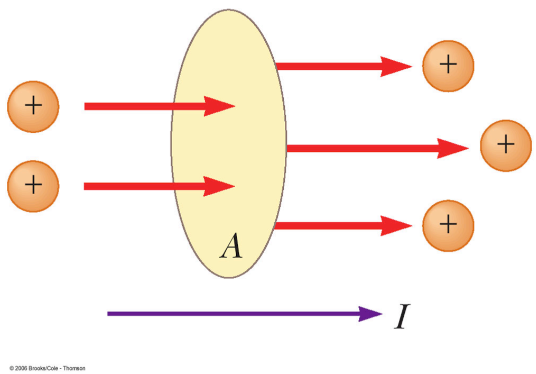
Ch. 17: Current & Resistance

Current: Rate at which charge flows through an area A (cross-section of a wire)



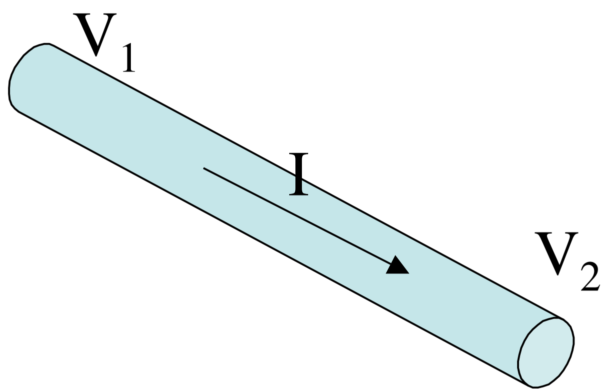
$$I \equiv \frac{\Delta Q}{\Delta t}$$

Flow is assumed to be perpendicular to area.

Units = Coul/sec = Amp.

Remember: I is defined as the direction in which positive charges will travel (in metal, the charge carriers are actually electrons)

Potential difference sets up E-field to drive Current



$V_1 - V_2 = \Delta V$

Example: Terminals of a battery

Example:

A flashlight bulb carries a current of 0.1 A.
Find the charge that passes through the bulb in 0.5 seconds:

$I = \Delta Q/\Delta T \rightarrow$: $\Delta Q = I \times \Delta T = 0.1 C/s \times 0.5 s = 0.05\ C$

How many electrons does this correspond to?

$\Delta Q = N \times e$

$N = \Delta Q/e = 0.05C / (1.6\times10^{-19}\ C/e^{-}) = 3.1\times10^{17}\ e^{-}$'s

Amp-hour

Unit of charge

charge = current $\times$ time

Ex.: Ni-metal hydride battery:
How much charge (in C) is equal to 2100 mAh?

Charge = $(2100 \times 10^{-3}\ \text{A})\ (1\ \text{hour})$
$= (2100 \times 10^{-3}\ \text{C/s})(3600\text{s})$
$=\ \ 7560$ C.

Amp-hour

If one of these batteries is used to power a device which draws 0.15 Amps, how long will the battery last?

$I = \Delta Q/\Delta T$

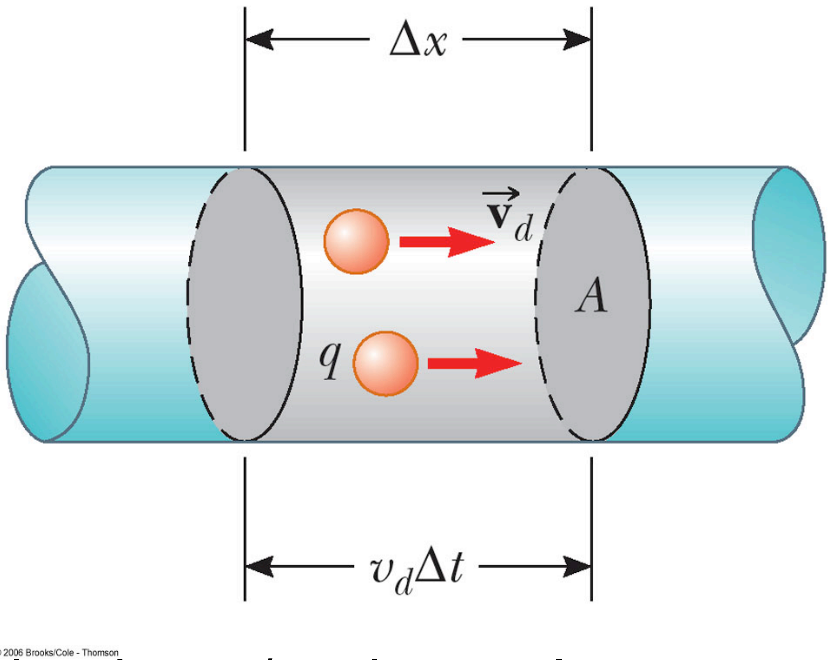
$\Delta T = \Delta Q / I = (2100 \times 10^{-3}$ Amp$\times$hr$) / 0.15$ Amps $= 14$ hours.

