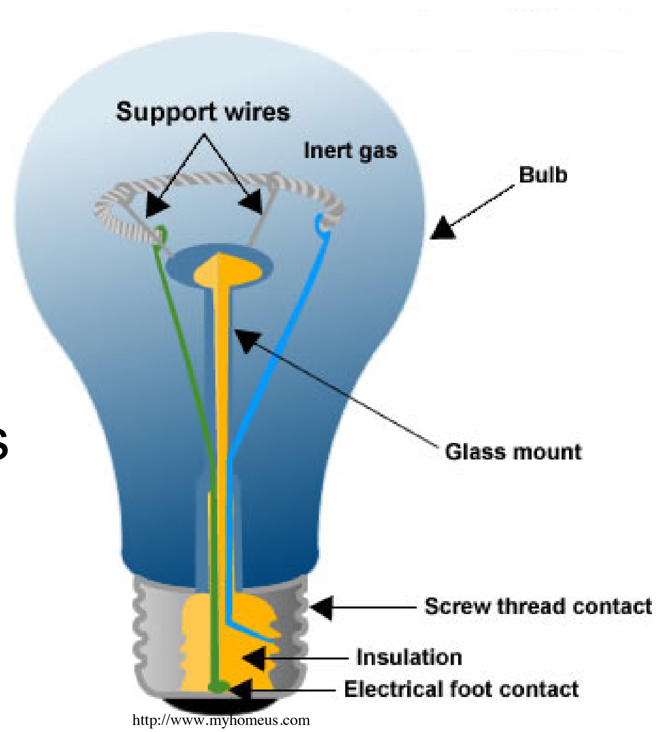
$$212ºC = T-20ºC$$

$$T = 232\ ºC$$

Light bulbs

Englishman Sir Joseph Swan (1878) & American Thomas Edison (1879).

Filament: The atoms are heated to 4000 F to emit visible light. Tungsten is durable under such extreme temperature conditions. (In weaker, less durable metals, atomic vibrations break apart rigid structural bonds, so material becomes molten/liquid)



Inert gas (typically Ar) is used to make sure that filament is housed in an O-free environment to prevent combustion reaction between W and O.

Typical tungsten filament: ~1 m long, but 0.05mm in radius.

Calculate typical R.

$A = \pi(5\text{x}10^{-5}\text{m})^2 = 7.9\text{x}10^{-9}\ \text{m}^2$

$\rho = 5.6\text{x}10^{-8}\ \Omega\text{m}$ (Table 21.1)

$R = \rho L/A = (5.6\text{x}10^{-8}\ \Omega\text{m})\ (1\text{m})/\ 7.9\text{x}10^{-9}\ \text{m}^2 = 7.1\ \ \Omega$

Note: the resistivity value used above is valid only at a temperature of 20°C, so this derived value of R holds only for T=20°C.

Calculate ρ at T=2000°C, assuming a linear ρ-T relation:

For tungsten, $\alpha = 4.5\text{x}10^{-3}$/°C

$\rho = \rho_0[1+\alpha(T-T_0)] = 5.5\text{x}10^{-7}\ \Omega\text{m}$

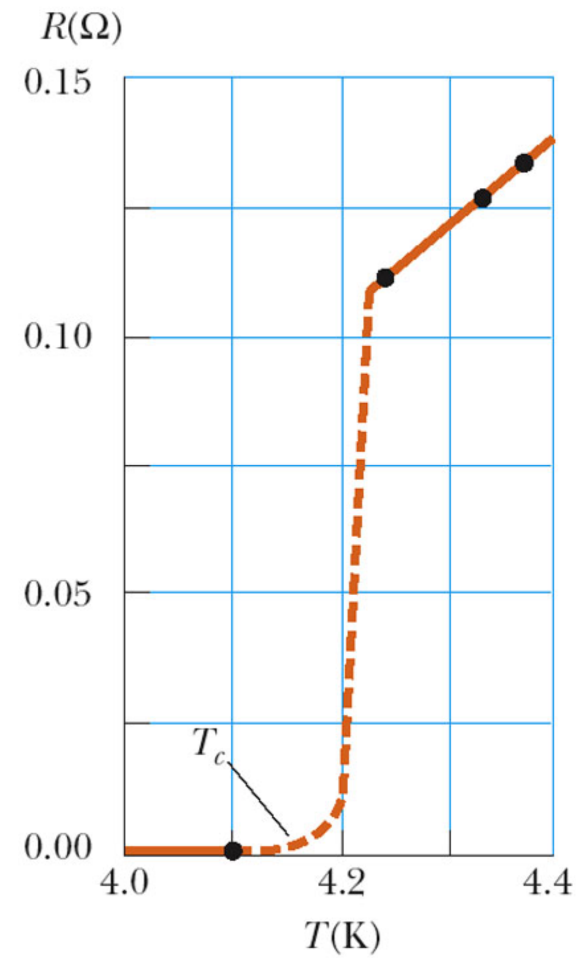
$R = \rho L/A = 70\ \Omega$.

