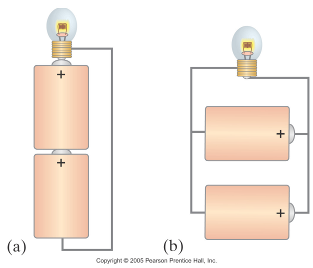
Chapter 25

Electric Currents and Resistance



Units of Chapter 25

- 25-1: The Electric Battery
- 25-2: Electric Current: 1, 2
- 25-3: Ohm's Law: Resistance and Resistors: 3, 4
- 25-4: Resistivity: 5, 6, 7, 8, 9, 10
- 25-5: Electric Power: 12, 14, 15

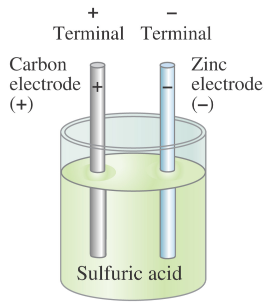
Units of Chapter 25

- 25-6: Power in Household Circuits: 11, 13
- †25-7: Alternating Current
- 25-8: Microscopic View of Electric Current
- 25-9: Superconductivity
- †*Electrical Conduction in the Human Nervous System*

25.1 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.



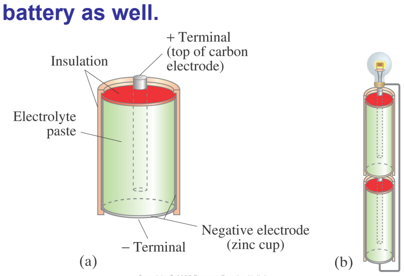
25.1 The Electric Battery

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.

25.1 The Electric Battery

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



25.2 Electric Current

Electric current is the rate of flow of charge through a conductor:

$$\bar{I} = \frac{\Delta Q}{\Delta t} \qquad \text{(25-1a)}$$

$$I = \frac{dQ}{dt} \qquad \text{(25-1b)}$$

Unit of electric current: the ampere, A.

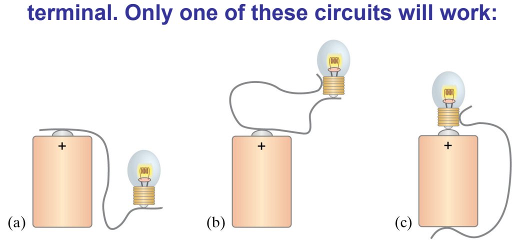
1 A = 1 C/s.

25.2 Electric Current

A complete circuit is one where current can flow all the way around. Note that the schematic drawing doesn't look much like the physical circuit!

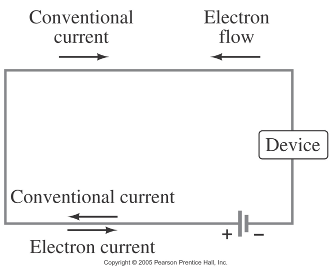
25.2 Electric Current

In order for current to flow, there must be a path from one battery terminal, through the circuit, and back to the other battery terminal. Only one of these circuits will work:



25.2 Electric Current

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



25.2 Electric Current

Application #1:

A steady current of 2.5 A flows in a wire for 4.0 min. (*a*) How much charge passed by any point in the circuit? (*b*) How many electrons would this be?

25.3 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:

$$I \propto V$$

25.3 Ohm's Law: Resistance and Resistors

The ratio of voltage to current is called the resistance:

$$R = \frac{V}{I} \qquad \text{(25-2a)}$$

$$V = IR \qquad \text{(25-2b)}$$

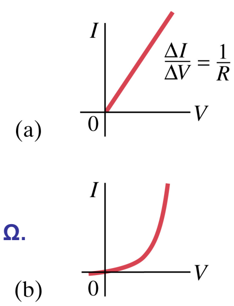
<Insert joke here>

25.3 Ohm's Law: Resistance and Resistors

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.