Drift Velocity, v_d

Volume = A Δx

n = density of charge carriers = # of charge carriers per unit vol.

N = Total # of charge carriers = n A Δx



Total charge in this volume: ΔQ = N × charge/carrier = n A Δx q

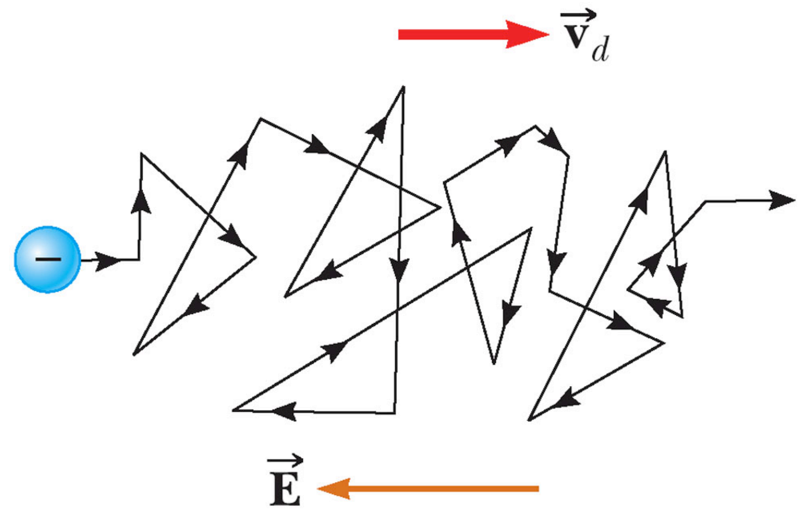
$$\Delta x = v_d \, \Delta t$$

$$\Delta Q = nA \, v_d \Delta t \, q$$

$$I = \Delta Q/\Delta t = n \, A \, v_d \, q$$

Drift Velocity, v_d

Electrons undergo repeated collisions and move randomly. Typical velocity for Cu is 2×10^6 m/s



In the presence of an external field, the average motion is a slow drift

Electric signal travels very fast -- almost at the speed of light: electrons interact and "push" other electrons in the conductor.

Example:

Find the drift velocity of electrons in a copper conductor whose diameter is 2 mm when the applied current is 0.5 A. The mass density of Cu is $\rho = 8.95 g/cm^3$. Each Cu atom contributes 1 electron. One mole of Cu has a mass of 63.5 gm.

Soln: Need to calculate density of charge carriers (# of e^-'s/m^3)

How many moles per cm^3? $(8.95 gm/cm^3)/(63.5 gm/mol) = 0.14 \ mol/cm^3$

Every mol contain $6x10^{23}$ atoms.

Number of atoms per cm^3: $(0.14 \ mol/cm^3)(6x10^{23} \ atoms/mol) = 8.4x10^{22} \ atoms/cm^3$