(note… I suspect the ρ-T relation in reality may not be strictly linear over such a wide range of temperature; my guess would be that the above value of α may only be valid for temperatures of tens to hundreds of °C. In a few slides, we derive R from the power consumption and get R=144 Ω, which is probably more realistic)

21.3: Superconductors

For some materials, as temperature drops, resistance suddenly plummets to 0 below some T_c.

Once a current is set up, it can persist without any applied voltage because $R \to 0$!



Superconductors

Applications:

•Energy storage at power plants
•Super conducting distribution power lines could eliminate resistive losses
•Superconducting magnets with much stronger magnetic fields than normal electromagnets

More recently: As the field has advanced, materials with higher values of T_c get discovered

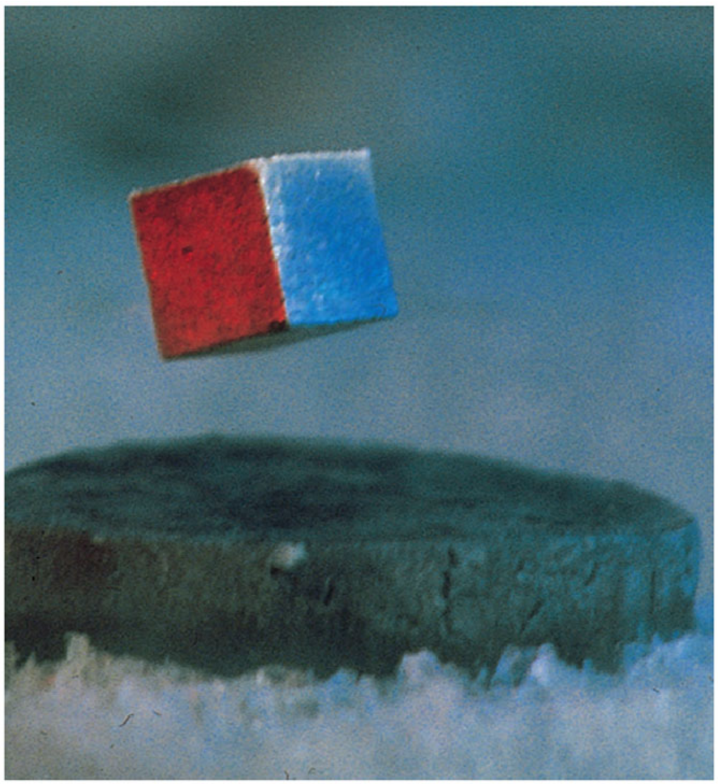


TABLE 21.3

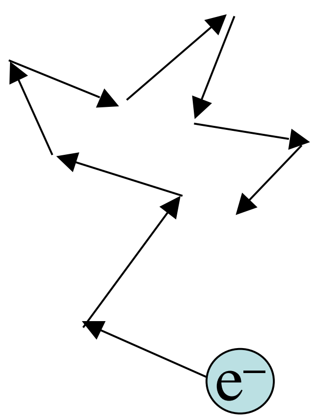
Critical Temperatures for Various Superconductors

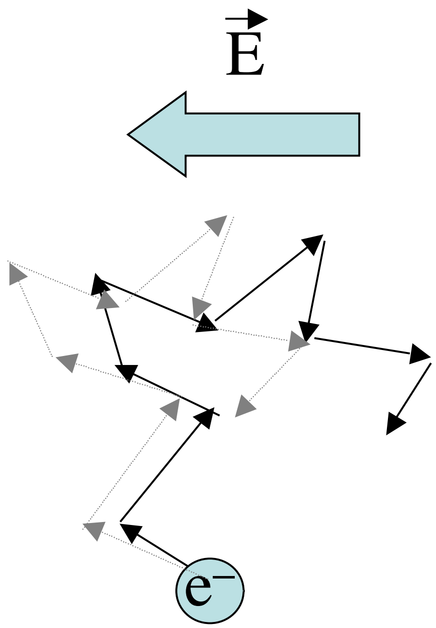
Material	T_c **(K)**
Zn	0.88
Al	1.19
Sn	3.72
Hg	4.15
Pb	7.18
Nb	9.46
Nb_3Sn	18.05
Nb_3Ge	23.2
$YBa_2Cu_3O_7$	90
Bi–Sr–Ca–Cu–O	105
Tl–Ba–Ca–Cu–O	125
$HgBa_2Ca_2Cu_3O_8$	134

