Lecture (07)
Electric Current and Resistance

By:

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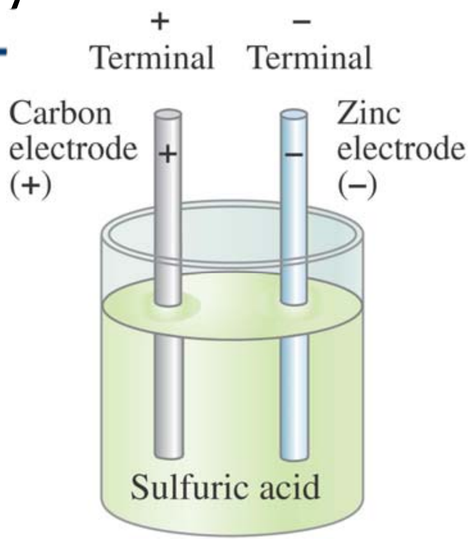
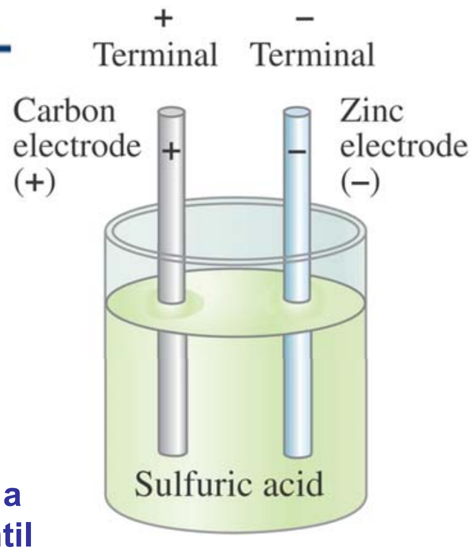
- The glow of the thin wire filament of a light bulb is caused by the electric current passing through it.
- Electric energy is transformed to thermal energy (via collisions between moving electrons and atoms of the wire), which causes the wire's temperature to become so high that it glows.
- Electric current and electric power in electric circuits are of basic importance in everyday life.

The Electric Battery

- **Volta discovered that electricity could be created if dissimilar metals were connected by a conductive solution called an electrolyte.**
- **This is a simple electric cell.**

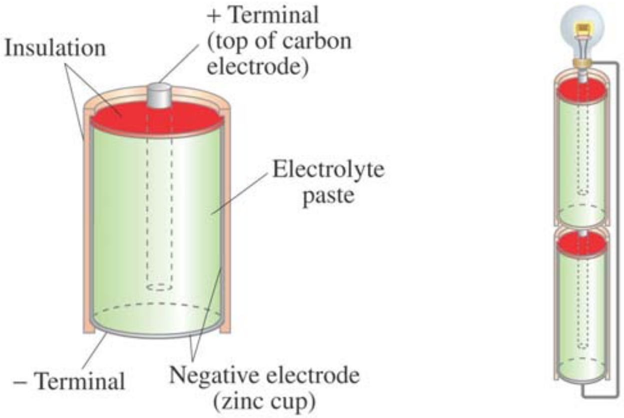


- **A battery transforms chemical energy into electrical energy.**
- **Chemical reactions within the cell create a potential difference between the terminals by slowly dissolving them.**
- **This potential difference can be maintained even if a current is kept flowing, until one or the other terminal is completely dissolved.**

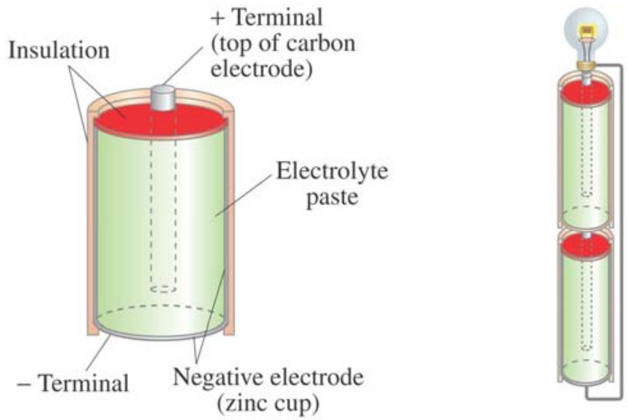


- **Several cells connected together make a battery, although now we refer to a single cell as a battery as well.**

(a) Diagram of an ordinary dry cell (like a D-cell or AA). The cylindrical zinc cup is covered on the sides; its flat bottom is the negative terminal.



- Two dry cells (AA type) connected in series.
- Note that the positive terminal of one cell pushes against the negative terminal of the other.



