Ch. 21: Current, Resistance, Circuits

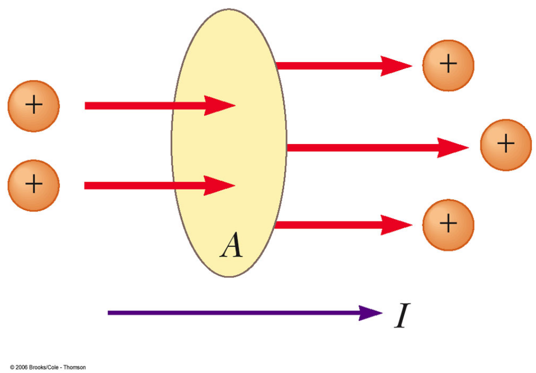
Current: How charges flow through circuits

Resistors: convert electrical energy into thermal/radiative energy

Electrical Energy & Power; Household Circuits

Time-Dependent Circuits

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



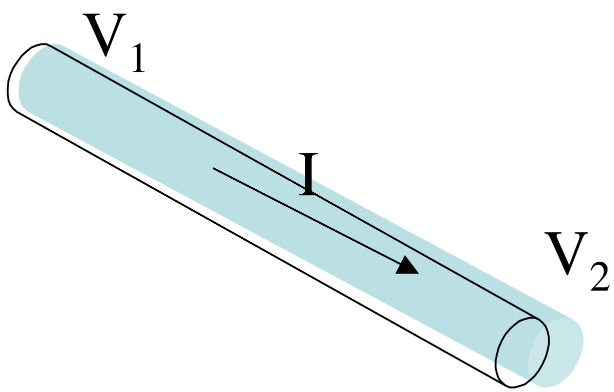
$$I \equiv \frac{\Delta Q}{\Delta t}$$

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

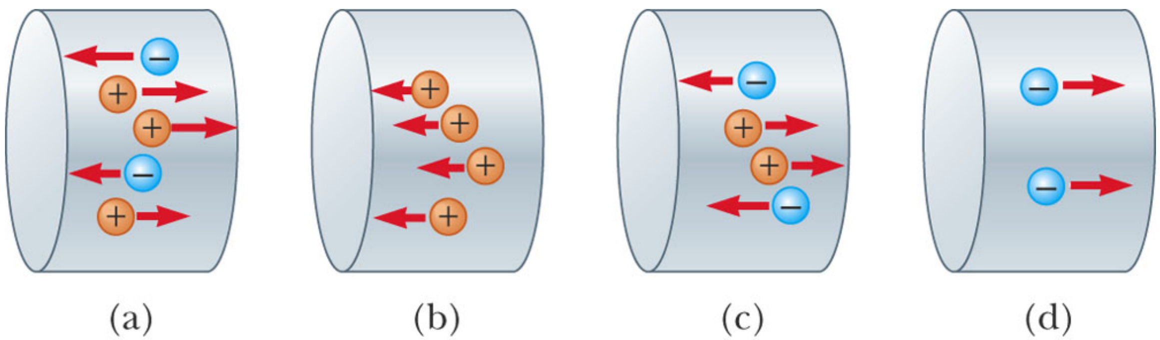
How many electrons does this correspond to?

$\Delta Q = N \times e$

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

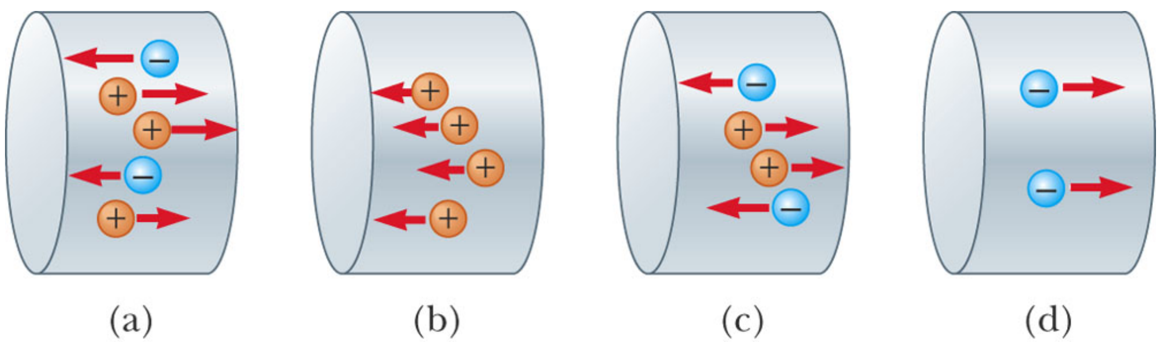
Remember: I is defined as the direction in which positive charges will travel (in metal, the charge carriers are actually electrons)

From quick quiz 21.1:
Rank the currents from lowest to highest:



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

From quick quiz 21.1:
Rank the currents from lowest to highest:



Negative charges moving left are equivalent to positive charges moving right.