Density of charge carriers (given that $1e^-$/atom) = $8.4x10^{22} \ e^-/cm^3$

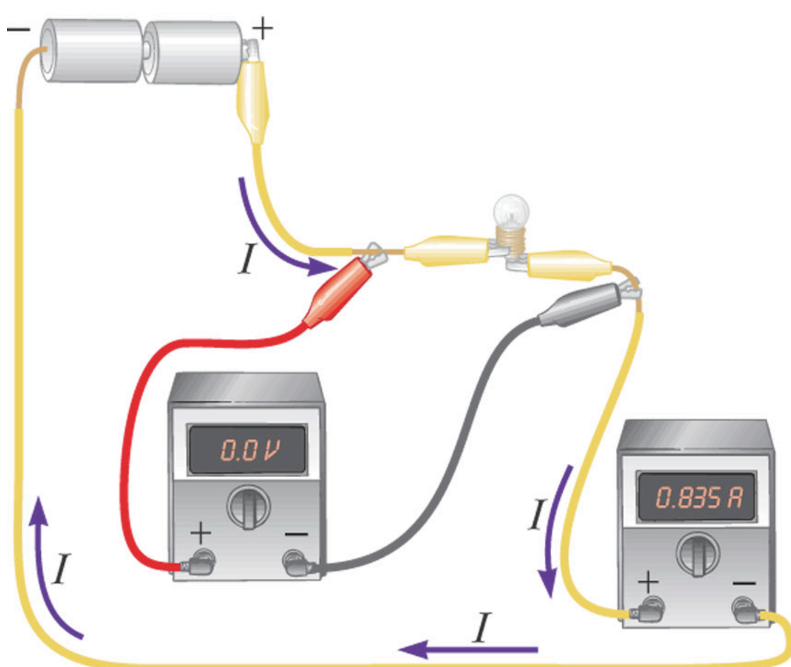
$v_d = I/(nqA) = 0.5A/(8.4x10^{28} e^-/m^3 \ 1.6x10^{-19}C \ \ 3.14(.001m)^2)$
$= 1.2x10^{-5}$ m/s = 0.012 mm/s

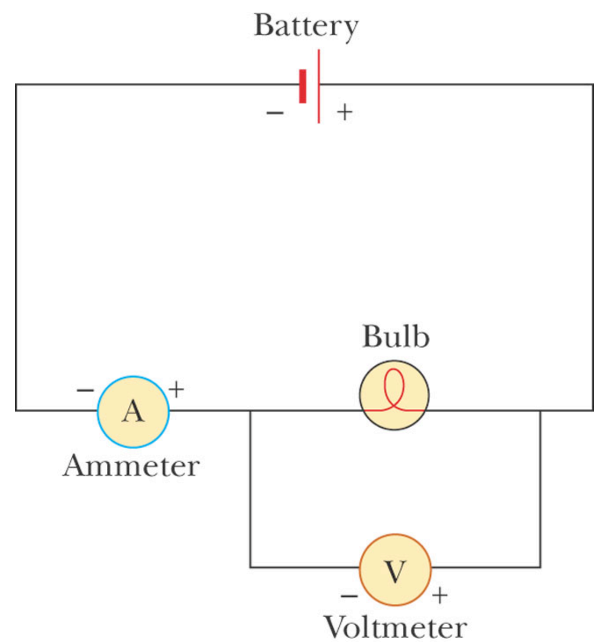
If A = 50 Amps: v_d would be 1.2 mm/s -- still a snail's pace!

Ammeter

Device used to measure current

All charge must pass through ammeter





Batteries

- Recall that a discharging capacitor delivers a large quantity of charge at once
- Batteries: Offer constant potential difference ΔV, yielding a steady amount of charge through relatively slow chemical reactions.

Batteries

- Electrons flow from the negative terminal to the positive terminal.
- Reaction doesn't take place unless the terminals are connected to something (so batt. can sit on shelf for a while and still have lots of power)
- If you attach a wire between the terminals directly, with no load, you'll wear out the battery quickly.

Parts of a battery

Example: Zn/C battery:
Negative terminal: Zn
Positive terminal: C
Electrolyte: sulfuric acid
conducting wire

$H_2SO_4 + Zn \rightarrow \quad SO_4^{-} + H^{+} + H^{+} + Zn^{2+} + e^{-} + e^{-}$

$Zn^{2+} + SO_4^{-} \rightarrow ZnSO_4$

The e^{-}'s from the zinc atoms flow through the wire and combine with H on the Carbon rod. (lower potential V: easier then combining with the H^{+} in the acid)

Different combinations of metals and electrolytes (medium) control the final voltage