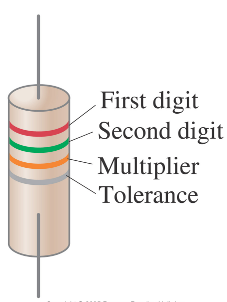
Unit of resistance: the ohm, Ω.

1 Ω = 1 V/A.



25.3 Ohm's Law: Resistance and Resistors

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



25.3 Ohm's Law: Resistance and Resistors

Resistor Color Code

Color	Number	Multiplier	Tolerance
Black	0	1	
Brown	1	10^1	
Red	2	10^2	
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%

25.3 Ohm's Law: Resistance and Resistors

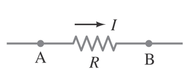
Some clarifications:

- 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.
- Current and charge do not get used up. Whatever charge goes in one end of a circuit comes out the other end.

25.3 Ohm's Law: Resistance and Resistors

Application #2:

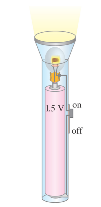
Current *I* enters a resistor *R* as shown below. (*a*) Is the potential higher at point A or at point B? (*b*) Is the current greater at point A or at point B?



25.3 Ohm's Law: Resistance and Resistors

Application #3:

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



How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

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

$$R = \rho \frac{L}{A} \qquad \textbf{(25-3)}$$

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

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

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	5.6×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.6×10^{-8}	0.003927
Mercury	98×10^{-8}	0.0009
Nichrome (Ni, Fe, Cr alloy)	100×10^{-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.

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

The reciprocal of resistivity is called the conductivity and has units of $(\Omega\cdot m)^{-1}$

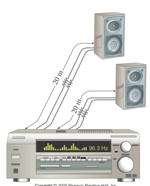
$$\sigma = \frac{1}{\rho} \qquad \text{(25-4)}$$

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

Application #4:

Suppose you want to connect your stereo to 8 Ω speakers. (*a*) If each wire must be 20 m long, what diameter 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 voltage drop across each wire?



How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

Application #5a:

Compare a wire of resistance *R* to one that has is twice its original length. What happens to its resistance? (Note: the diameter will remain constant)

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

Application #5b:

Compare a wire of resistance *R* to one that has is one-half its original diameter. What happens to its resistance? (Note: the length will remain constant)

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

Application #5c:

A wire of resistance *R* is stretched uniformly until it is twice its original length. What happens to its resistance? (Note: the total volume will be constant)

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

For any given material, the resistivity increases with temperature:

$$\rho_T = \rho_0\left[1 + \alpha\left(T - T_0\right)\right] \qquad \textbf{(25-5)}$$

Semiconductors are complex materials, and may have resistivities that decrease with temperature.

How do we describe and apply the concept of conductivity, resistivity, and resistance?

25.4 Resistivity

Application #6 (In Journal for Warm-Up):

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 20°C 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?

How do we determine the amount of required power?

25.5 Electric Power

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

$$P = \frac{\text{energy transformed}}{\text{time}} = \frac{QV}{t}$$

$$P = \frac{dU}{dt} = \frac{dq}{dt}V$$

$$P = IV \qquad \textbf{(25-6)}$$

How do we determine the amount of required power?

25.5 Electric Power

The unit of power: the watt, W.

1 W = 1 J/s.

For ohmic devices, we can make the substitutions:

$$P = IV = I(IR) = I^2R \qquad \textbf{(25-7b)}$$

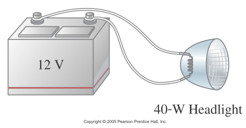
$$P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R} \qquad \textbf{(25-7c)}$$

How do we determine the amount of required power?

25.5 Electric Power

Application #7:

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



How do we determine the amount of required power?

25.5 Electric Power

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.

$$\text{One kWh} = (1000\ \text{W})(3600\ \text{s}) = 3.60 \times 10^6\ \text{J}$$

How do we determine the amount of required power?

25.5 Electric Power

Application #8:

An electric heater draws a steady 15.0 A on a 120-V line. How much power does it require and how much does it cost per month (30 days) if it operates 3.0 hours per day and the electric company charges 10.5 cents per kWh?