(a) Equivalent to 5 +'s moving right.

(b) 4 +'s moving left

(c) Equivalent to 4 +'s moving right

(d) Equivalent to 2 +'s moving right

Amp-hour

Unit of charge

charge = current × time

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

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

Amp-hour

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

$I = \Delta Q / \Delta T$

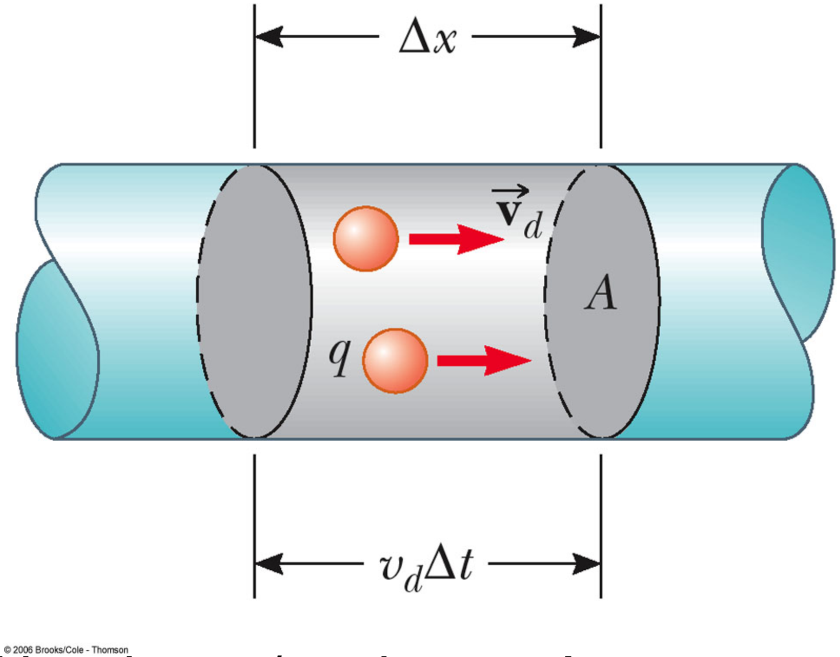
$\Delta T = \Delta Q / I = (2100 \times 10^{-3}$ $\text{Amp} \times \text{hr}) / 0.15$ Amps = 14 hours.

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

$\Delta x = v_d \Delta t$

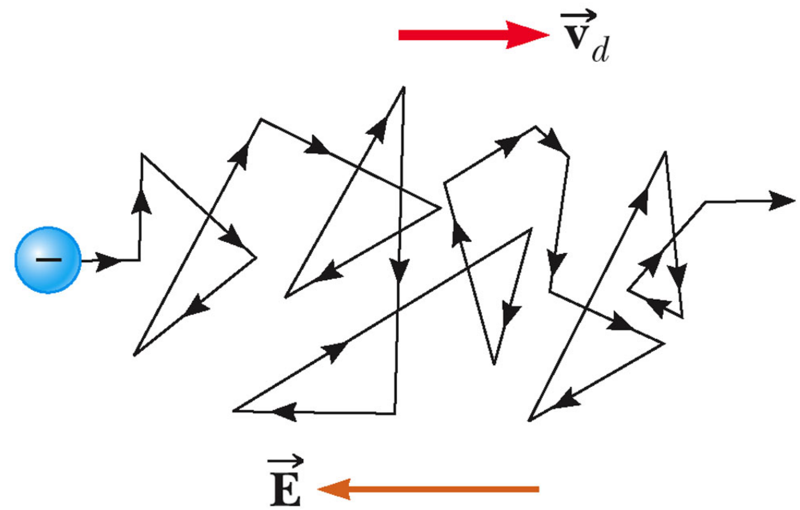
$\Delta Q = nA\, v_d \Delta t\, q$

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

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!