21.4: Electrical Conduction: A Microscopic View

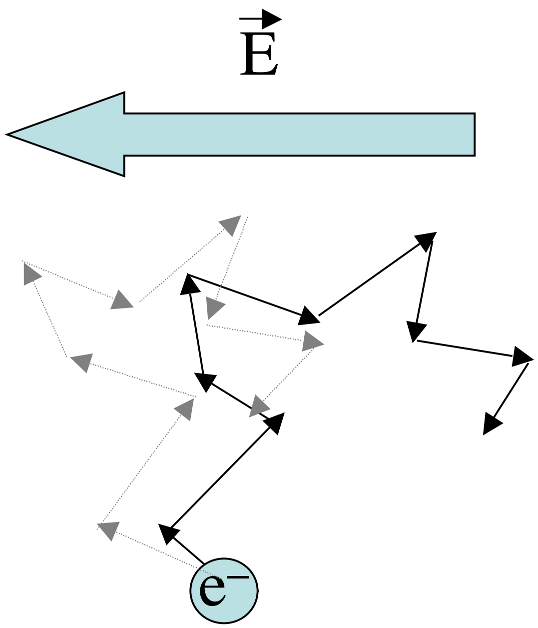
Re-cap: Microscopic motions of charge carriers are random, v of ~ 10^6 m/s; collisions with molecules

When applied E-field is 0, net velocity is zero, and I=0





When an E-field is applied, electrons drift opposite to field lines. Average motion is v_{drift}, typically tenths to a few mm/s



Stronger applied E-field means larger v_{drift},

v_{drift} prop to E

I prop to v_{drift}

The excess energy acquired by the electrons in the field is lost to the atoms of the conductor during the collision

The energy given up to the atoms increases their vibration and therefore the temperature of the conductor increases

21.5 Electrical Energy and Power

Power dissipated in a R is due to collisions of charge carriers with the lattice. Electrical potential energy is converted to thermal energy in the resistor--
a light bulb filament thus <u>glows</u>
or toaster filaments give off heat (and turn orange)

Power dissipated in a resistor

Power = work / time = $q\Delta V/\Delta t$

$P = I * \Delta V$

$P = I^2 R$

$P = \Delta V^2 / R$

UNITS:
P = I V = Amp * Volt = C/s * J/C = J/s = WATT

Example: A typical household incandescent lightbulb is connected to a 120V outlet. The power output is 100 Watts. What's the current through the bulb? What's R of the filament?

ΔV = 120 V (rel. to ground)
$P = I\Delta V \rightarrow I = P/\Delta V$ = 100W/120V = 0.83 A

$P = \Delta V^2 / R \rightarrow$ ----> $R = \Delta V^2 / P = (120V)^2 / 100$ W = 144 Ω

Note -- a few slides earlier, we'd estimated the typical resistance of a tungsten light bulb filament at 2000^{o}C -- that estimate of ~70 Ω assumed for simplicity a constant coefficient of resistivity α from 20^{o}C to 2000^{o}C, which might not be the case in reality. If the actual value of α increases as T increases, then the dependence of ρ on T will also be non-linear

Electric Range

A heating element in an electric range is rated at 2000 W. Find the current required if the voltage is 240 V. Find the resistance of the heating element.

$P = I\Delta V \rightarrow I = P/\Delta V = 2000W/240V = 8.3\ A$

$R = \Delta V^2 / P = (240V)^2/2000W = 28.8\ \Omega$

Cost of electrical power

1 kilowatt-hour = 1000 W * 1 hour = 1000 J/s (3600s) = 3.6×10^6 J.

1kWh costs about $0.13, typically

How much does it cost to keep a single 100W light bulb on for 24 hours?
(100W)*24hrs = 2400 W-hr = 2.4kWh
2.4kWh*$0.13 = $0.31

Power Transmission

Transmitting electrical power is done much more efficiently at higher voltages due to the desire to minimize (I^2R) losses.

Consider power transmission to a small community which is 100 mi from the power plant and which consumes power at a rate of 10 MW.