- **Zinc-carbon battery** - Also known as a **standard carbon** battery, zinc-carbon chemistry is used in all inexpensive AA, C and D dry-cell batteries. The electrodes are zinc and carbon, with an acidic paste between them that serves as the electrolyte.
- **Alkaline battery** - Alkaline chemistry is used in common Duracell and Energizer batteries, the electrodes are zinc and manganese-oxide, with an alkaline electrolyte.
- **Lithium-iodide battery** - Lithium-iodide chemistry is used in pacemakers and hearing aides because of their long life.
- **Lead-acid battery** - Lead-acid chemistry is used in automobiles, the electrodes are made of lead and lead-oxide with a strong acidic electrolyte (rechargeable).
- **Nickel-cadmium battery** - The electrodes are nickel-hydroxide and cadmium, with potassium-hydroxide as the electrolyte (rechargeable).
- **Nickel-metal hydride battery** - This battery is rapidly replacing nickel-cadmium because it does not suffer from the memory effect that nickel-cadmiums do (rechargeable).
- **Lithium-ion battery** - With a very good power-to-weight ratio, this is often found in high-end laptop computers and cell phones (rechargeable).
- **Zinc-air battery** - This battery is lightweight and rechargeable.
- **Zinc-mercury oxide battery** - This is often used in hearing-aids.
- **Silver-zinc battery** - This is used in aeronautical applications because the power-to-weight ratio is good.

(http://electronics.howstuffworks.com/battery.htm)

Lemon Battery

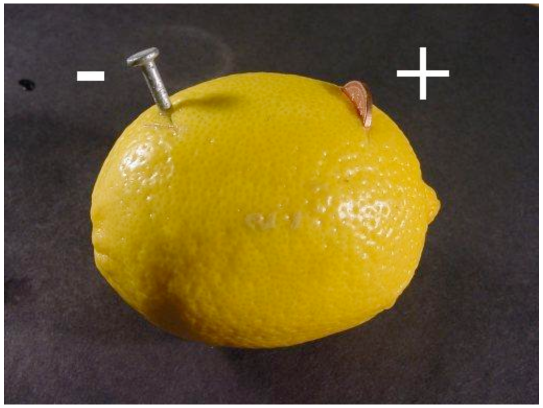
http://hilaroad.com/camp/projects/lemon/lemon_battery.html
http://www.ehow.com/how-does_5474935_lemon-battery-works.html

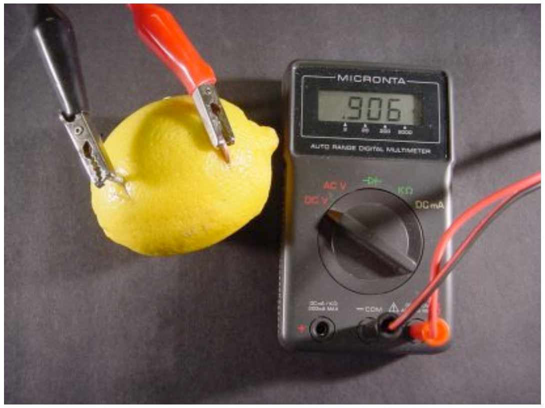
Lemons contain citric acid (electrolyte)
Negative terminal: Galvanized nail (Zn coating)
Positive terminal: Cu penny

$Zn \rightarrow Zn^{2+} + 2\ e^{-}$

The copper attracts the electrons

When the electrons reach the other end:
$2H^{+} + 2e^{-} \rightarrow H_2$





http://amctv.com

Walt uses everyday materials to build a homemade Galvanic Cell.

http://www.scriptphd.com

Anode(neg.): Zn from coins, galvanized nuts, bolts, washers

Cathode (pos.): graphite + mercuric oxide from the brake pads

Electrolyte: sponge in potassium hydroxide: (supply K+ and OH- ions)