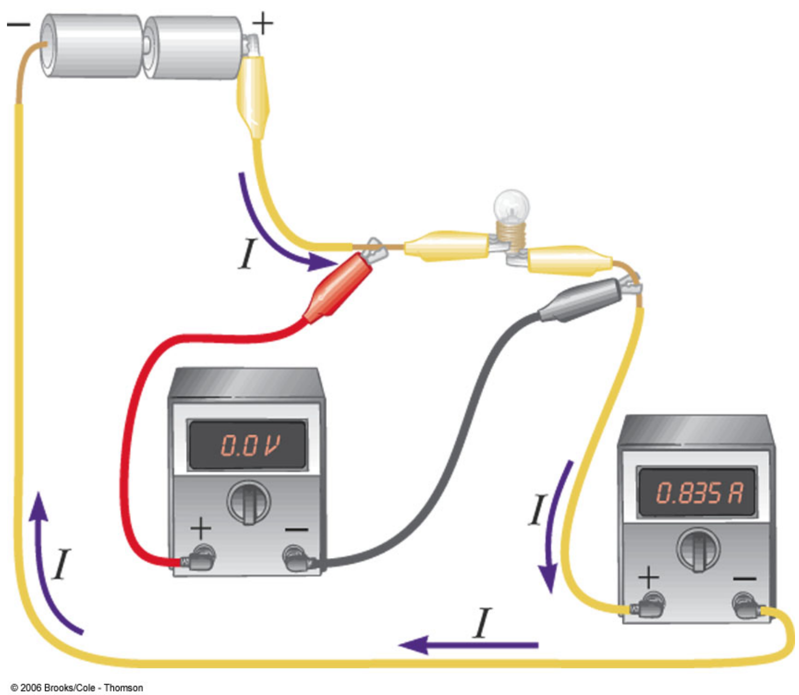
Current Density
$J = I/A = n\, q\, v_d$

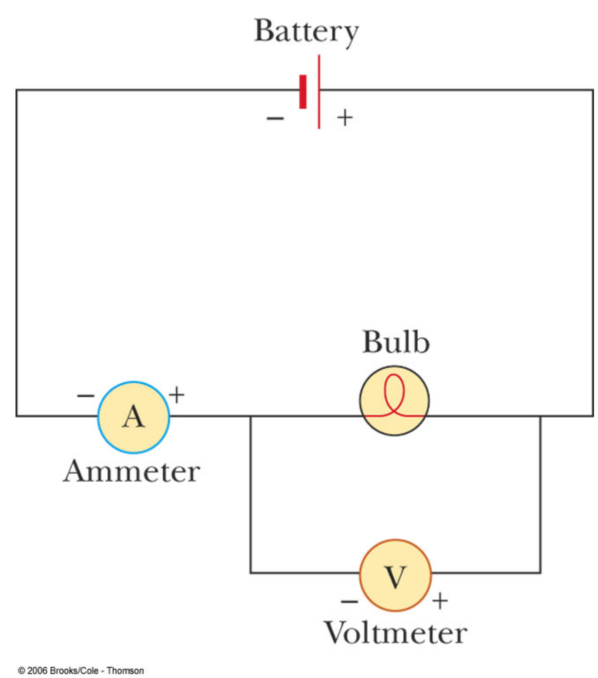
SI unit: Amps / m^2

Ammeter

Device used to measure current

All charge must pass through ammeter





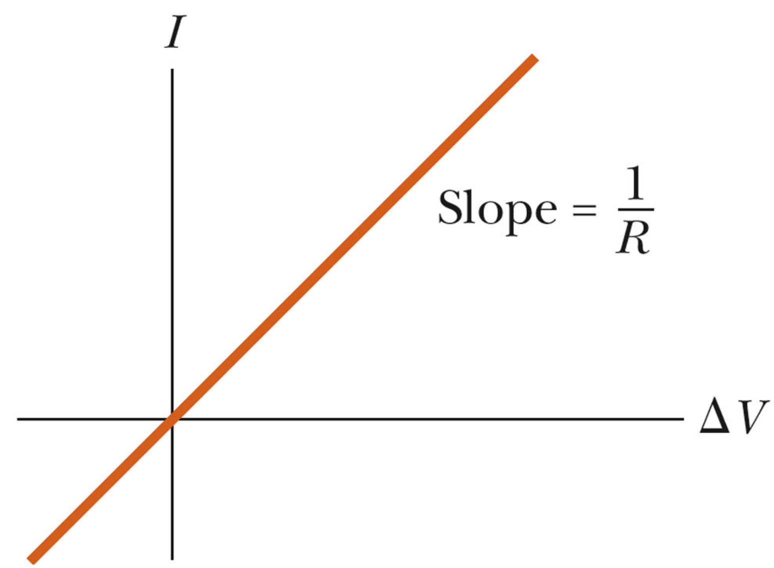
21.2: Resistance & Ohm's Law

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.

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

$\Delta V = IR$

Units of R: Ohms (Ω)



Resistors

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