Electric Current

- **Electric current is the rate of flow of charge through or past a point:**

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

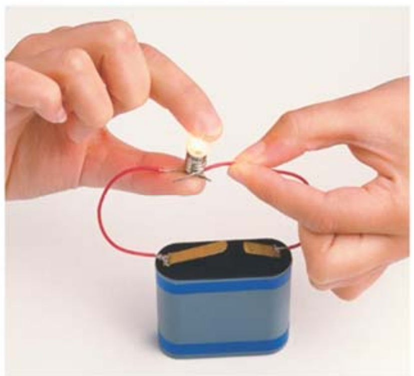
- **The instantaneous current is given by:**

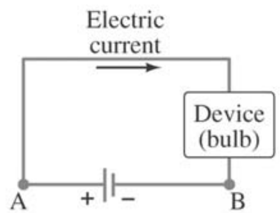
$$I = \frac{dQ}{dt}$$

- **Unit of electric current: the ampere, A:**

1 A = 1 C/sec

- **A complete circuit is one where current can flow all the way around.**





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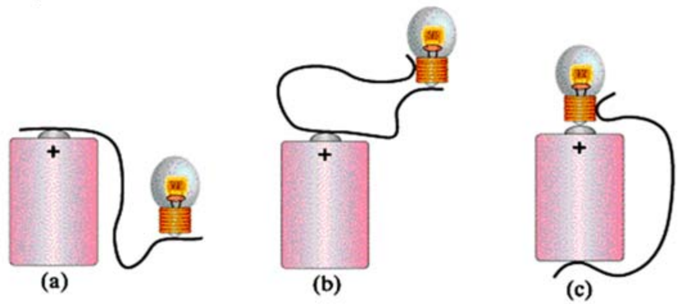
Example 01

- **Current is flow of charge. A steady current of 2.5 A exists in a wire for 4.0 min.**
- **(a) How much total charge passed by a given point in the circuit during those 4.0 min?**
- **(b) How many electrons would this be?**

- $\Delta Q = I\,\Delta t = 2.5\ \times 240 = 600\ C$
- $e = 1.6\ \times\ 10^{-19}\ C$
- $\therefore 600\ C\ contains = \frac{600}{1.6 \times 10^{-19}} = 3.8\ \times 10^{21}\ electrons$

MCQ

- Which is the correct way to light the light bulb with the battery?



- d) all are correct
- e) none are correct

MCQ

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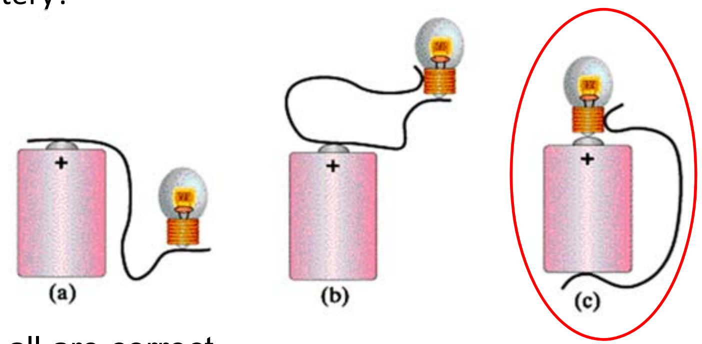
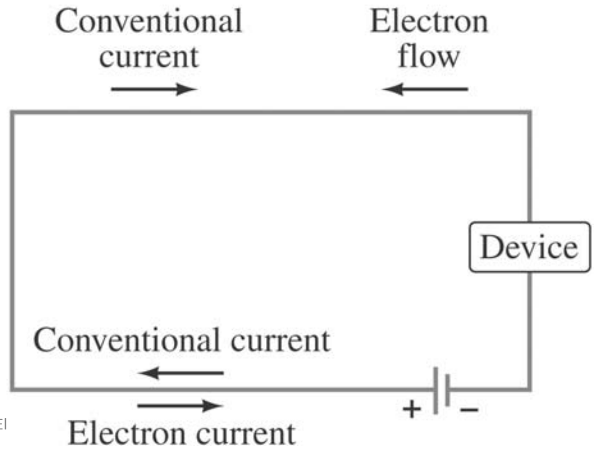


- d) all are correct
- e) none are correct

- By convention, current is defined as flowing from + to -. Electrons actually flow in the opposite direction, but not all currents consist of electrons.

Conventional current from + to - is equivalent to a negative electron flow from – to +.



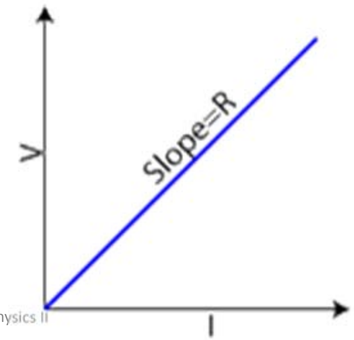
Ohm’s Law: Resistance and Resistors

- Experimentally, it is found that the current in a wire is proportional to the potential difference between its ends:

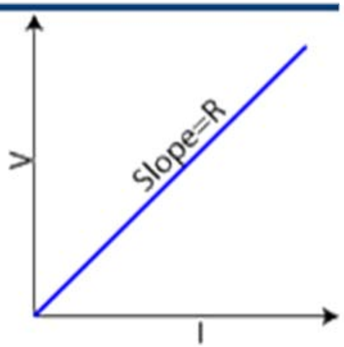
$$I \propto V$$

- The ratio of voltage to current is called the resistance (R):

$$R = \frac{V}{I}$$

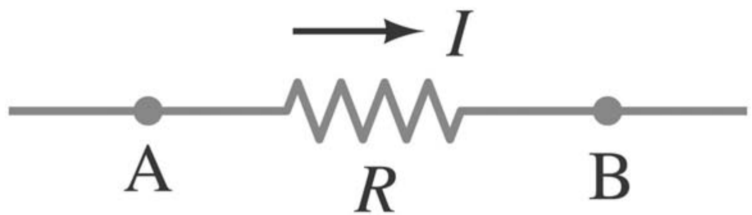


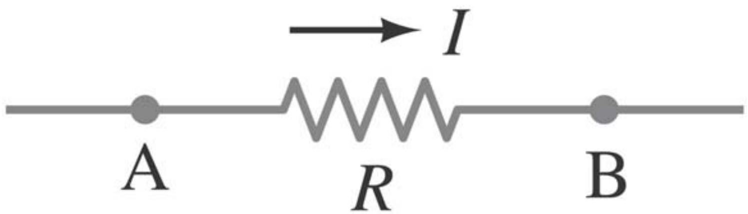
- **In many conductors, the resistance is independent of the voltage; this relationship is called Ohm’s law.**
- **Materials that do not follow Ohm’s law are called nonohmic.**
- **Unit of resistance: the ohm, Ω:**
- **1 Ω = 1 V/A**



Example

- Current I enters a resistor R as shown.
- (a) Is the potential higher at point A or at point B?
- (b) Is the current greater at point A or at point B?

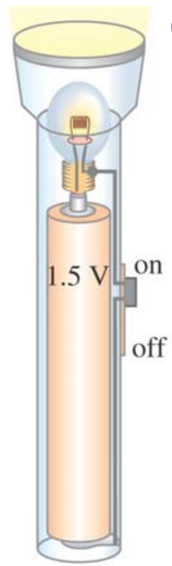




- a. Point A is at higher potential (current flows “downhill”).
- b. The current is the same – all the charge that flows past A also flows past B.

Example

- Flashlight bulb resistance.
- A small flashlight bulb draws 300 mA from its 1.5-V battery.
- (a) What is the resistance of the bulb?
- (b) If the battery becomes weak and the voltage drops to 1.2 V, how would the current change?



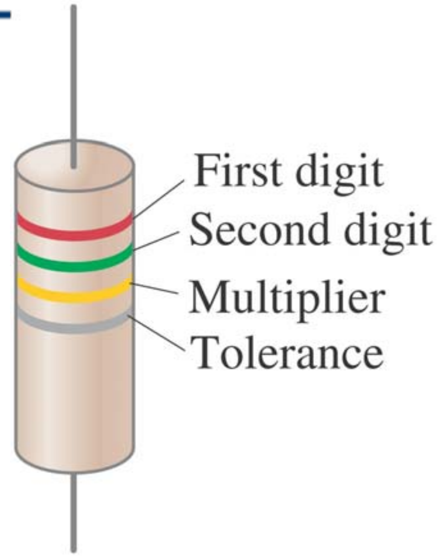
- a.

$$R = \frac{V}{I} = \frac{1.5}{300 \ \times 10^{-3}} = 0.5 \ \Omega$$

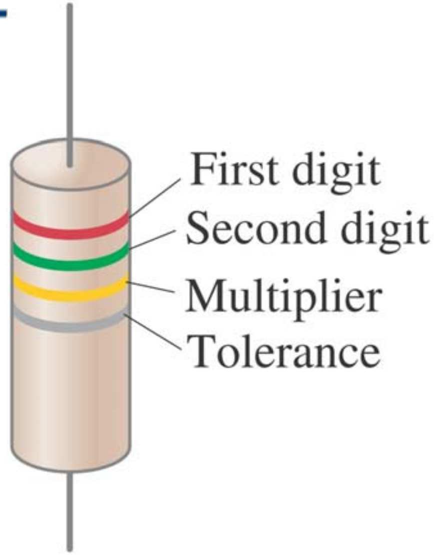
- b.

$$I = \frac{V}{R} = \frac{1.2}{0.5} = 2.4 \ A$$

- Standard resistors are manufactured for use in electric circuits; they are color-coded to indicate their value and precision



- The resistance value of a given resistor is written on the exterior, or may be given as a color code
- the first two colors represent the first two digits in the value of the resistance,
- the third color represents the power of ten that it must be multiplied by, and
- the fourth is the manufactured tolerance.



- This is the standard resistor color code. Note that the colors from red to violet are in the order they appear in a rainbow.