Conductor: Cu wire

Connecting cells in series

$\Delta V_{total} = \Delta V_1 + \Delta V_2 + \ldots + \Delta V_6$

$9V = 1.5V + 1.5V + \ldots. + 1.5V$

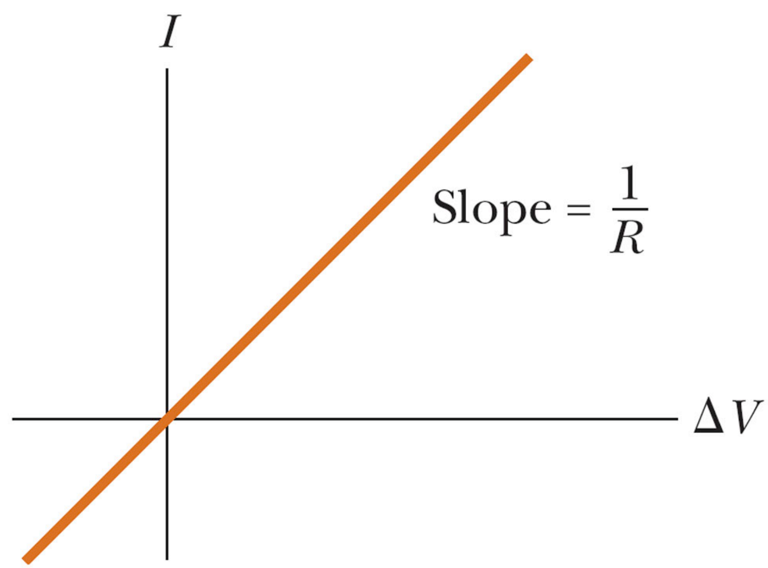
Resistance

Resistance of a conductor is defined as ratio of potential difference across it to the current that results:
Ohm's Law: For many materials, R remains constant over a wide range of applied ΔV or I.

$$R \equiv \frac{\Delta V}{I}$$

$$\mathbf{\Delta V = IR}$$

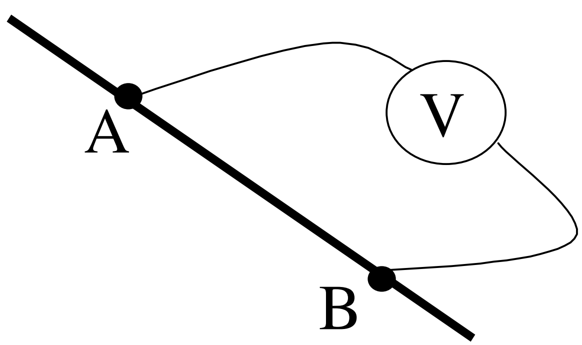
Units of R: Ohms (Ω)

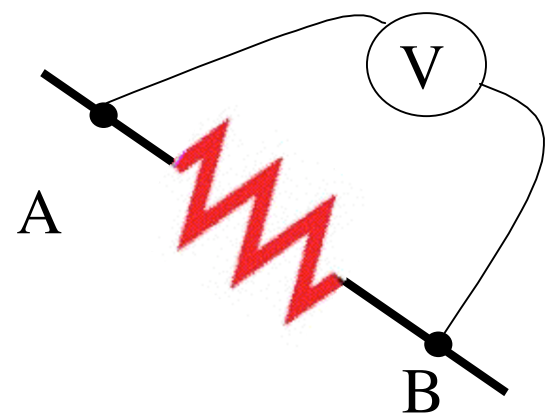


Resistors

In a circuit: the resistance of the conducting wires is negligible, so $\Delta V = 0$ (no extra loss in potential) between points A & B.

But a resistor can cause a significant drop in ΔV (comparing V before/after the resistor):