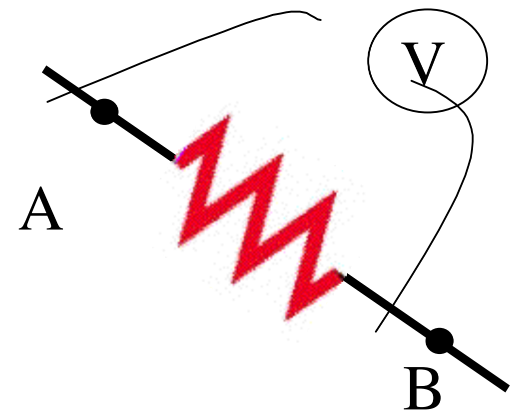
But a resistor can cause a significant drop in ΔV (comparing V before/after the resistor):

Resistors

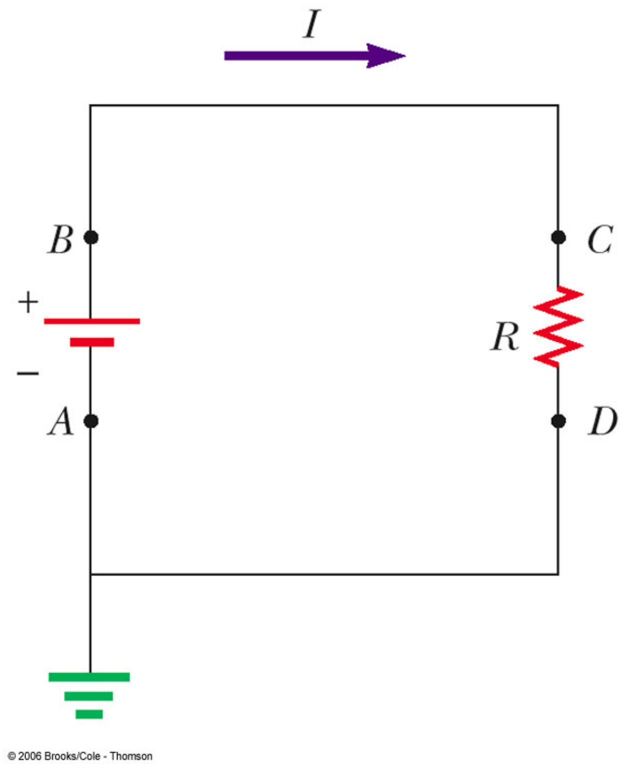
Analogy: Waterfalls: sudden drop in gravitational potential energy

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

+qΔV (battery)

or –qΔV (resistor)

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

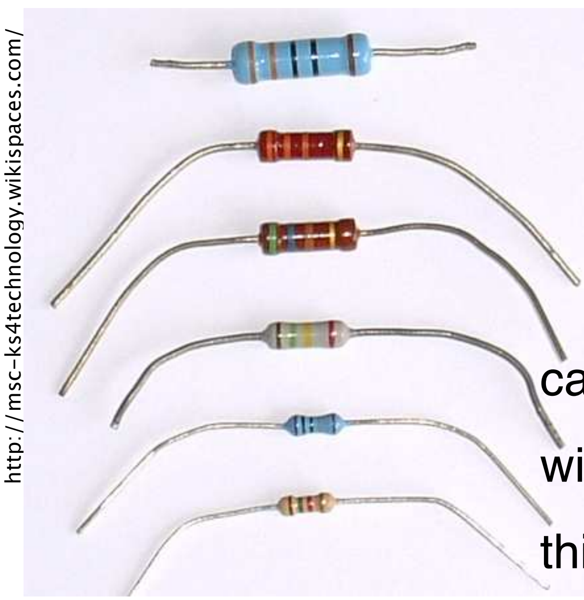
Points B and C are both at higher potential