In other words, the generating station needs to supply whatever power it takes such that P_{req} =10 MW arrives at the end user (compensating for I^2R losses): $P_{generated} = P_{loss} + P_{req}$

Consider three cases:

A: V=2000 V; I=5000 A ($P_{req} = IV = 10^7$ W)

B: V=20000 V; I=500 A ($P_{req} = IV = 10^7$ W)

C: V=200000 V; I=50 A ($P_{req} = IV = 10^7$ W)

Power Transmission

Resistance/length = 0.0001 Ω / foot.
Length of transmission line = 100 mile = 528000 feet.
Total R = 52.8 Ω.

A: $P_{loss} = I^2R = (5000A)^2(52.8\Omega) = 1.33\times10^3$ MW
$P_{generated} = P_{loss} + P_{req} = 1.33\times10^3$ MW + 10 MW = 1.34×10^3 MW
Efficiency of transmission = $P_{req} / P_{generated}$ = 0.75%

B: $P_{loss} = I^2R = (500A)^2(52.8\Omega)$ = 13.3 MW
$P_{generated} = P_{loss} + P_{req}$ = 13.3 MW + 10 MW = 23.3 MW
Efficiency of transmission = $P_{req} / P_{generated}$ = 43%

C: $P_{loss} = I^2R = (50A)^2(52.8\Omega)$ = 0.133 MW
$P_{generated} = P_{loss} + P_{req}$ = 0.133 MW + 10 MW = 10.133 MW
Efficiency of transmission = $P_{req} / P_{generated}$ = 98.7% (most reasonable)

Lower current during transmission yields a reduction in P_{loss}!

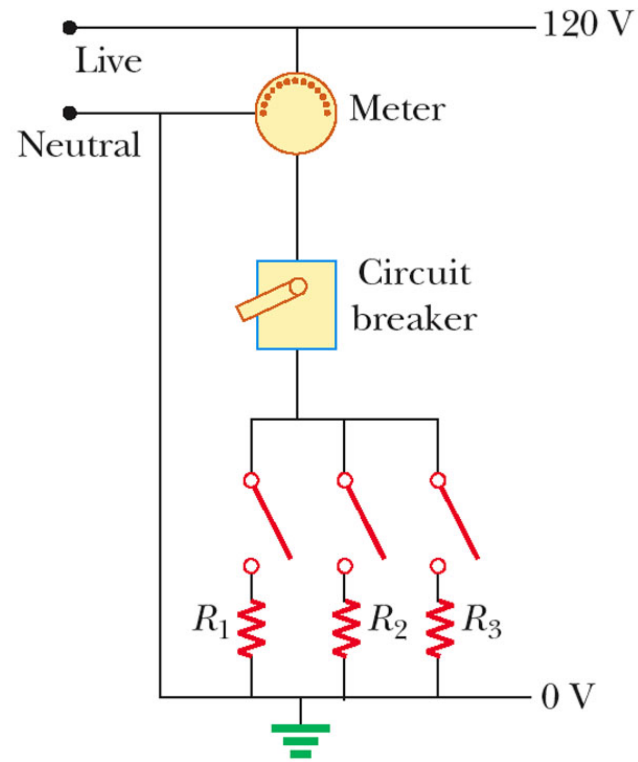
You can do the same exercise for local distribution lines (assume P_{req} = 0.1 MW), which are usually a few miles long (so the value of R is ~ a few) and need to distribute power from substations to local neighborhoods at a voltage of at least a few thousand volts (keeping currents under ~30A, roughly) to have a transmission efficiency above ~90%.

Household circuits

Circuits are in parallel. All devices have same potential. If one device fails, others will continue to work at required potential.

ΔV is 120 V above ground potential

Heavy-duty appliances (electric ranges, clothes dryers) require 240 V. Power co. supplies a line which is 120V BELOW ground potential so TOTAL potential drop is 240 V

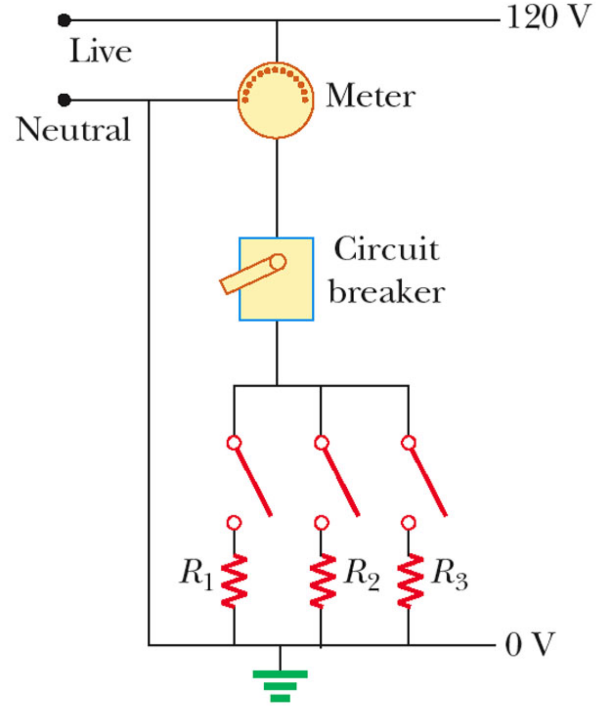


Circuit breakers or fuses are connected in series.