25.5 Electric Power

Application #9:

A typical lightning bolt can transfer 10^9 J of energy across a potential difference of 5 x 10^7 V during a time interval of 0.2 s. Use this information to estimate the total amount of (*a)* charge transferred [to your friend as he was about to call *you* "stupid"], (*b*) the current, and (*c*) the average power over the 0.2 s. (As you probably are already aware having studied part of E & M, you wrapped yourself in chicken wire. Nice move smarty pants)

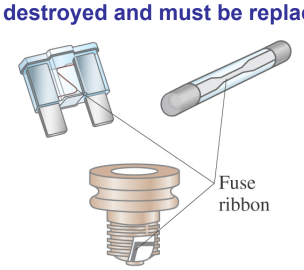
25.6 Power in Household Circuits

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.

25.6 Power in Household Circuits

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

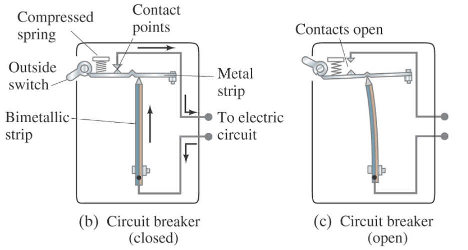


(a) Types of fuses

How do we determine the amount of required power?

25.6 Power in Household Circuits

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.



How do we determine the amount of required power?

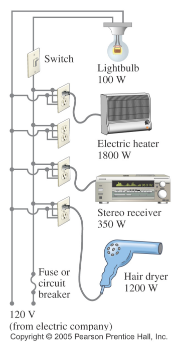
25.6 Power in Household Circuits

Application #10:

(*a*) Determine the total current drawn by all the devices in the circuit.

(*b*) If the circuit circuit is designed for a 20-A fuse, will the circuit blow?

(*c*) Predict the amount power Mr. Roe's water heater requires.



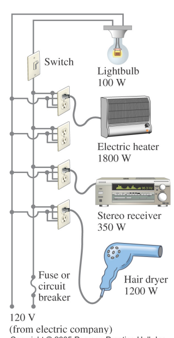
How do we determine the amount of required power?

25.6 Power in Household Circuits

Application #10:

(*d*) If Mr. Roe's water heater can go from 20-100 in5 min and 3 seconds, how much energy is used?

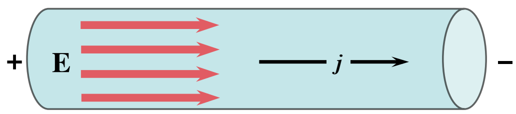
(Note: Never replace a fuse with a higher-rated one)



25.8 Microscopic View of Electric Current

The current density, *j* , is defined as the electric current per unit cross-sectional area at any point in space.

$$j = \frac{I}{A} \quad \text{or} \quad I = jA; \quad \text{Also recall } I = \frac{\Delta Q}{\Delta t}$$



25.8 Microscopic View of Electric Current

After the electric potential is applied the electrons begin to move until they reach an average speed known as drift velocity, v_d. We can relate the microscopic drift velocity, v_d, to the macrosopic current, *I* in the wire by

$$\Delta Q = (\#\text{ of particles, } N)(\text{charge per particle, } q)$$

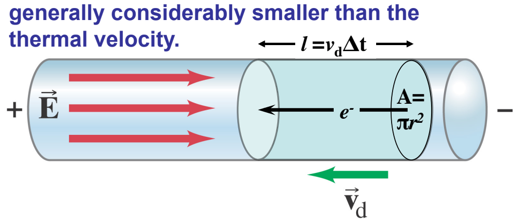
$$\text{where} \quad N = (\#\text{ of free charges, } n)(\text{Volume, } Vol)$$

$$\text{where} \quad Vol = (\text{length, } l)(\text{Area, } A)$$

$$\text{where} \quad l = (\text{drift velocity, } v_d)(\text{change in time, } \Delta t)$$

25.8 Microscopic View of Electric Current

Electrons in a conductor have large, random speeds just due to their temperature. When a potential difference is applied, the electrons also acquire an average drift velocity, which is generally considerably smaller than the thermal velocity.