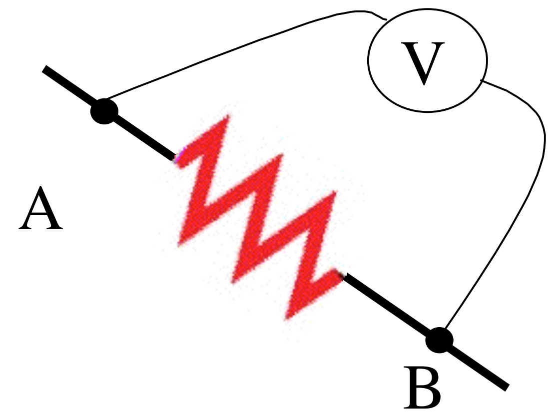


Resistors

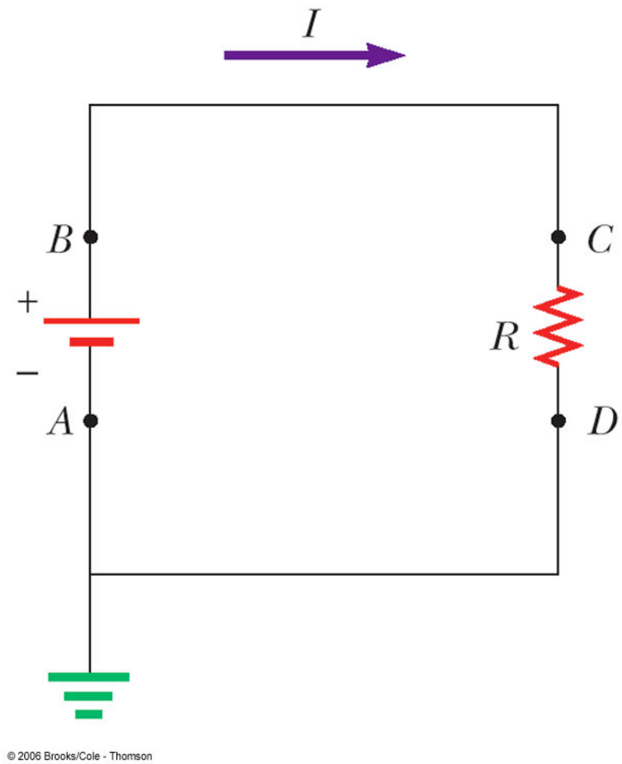
Analogy: Waterfalls: sudden drop in gravitational potential energy

ΔPE converted to kinetic energy of water

$$q\Delta V = \Delta PE$$



electrical potential energy converted to thermal energy in resistor



Change in PE is

$+q\Delta V$ (battery)

or $-q\Delta V$ (resistor)

Points A and D are “grounded” -- Potential V = 0.

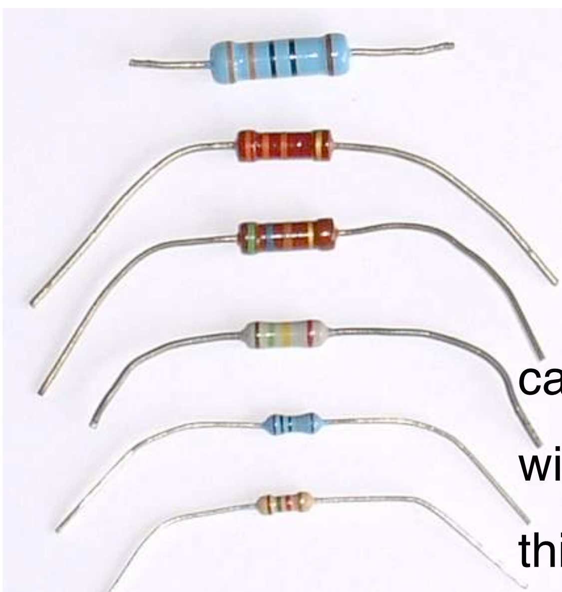
Points B and C are both at higher potential

Resistors

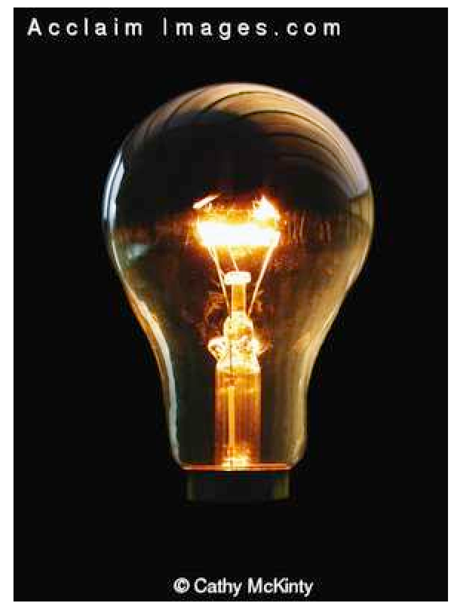
RESISTANCE regulates current and causes conversion of electrical potential energy to heat.