Fuses: melt when I gets too high, opening the circuit

Circuit breakers: opens circuit without melting. So they can be reset.

Many circuit breakers use electromagnets, to be discussed in future chapters



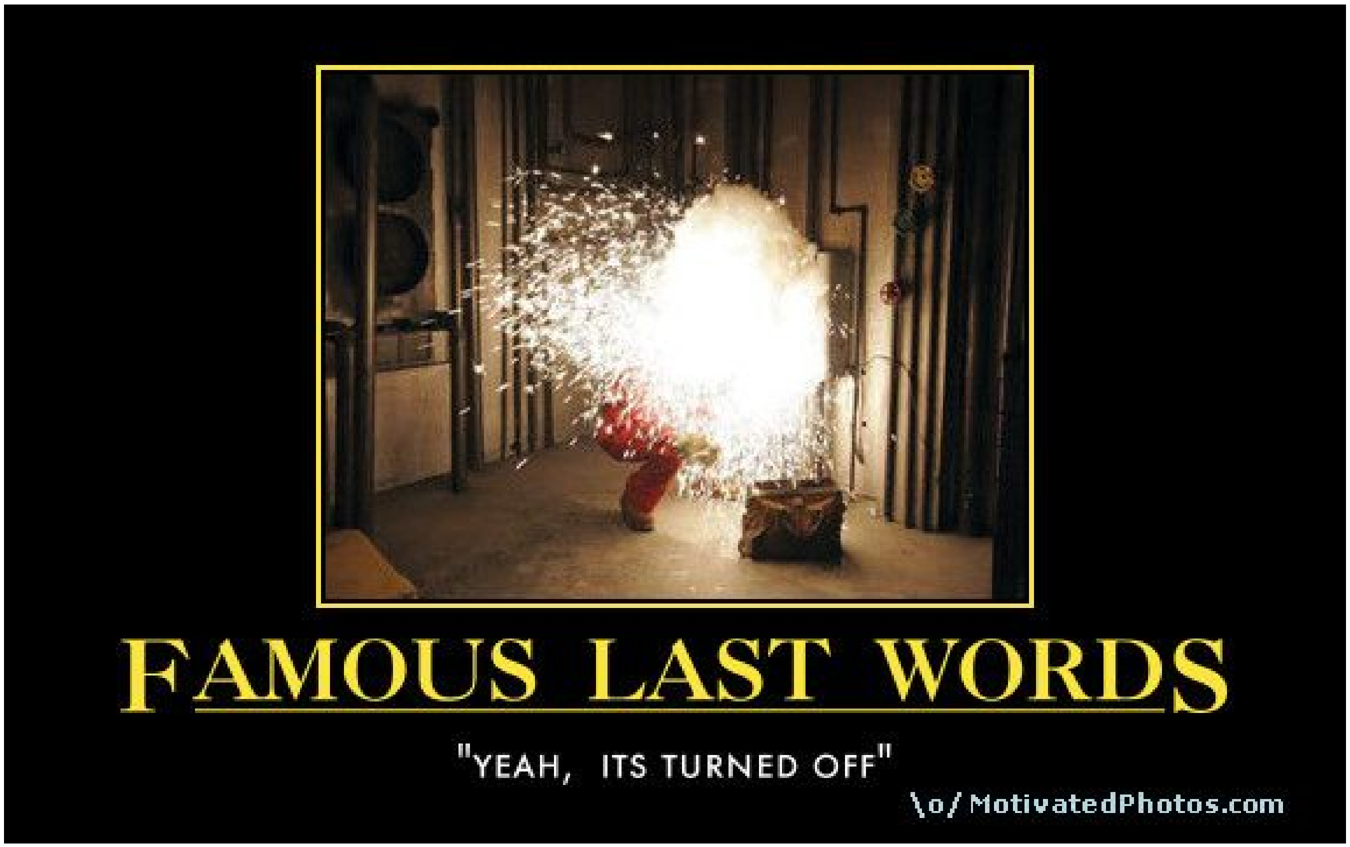
Example: Consider a microwave oven, a toaster, and a space heater, all operating at 120 V:

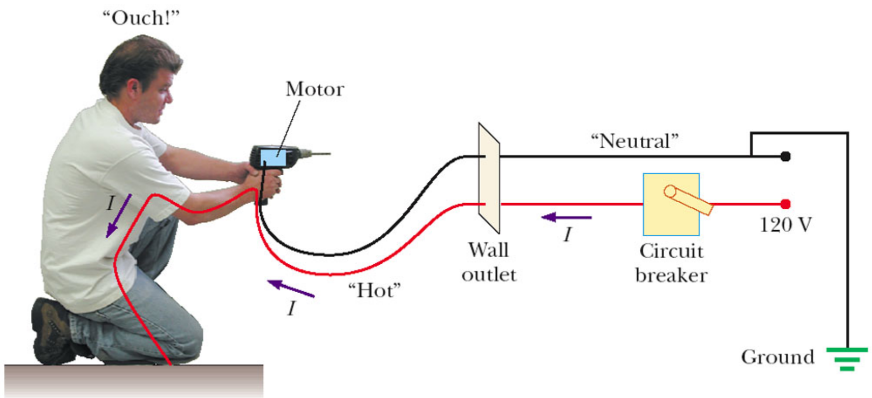
Toaster: 1000 W
Microwave: 800 W
Heater: 1300 W

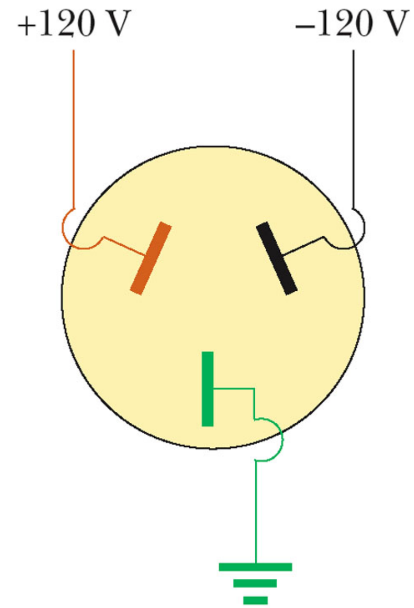
How much current does each draw? $I = P/\Delta V$
Toaster: $I = 1000W/120V = 8.33A$
Micro: $I = 800W/120V = 6.67A$
Heater: $I = 1300W/120V = 10.8\ A$

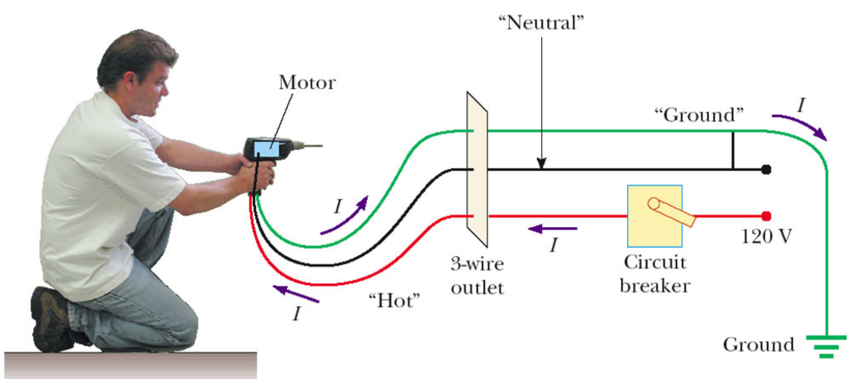
Total current (if all operated simultaneously)= 25.8 A
(So the breaker should be able to handle this level of current, otherwise it'll trip)

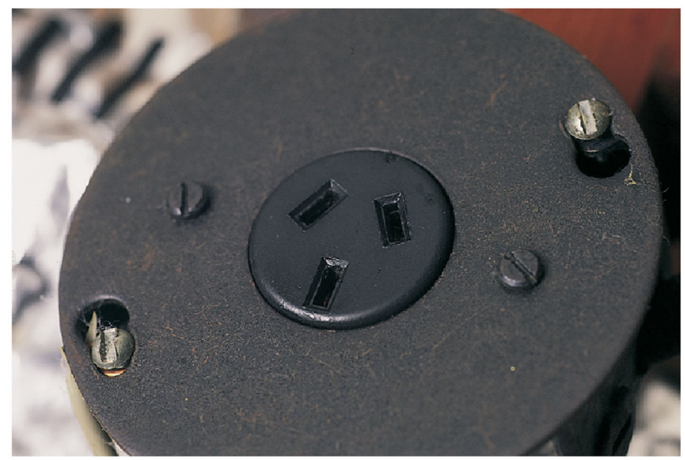
Electrical Safety




"Ouch!"
Motor
I
"Neutral"
120 V
I
Wall
outlet
Circuit
breaker
I
"Hot"
Ground


+120 V
–120 V


"Neutral"
Motor
"Ground"
I
I
120 V
I
3-wire
outlet
Circuit
breaker
"Hot"
I
Ground