25.8 Microscopic View of Electric Current

This drift speed is related to the current in the wire, and also to the number of electrons per unit volume.

$$\Delta Q = (\text{number of charges, } N) \times (\text{charge per particle}) = (nV)(e) = (nAv_d\,\Delta t)(e).$$

$$I = \frac{\Delta Q}{\Delta t} = neAv_d \qquad \textbf{(25-13)}$$

25.8 Microscopic View of Electric Current

This drift speed is related to the current in the wire, and also to the number of electrons per unit volume.

$$\Delta Q = (\text{number of charges, } N) \times (\text{charge per particle}) = (nV)(e) = (nAv_d\,\Delta t)(e).$$

$$I = \frac{\Delta Q}{\Delta t} = neAv_d \qquad \textbf{(25-13)}$$

25.5 Electric Power

Prediction: So how long does it take an electron to travel 12 m?

25.5 Electric Power

Application #11:

A copper wire 8.6 mm in diameter, carries a 5.0 A current. Determine (*a)* the current density in the wire, and (*b*) the the drift velocity of the free electrons. The mass density, ρ_D, of copper is 8.9 x 10^3 kg/m^3. Assume that one electron per Cu atom is free to move (the others remain bound to the atom).

25.5 Electric Power

Application #11:

A copper wire 8.6 mm in diameter, carries a 5.0 A current. Determine (*a)* the current density in the wire, and (*b*) the the drift velocity of the free electrons. The mass density, ρ_D, of copper is 8.9 x 10^3 kg/m^3. Assume that one electron per Cu atom is free to move (the others remain bound to the atom). [Hint: use 1mol Cu]

$$\Delta Q = nAv_d \Delta t q$$

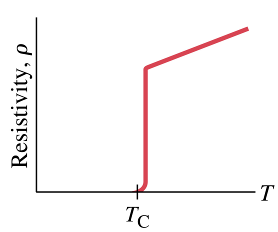
$$\frac{\Delta Q}{\Delta t} = I = nA_{wire} v_d q = \frac{N}{Vol}\left(\tfrac{1}{4}\pi d^2\right) v_d q = \frac{N}{m/\rho_D}\left(\tfrac{1}{4}\pi d^2\right) v_d q$$

$$v_d = \frac{4Im}{N\rho_D \pi d^2 e}$$

$$= \frac{4(5.0 \text{ C/s})(63.546 \text{ g/mol})}{(6.02 \text{ x } 10^{23} \text{ electrons/mol})(8.96 \text{ x } 10^6 \text{ g/m}^3)\pi(0.0086 \text{ m})^2(1.6 \text{ x } 10^{-19} \text{ C/electron})}$$

25.9 Superconductivity

In general, resistivity decreases as temperature decreases. Some materials, however, have resistivity that falls abruptly to zero at a very low temperature, called the critical temperature, T_C.



25.9 Superconductivity

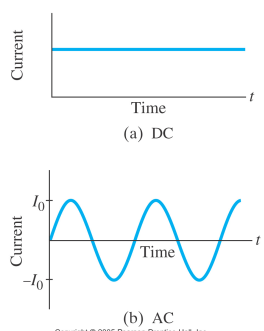
Experiments have shown that currents, once started, can flow through these materials for years without decreasing even without a potential difference.

Critical temperatures are low; for many years no material was found to be superconducting above 23 K.

More recently, novel materials have been found to be superconducting below 90 K, and work on higher temperature superconductors is continuing.