Common examples: heating elements in toasters, hair dryers, space heaters; light bulb filaments

http://msc-ks4technology.wikispaces.com/



kidbots.com



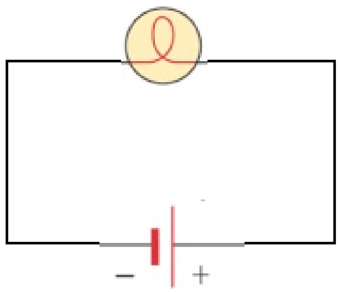
carbon resistors

wire wound resistors

thin metal film resistors

Examples:

Consider a simple V-R circuit comprising a light bulb. Assume there is a 1.5-volt battery and the light bulb draws a current of 0.2 Amps. Find the R of the light bulb filament:



$R = \Delta V/I = 1.5V/0.2\ A = 7.5\ \Omega$

A 120-Volt (rel. to ground) household circuit is connected to a lamp; the light bulb filament has R = 240 Ω. Find I.

$I = \Delta V/R = 120V/240\Omega = 0.5\ A$

Resistance is determined by geometry & resistivity

$$R = \rho \frac{L}{A}$$

ρ = resistivity.
units are Ωm

TABLE 17.1

Resistivities and Temperature Coefficients of Resistivity for Various Materials (at 20°C)

Material	Resistivity ($\Omega \cdot$ m)	Temperature Coefficient of Resistivity [(°C)$^{-1}$]
Silver	1.59×10^{-8}	3.8×10^{-3}
Copper	1.7×10^{-8}	3.9×10^{-3}
Gold	2.44×10^{-8}	3.4×10^{-3}
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Tungsten	5.6×10^{-8}	4.5×10^{-3}
Iron	10.0×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[a]	150×10^{-8}	0.4×10^{-3}
Carbon	3.5×10^{5}	-0.5×10^{-3}
semi-conductors { Germanium	0.46	-48×10^{-3}
Silicon	640	-75×10^{-3}
insulators { Glass	10^{10}–10^{14}	
Hard rubber	$\approx 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

[a]A nickel–chromium alloy commonly used in heating elements.

$$R = \rho \frac{L}{A}$$

Resistance caused by charge carriers colliding with the lattice of the conductor.
More collisions = more resistance

L = length

Double the length → double the resistance

(electrons must undergo twice as many collisions across the resistor)

$$R = \rho \frac{L}{A}$$

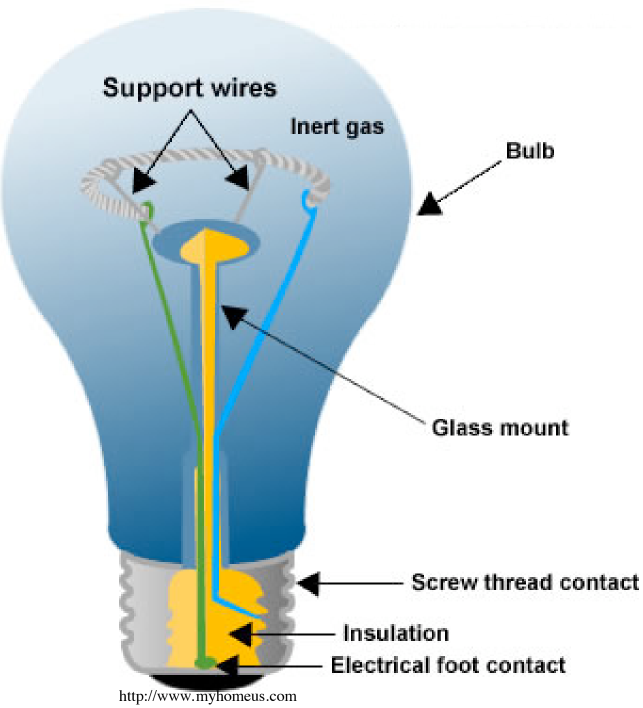
A = cross-section area

Decrease Area: Resistance is raised since flow of charge carriers is constricted

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.

Please note -- I edited some values here compared to the slide I presented in lecture!

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

Calculate typical R.