$R_{skin(dry)} \sim 10^5\ \Omega$

TABLE 28-1 *Effects of Externally Applied Current on the Human Organism*

CURRENT RANGE	EFFECT
0.5–2 mA	Threshold of sensation
10–15 mA	Involuntary muscle contractions; can't let go
15–100 mA	Severe shock; muscle control lost; breathing difficult
100–200 mA	Fibrillation of heart; death within minutes
>200 mA	Cardiac arrest; breathing stops; severe burns

So for ΔV = 10,000V:

$I = \Delta V/R = 10{,}000\text{V}/10^5\ \Omega = 0.1\ \text{A}$ = dangerous.

But $R_{skin(wet)}$ is much, much lower, $\sim 10^3 \Omega$:

So in this case, when ΔV = 120V, I is also ~ 0.1 A = dangerous

21.6-21.9: Direct-Current Circuits

EMF

Resistors in Series & in Parallel

Kirchoff's Junction & Loop Rules for complex circuits

RC Circuits

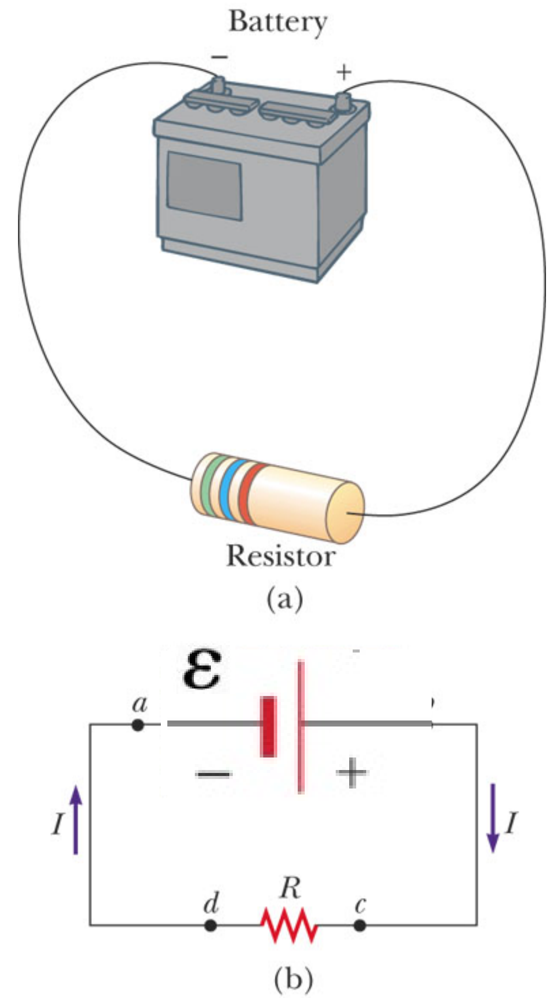
21.6: Sources of EMF

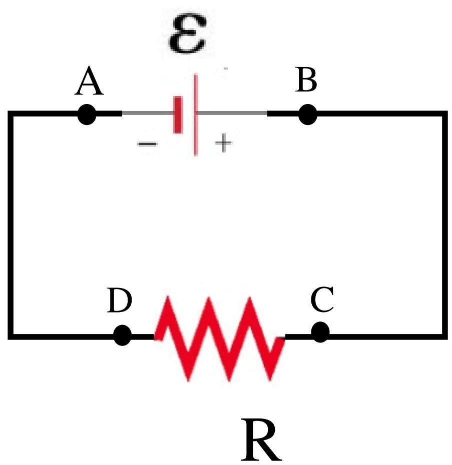
In a closed circuit, the source of EMF is what drives and sustains the current.

EMF = work done per charge: Joule / Coulomb = Volt

Assume internal resistance r of battery is negligible.