Resistor Color Code

Color	Number	Multiplier	Tolerance
Black	0	1	
Brown	1	10^1	1%
Red	2	10^2	2%
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold		10^{-1}	5%
Silver		10^{-2}	10%
No color			20%

- For example, a resistor whose four colors are red, green, yellow, and silver has a resistance of 25 x 10^4 Ω = 250,000 Ω = 250 kΩ, plus or minus 10%.

Resistor Color Code

Color	Number
Black	0
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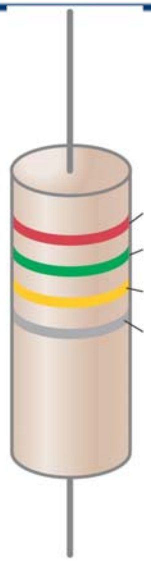
Green	5
Blue	6
Violet	7
Gray	8
White	9
Gold	
Silver	
No color	



- **Some clarifications:**
- Batteries maintain a (nearly) constant potential difference; the current varies.
- Resistance is a property of a material or device.
- Current is not a vector but it does have a direction.
- Whatever charge goes in one end of a circuit comes out the other end.

Resistivity

- The resistance of a wire is directly proportional to its length and inversely proportional to its cross-sectional area:

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

- The constant ρ, the resistivity, is characteristic of the material.

- This table gives the resistivity and temperature coefficients of typical conductors, semiconductors, and insulators.

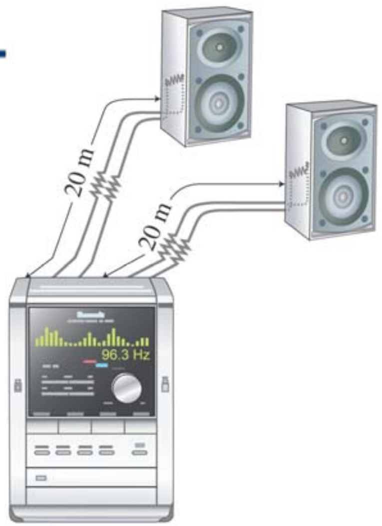
TABLE 25–1 Resistivity and Temperature Coefficients (at 20°C)

Material	Resistivity, ρ ($\Omega \cdot$ m)	Temperature Coefficient, α (C°)$^{-1}$
Conductors		
Silver	1.59×10^{-8}	0.0061
Copper	1.68×10^{-8}	0.0068
Gold	2.44×10^{-8}	0.0034
Aluminum	2.65×10^{-8}	0.00429
Tungsten	5.60×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.60×10^{-8}	0.003927
Mercury	98.00×10^{-8}	0.0009
Nichrome (Ni, Fe, Cr alloy)	100.00×10^{-8}	0.0004
Semiconductors†		
Carbon (graphite)	$(3-60) \times 10^{-5}$	−0.0005
Germanium	$(1-500) \times 10^{-3}$	−0.05
Silicon	0.1 – 60	−0.07
Insulators		
Glass	$10^{9} - 10^{12}$	
Hard rubber	$10^{13} - 10^{15}$	

† Values depend strongly on the presence of even slight amounts of impurities.

Example

- **Suppose you want to connect your stereo to remote speakers.**
- **(a) If each wire must be 20 m long, what radius of copper wire should you use to keep the resistance less than 0.10 Ω per wire?**
- **(b) If the current to each speaker is 4.0 A, what is the potential difference, or voltage drop, across each wire?**

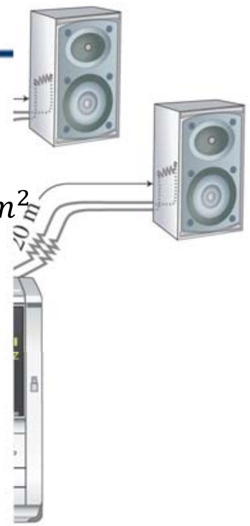


a.

- $\rho_{copper} = 1.68 \times 10^{-8} \Omega$ m
- $A = \rho \frac{l}{R} = 1.68 \times 10^{-8} \frac{20}{0.1} = 3.36 \times 10^{-6} m^2$
- $A = \pi r^2$
- $\therefore r = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{3.36 \times 10^{-6}}{3.14}} = 1.03 \times 10^{-3} m$

B.

- $V = I R = 4 \times 0.1 = 0.4 \, volt$



MCQ

- You double the *voltage* across a certain conductor and you observe the *current* increases three times. What can you conclude?

1) Ohm's law is obeyed since the current still increases when V increases

2) Ohm's law is not obeyed

3) this has nothing to do with Ohm's law

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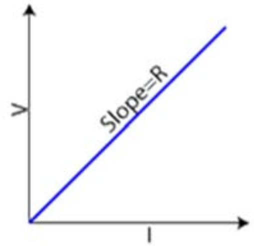

Ohm's law, $V = IR$, states that the relationship between voltage and current is linear. Thus, for a conductor that obeys Ohm's law, the current must double when you double the voltage.

MCQ

- A wire of resistance R is stretched uniformly (keeping its volume constant) until it is twice its original length. What happens to the resistance?