$A = \pi(5x10^{-5}m)^2 = 7.9x10^{-9}\ m^2$

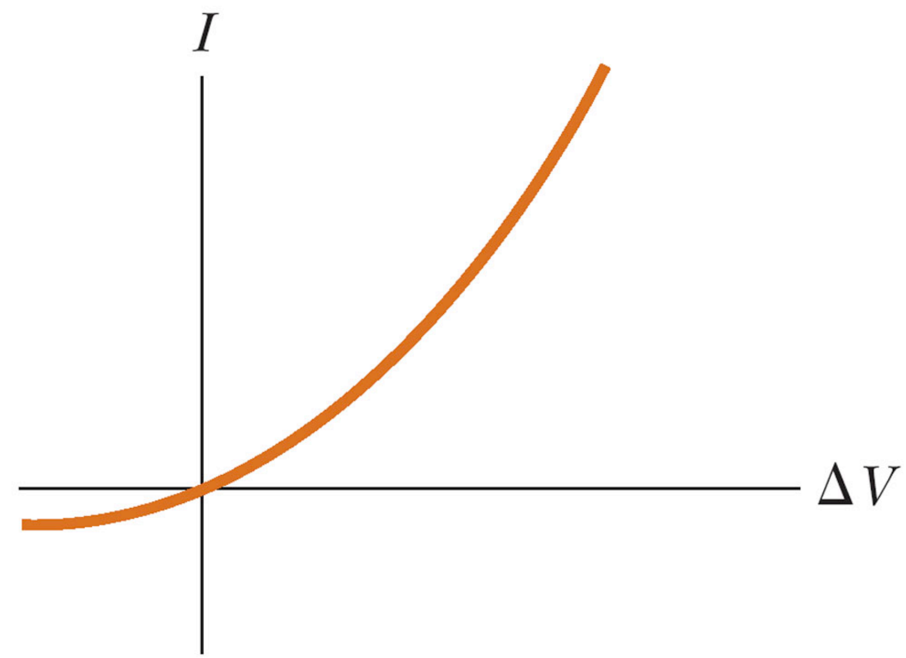
$\rho = 5.6x10^{-8}\ \Omega m$ (Table 17.1)

$R = \rho L/A = (5.6x10^{-8}\ \Omega m)\ (1m)/\ 7.9x10^{-9}\ m^2 = 7.1\ \ \Omega$

(Note: As per section 17.6, 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. At T=4000°C, $\rho = \rho_0[1+\alpha(T-T_0)] = 8.3x10^{-7}\ \Omega m$ (for tungsten, $\alpha = 4.5x10^{-3}/°C$), and $R = 106\ \Omega$.)

Some materials exhibit non-Ohmic resistance

Current-voltage curve for a semi-conducting diode: it's non-linear



In this course, assume Ohmic resistance unless otherwise stated

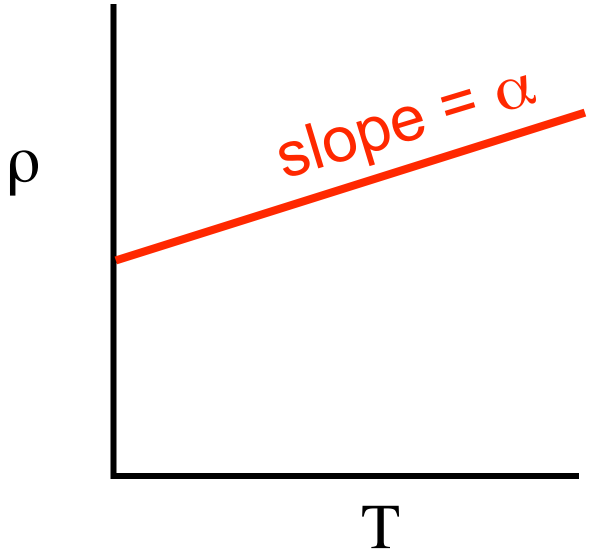
Temperature dependence of resistance

At higher T, the charge carriers' collisions with the lattice are more frequent.

v_d becomes lower. So I becomes lower.

And R becomes larger for a given potential.

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?

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

$$R = 50\Omega\,[1 + 3.92 \times 10^{-3}\,(ºC)^{-1}\,(30.0\,ºC)] = 55.88\,\Omega$$

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?

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

$$91.6\Omega = 50\Omega\ [1 + 3.92 \times 10^{-3}\ (ºC)^{-1}\ (T - 20ºC)]$$

$$1.83 = [1 + 3.92 \times 10^{-3}\ (ºC)^{-1}\ (T - 20ºC)]$$

$$0.83 = 3.92 \times 10^{-3}\ (ºC)^{-1}\ (T - 20ºC)$$

$$212ºC = T - 20ºC$$

$$T = 232\ ºC$$