†25.7 Alternating Current

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



†25.7 Alternating Current

The voltage varies sinusoidally with time:

$$V = V_0 \sin 2\pi f t = V_0 \sin \omega t$$

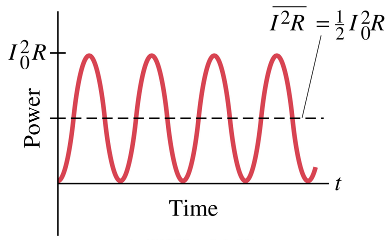
as does the current:

$$I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t \quad \text{(25-8)}$$

†25.7 Alternating Current

Multiplying the current and the voltage gives the power:

$$P = I^2R = I_0^2 R \sin^2 \omega t$$



†25.7 Alternating Current

Usually we are interested in the average power:

$$\overline{P} = \tfrac{1}{2} I_0^2 R$$

$$\overline{P} = \frac{1}{2}\frac{V_0^2}{R}$$

†25.7 Alternating Current

The current and voltage both have average values of zero, so we square them, take the average, then take the square root, yielding the root mean square (rms) value.

$$I_{\text{rms}} = \sqrt{\overline{I^2}} = \frac{I_0}{\sqrt{2}} = 0.707 I_0 \quad \textbf{(25-9a)}$$

$$V_{\text{rms}} = \sqrt{\overline{V^2}} = \frac{V_0}{\sqrt{2}} = 0.707 V_0 \quad \textbf{(25-9b)}$$

†Electrical Conduction in the Human Nervous System

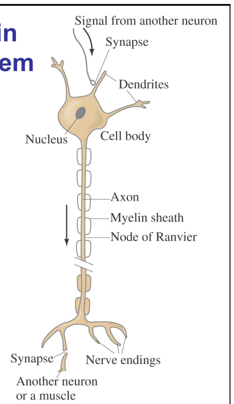
The human nervous system depends on the flow of electric charge.

The basic elements of the nervous system are cells called neurons.

Neurons have a main cell body, small attachments called dendrites, and a long tail called the axon.

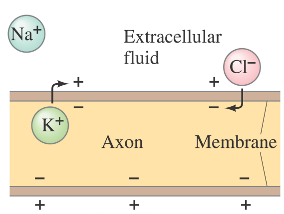
†Electrical Conduction in the Human Nervous System

Signals are received by the dendrites, propagated along the axon, and transmitted through a connection called a synapse.



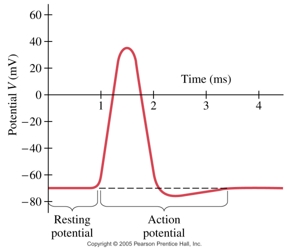
†Electrical Conduction in the Human Nervous System

This process depends on there being a dipole layer of charge on the cell membrane, and different concentrations of ions inside and outside the cell.



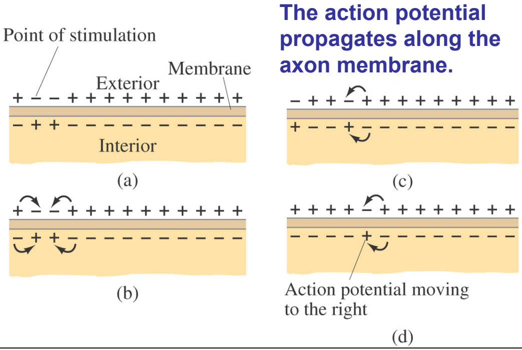
†Electrical Conduction in the Human Nervous System

This applies to most cells in the body. Neurons can respond to a stimulus and conduct an electrical signal. This signal is in the form of an action potential.



†Electrical Conduction in the Human Nervous System

The action potential propagates along the axon membrane.



Summary of Chapter 25

- A battery is a source of constant potential difference.
- Electric current is the rate of flow of electric charge.
- Conventional current is in the direction that positive charge would flow.
- Resistance is the ratio of voltage to current:

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

Summary of Chapter 25

- Ohmic materials have constant resistance, independent of voltage.
- Resistance is determined by shape and material:

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

- ρ is the resistivity.

Summary of Chapter 25

- Power in an electric circuit:

$$P = IV$$

- Direct current is constant
- †Alternating current varies sinusoidally

$$I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t$$

Summary of Chapter 25

- *The average (rms) current and voltage:

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

$$V_{\text{rms}} = \sqrt{\overline{V^2}} = \frac{V_0}{\sqrt{2}} = 0.707 V_0$$

- Relation between drift speed and current:

$$I = \frac{\Delta Q}{\Delta t} = neAv_{\text{d}}$$