1) it decreases by a factor of 4

2) it decreases by a factor of 2

3) it stays the same

4) it increases by a factor of 2

5) it increases by a factor of 4

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Keeping the volume (= area x length) constant means that if the length is doubled, the area is halved.

Since $R = \rho \frac{\ell}{A}$, this increases the resistance by a factor of 4.

Temperature Dependence of Resistivity

- The resistivity of a material depends somewhat on temperature.
- The resistance of metals generally increases with temperature.
- This is not surprising, for at higher temperatures, the atoms are moving more rapidly and are arranged in a less orderly fashion.
- So they might be expected to interfere more with the now of electrons.

$$\rho_r = \rho_0 \, [1 + \alpha \, (T_r - T_0)]$$

- Where α is material temperature coefficient

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Example

- The variation in electrical resistance with temperature can be used to make precise temperature measurements.
- Platinum is commonly used since it is relatively free from corrosive effects and has a high melting point
- Suppose at 20c the resistance of a platinum resistance thermometer is 164.2 Ω. When placed in a particular solution, the resistance is 187.4 Ω. What is the temperature of this solution?

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- Since the resistance *R* is directly proportional to the resistivity *p,* we can combine

$$\rho_r = \rho_0 \, [1 + \alpha \, (T_r - T_0)]$$

$$R = \rho \, \frac{l}{A}$$

$$\therefore \; R_1 = R_0 [1 + \alpha \, (T_1 - T_0)]$$

$$T_1 = T0 + \left(\frac{1}{\alpha}\left(\left(\frac{R1}{R0}\right) - 1\right)\right) = T0 + \left(\frac{R1 - R0}{\alpha \, R0}\right)$$

$$T1 = 20 + \frac{187.4 - 164.2}{0.003927 \times 164.2} = 20 + 35.979 = 55.979 \text{ °C}$$

Electric Power

- **Power, as in kinematics, is the energy transformed by a device per unit time:**

$$P = \frac{dU}{dt} = \frac{dQ}{dt}\,V = I\,V$$

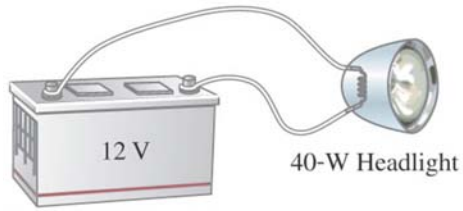
- **The unit of power is the watt, W.**
- **For ohmic devices, we can make the substitutions:**

$$P = V\,I = (I\,R)\,I = I^2\,R$$

$$P = V\,I = V\left(\frac{V}{R}\right) = \frac{V^2}{R}$$

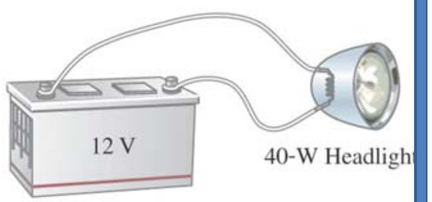
Example

- **Calculate the resistance of a 40-W automobile headlight designed for 12 V.**



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

$$R = \frac{V^2}{P} = \frac{12^2}{40} = 3.6\;ohm$$



- **What you pay for on your electric bill is not power, but energy – the power consumption multiplied by the time.**
- **We have been measuring energy in joules, but the electric company measures it in kilowatt-hours, kWh:**
  - **1 kWh = (1000 W)(3600 s) = 3.60 x 10^6 J.**

Example

- A 100 W light bulb is plugged into a standard 120 V outlet.
- a) At $0.08/kW-hr, how much does it cost to have the bulb on 24 hrs/day for a 31-day month?
- b) What is the resistance of the bulb?
- c) What is the current in the bulb?

$$Cost = 100 \times 10^{-3} \times 0.08 \times 24 \times 31 = 5.952\ \$$$

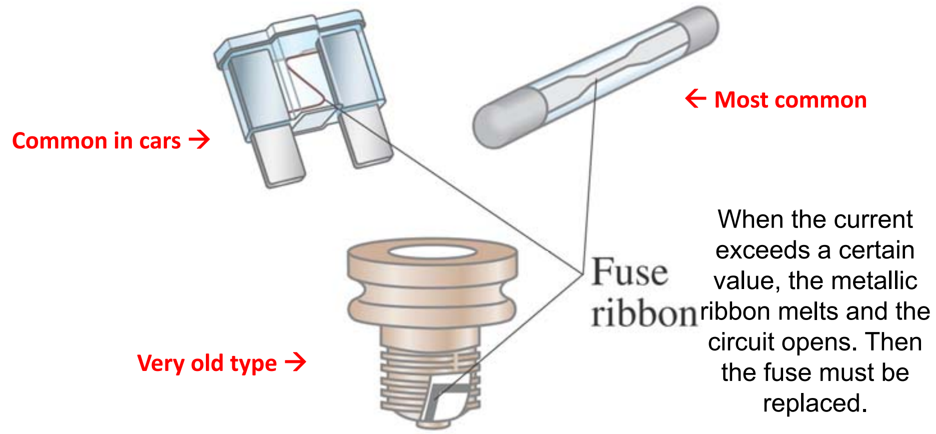
$$R = \frac{V^2}{P} = \frac{120^2}{100} = 144\ ohm$$