Here, $\mathcal{E} = IR$

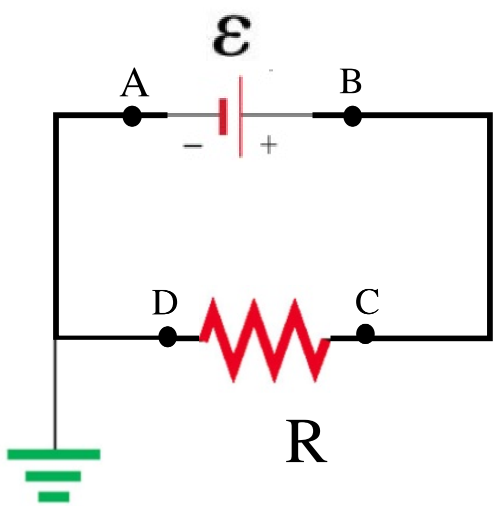




From A to B: Potential increases by $\Delta V = +\varepsilon$.

From B to A: Potential decreases by $\Delta V = -\varepsilon$.

From C to D: Potential decreases by $\Delta V = -IR = -\varepsilon$



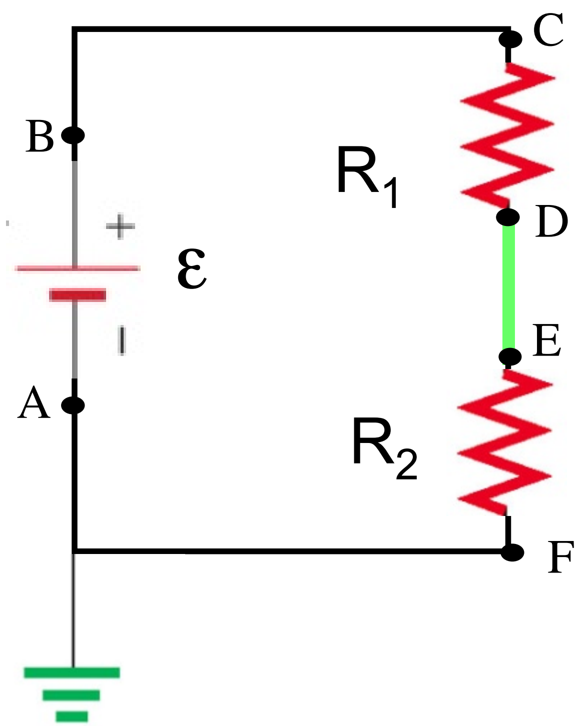
From A to B: Potential increases by $\Delta V = +\varepsilon$

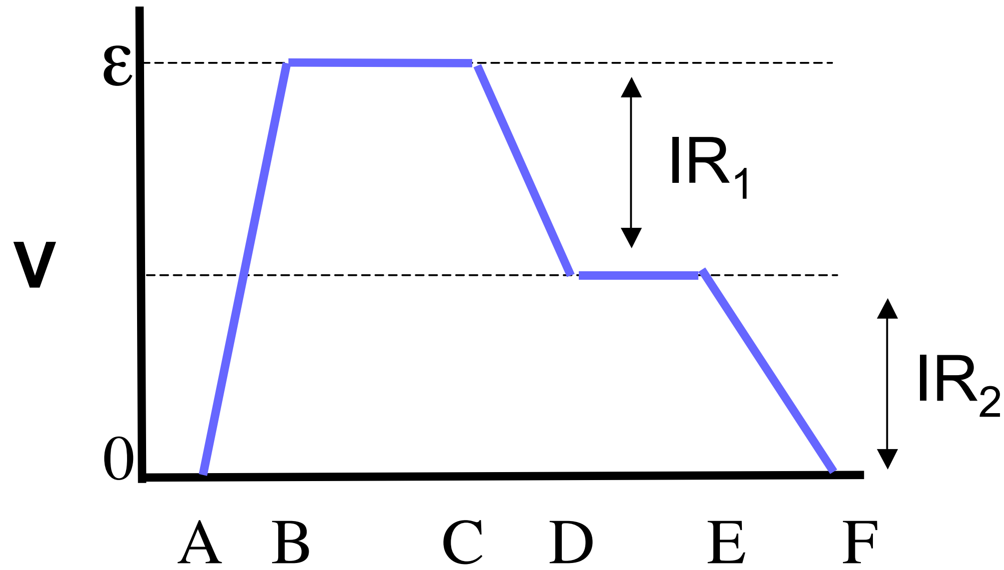
From B to A: Potential decreases by $\Delta V = -\varepsilon$.

From C to D: Potential decreases by $\Delta V = -IR$ $= -\varepsilon$

If circuit is grounded: V at points A & D will be zero.

Why is this useful?





The middle voltage can be 'tailored' to any voltage we desire (between 0 and ε) by adjusting R_1 and R_2!

A battery's internal resistance *r*

In reality, there will be some ΔV lost within the battery due to internal resistance: Ir

Terminal Voltage actually supplied: ΔV = ε – Ir.