Resistors

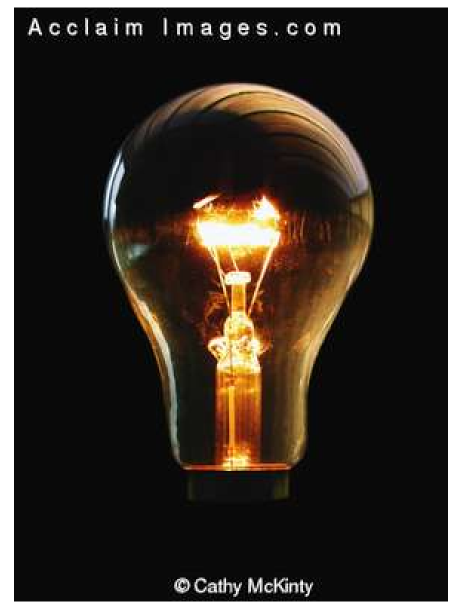
RESISTANCE regulates current and causes conversion of electrical potential energy to heat.

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

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



kidbots.com



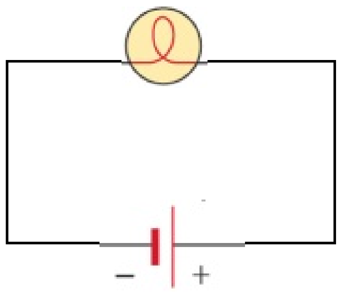
carbon resistors

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 21.1 Resistivities and Temperature Coefficients of Resistivity for Various Materials

Material	Resistivity[a] ($\Omega \cdot m$)	Temperature Coefficient α [(°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	10×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[b]	1.50×10^{-6}	0.4×10^{-3}
Carbon	3.5×10^{-5}	-0.5×10^{-3}
Germanium	0.46	-48×10^{-3}
Silicon	640	-75×10^{-3}
Glass	10^{10} to 10^{14}	
Hard rubber	$\sim 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

semi-conductors { (Germanium, Silicon)

insulators { (Glass, Hard rubber, Sulfur, Quartz)

[a]All values are at 20°C.
[b]Nichrome is a nickel–chromium alloy commonly used in heating elements.

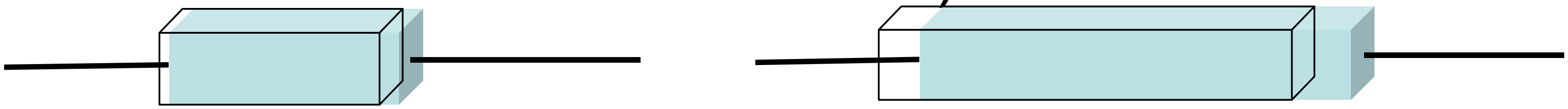
$$R = \rho \frac{L}{A}$$

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

L = length

Double the length → double the resistance

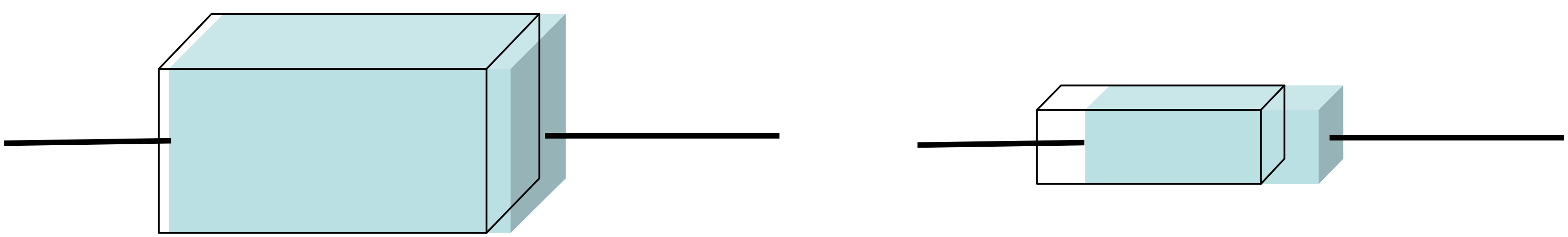
(electrons must undergo twice as many collisions across the resistor)