$$I = \frac{P}{V} = \frac{100}{120} = 0.83\ Amp$$

Power in Household Circuits

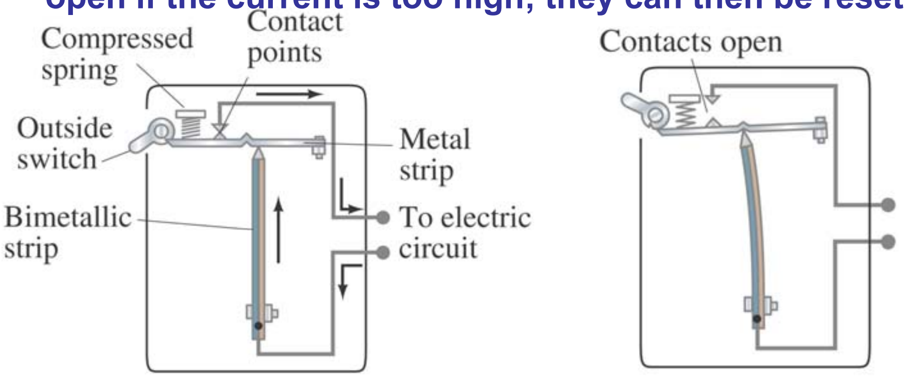
- The wires used in homes to carry electricity have very low resistance. However, if the current is high enough, the power will increase and the wires can become hot enough to start a fire.
- To avoid this, we use fuses or circuit breakers, which disconnect when the current goes above a predetermined value.

- Fuses are one-use items – if they blow, the fuse is destroyed and must be replaced.



(a) Types of fuses

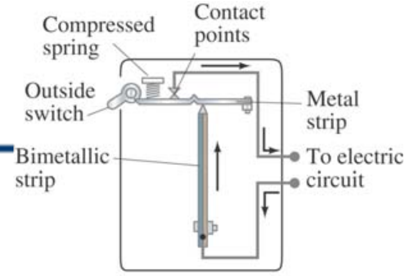
- **Circuit breakers, which are now much more common in homes than they once were, are switches that will open if the current is too high; they can then be reset**



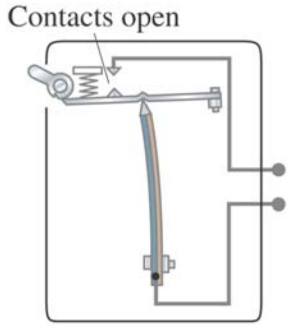
(b) Circuit breaker (closed)

(c) Circuit breaker (open)

- The electric current passes through a bimetallic strip.
- When the current exceeds a safe level, the heating of the bimetallic strip causes the strip to bend so far to the left that the notch in the spring-loaded metal strip drops down over the end of the bimetallic strip;
- the circuit then opens at the contact points (one is attached to the metal strip) and the outside switch is also flipped.
- As soon as the bimetallic strip cools down, it can be reset using the outside switch.



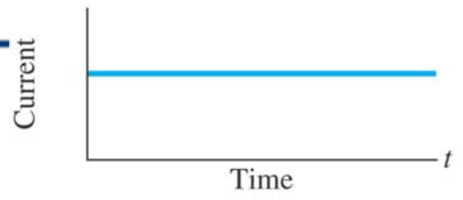
(b) Circuit breaker (closed)



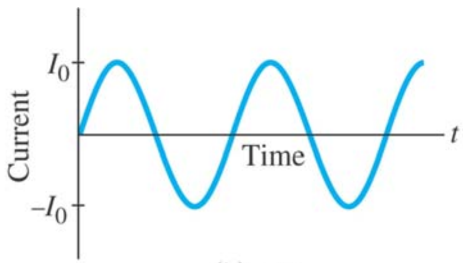
(c) Circuit breaker (open)

Alternating Current

- **Current from a battery flows steadily in one direction (direct current, DC). Current from a power plant varies sinusoidally (alternating current, AC).**



(a) DC

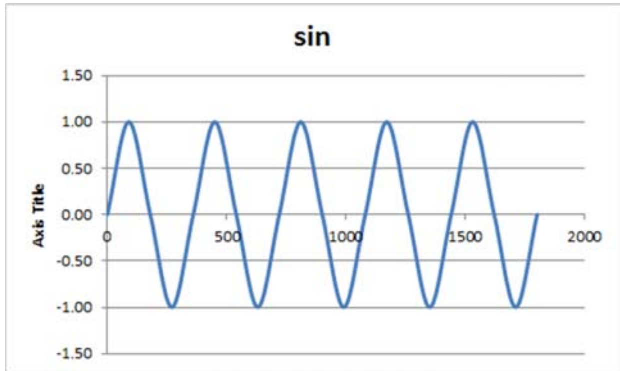


(b) AC

- **The voltage varies sinusoidally with time:**

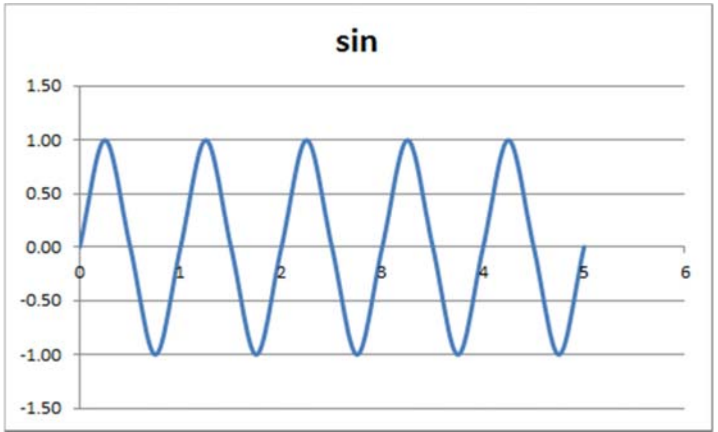
$$V = V_0 \sin \theta$$

θ	0	90	180	270	360	450	540	630	720	810	900	990	1080	1170	1260	1350	1440	1530	1620	1710	1800
sin (θ)	0	1	0	-1	0	1	0	-1	0	1	0	-1	0	1	0	-1	0	1	0	-1	0

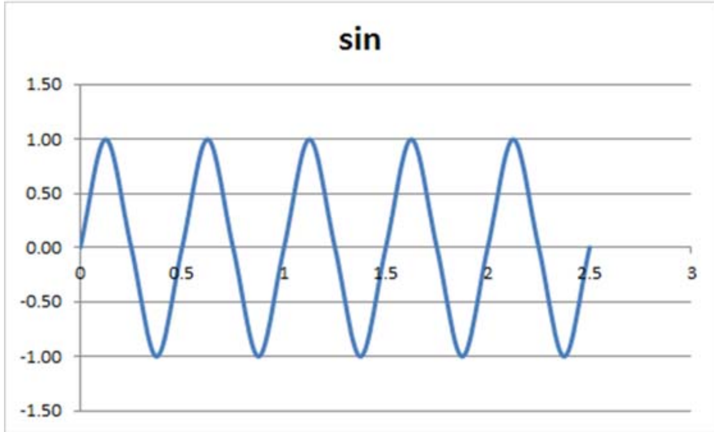


$$V = V_0\,(\sin 2\,\pi\,f\,t) = I_0\,\mathrm{R}\,\sin(\omega\,t)$$

t	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00
f	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
sin(2 pi f t)	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00



t	0.00	0.125	0.250	0.375	0.500	0.625	0.750	0.875	1.000	1.125	1.250	1.375	1.500	1.625	1.750	1.875	2.000	4.25	4.50	4.75	5.00
f	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00
sin(2 pi f t)	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	-1.00	0.00

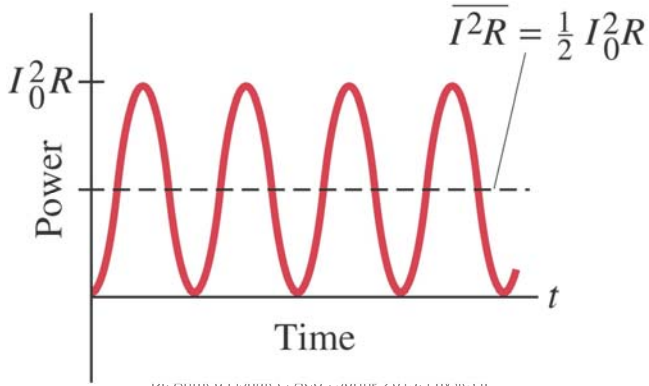


- **as does the current:**

$$I = \frac{V_0}{R}\sin(2\,\pi\,f\,t) = I_0\,\sin(2\,\pi\,f\,t) = I_0\,\sin(\omega\,t)$$

- **Multiplying the current and the voltage gives the power:**

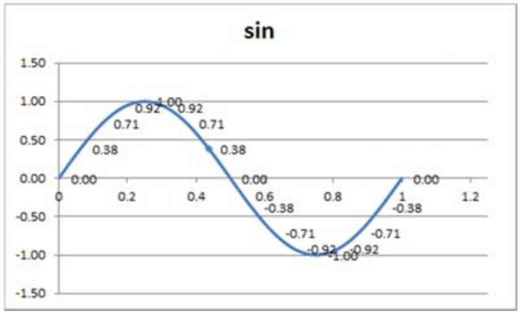
$$P = I^2\,R = {I_0}^2\,R\,sin^2\,(\omega\,t)$$