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

A = cross-section area

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



Conductivity σ

$\sigma = 1/\rho$

$R = \rho L/A$

$R = L/(\sigma A)$

$V/I = L/(\sigma A)$

$V/L = I/(\sigma A)$

$E = J/\sigma$

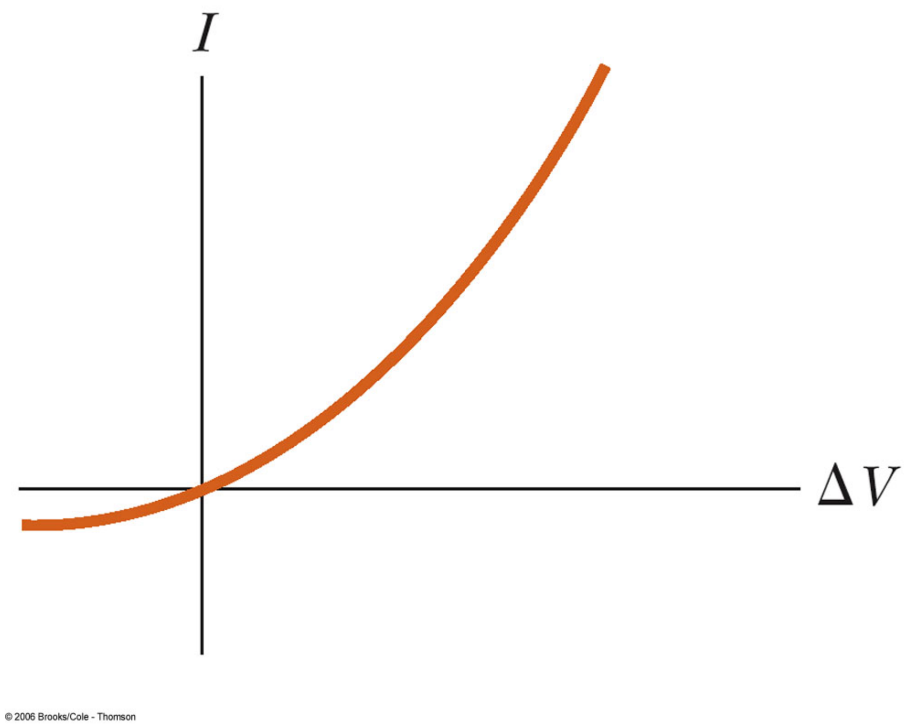
$J = \sigma E$

Resistivity and conductivity are "microscopic" properties of the material

Resistance is a macroscopic property of an object, and is a function of geometry and resistivity

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

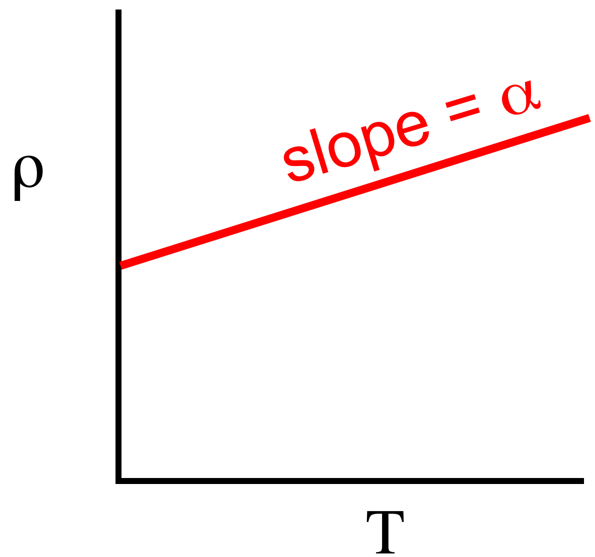
Temperature dependence of resistance

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 $(^oC)^{-1}$

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

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 = 50Ω [1 + 3.92 $\times10^{-3}$ $(ºC)^{-1}$ (30.0 ºC)] = 55.88 Ω

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?

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

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

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

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

$$212ºC = T - 20ºC$$

$$T = 232\ ºC$$