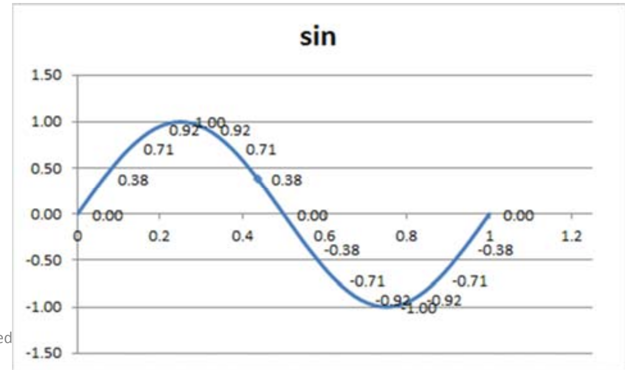
t	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00
f	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
sin^2(2 pi f t)	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00

- To calculate the effective voltage or current of an AC wave, get the average of sine wave

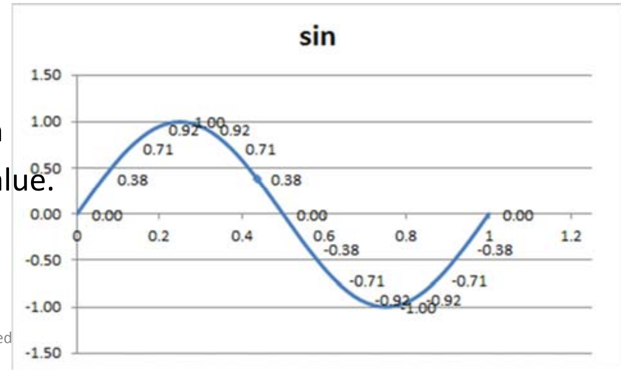
t	sin (2 pi f t)	Average
0	0.00	0.000
0.0625	0.38	
0.125	0.71	
0.1875	0.92	
0.25	1.00	
0.3125	0.92	
0.375	0.71	
0.4375	0.38	
0.5	0.00	
0.5625	-0.38	
0.625	-0.71	
0.6875	-0.92	
0.75	-1.00	
0.8125	-0.92	
0.875	-0.71	
0.9375	-0.38	
1	0.00	



- *Root-mean-square (rms)* refers to the most common mathematical method of defining the effective voltage or current of an AC wave.
- In a circuit whose impedance consists of a pure resistance, the rms value of an AC wave is often called the effective value or DC-equivalent value



- For the simplest level, say that you sample the current (or potential difference) at tiny intervals of time.
- Square each value, add up the squares (which are all positive) and divide by the number of samples to find the average square or mean square.
- Then take the square root of that.
- This is the 'root mean square' (rms) average value.



t	sin	sin^2	average	average^0.5
0	0.000	0.000		
0.0625	0.383	0.146		
0.125	0.707	0.500		
0.1875	0.924	0.854		
0.25	1.000	1.000		
0.3125	0.924	0.854		
0.375	0.707	0.500		
0.4375	0.383	0.146	0.500	0.7071 07
0.5	0.000	0.000		
0.5625	-0.383	0.146		
0.625	-0.707	0.500		
0.6875	-0.924	0.854		
0.75	-1.000	1.000		
0.8125	-0.924	0.854		
0.875	-0.707	0.500		
0.9375	-0.383	0.146		

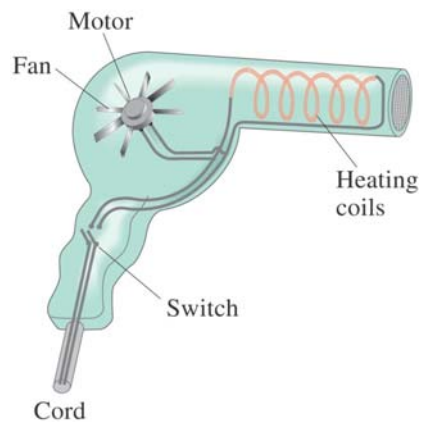
$$I_{rms} = \sqrt{\overline{I^2}} = \frac{I_0}{\sqrt{2}} = 0.707\, I_0$$

$$V_{rms} = \sqrt{\overline{I^2}} = \frac{V_0}{\sqrt{2}} = 0.707\, V_0$$

For a sine wave, the rms value is 0.707 times the peak value, or 0.354 times the peak-to-peak value.

Example

- **Hair dryer.**
- **(a) Calculate the resistance and the peak current in a 1000-W hair dryer connected to a 120-V line.**
- **(b) What happens if it is connected to a 240-V line in Britain?**



$$Irms = \frac{P}{V} = \frac{1000}{120} = 8.33\ Amp$$

$$Ip - p = \frac{Irms}{\sqrt{2}} = \frac{8.33}{0.7.7} = 11.78\ Amp$$

$$R = \frac{V}{I} = \frac{120}{8.33} = 14.4\ Ohm$$