Summary

An electric **battery** serves as a source of nearly constant potential difference by transforming chemical energy into electric energy. A simple battery consists of two electrodes made of different metals immersed in a solution or paste known as an electrolyte.

Electric current, I, refers to the rate of flow of electric charge and is measured in **amperes** (A): 1 A equals a flow of 1 C/s past a given point.

The direction of **conventional current** is that of positive charge flow. In a wire, it is actually negatively charged electrons that move, so they flow in a direction opposite to the conventional current. A positive charge flow in one direction is almost always equivalent to a negative charge flow in the opposite direction. Positive conventional current always flows from a high potential to a low potential.

The **resistance** R of a device is defined by the relation

$$V = IR, \quad (18\text{–}2)$$

where I is the current in the device when a potential difference V is applied across it. For materials such as metals, R is a constant independent of V (thus $I \propto V$), a result known as **Ohm's law**. Thus, the current I coming from a battery of voltage V depends on the resistance R of the circuit connected to it.

Voltage is applied *across* a device or between the ends of a wire. Current passes *through* a wire or device. Resistance is a property *of* the wire or device.

The unit of resistance is the **ohm** (Ω), where $1\,\Omega = 1\,\text{V/A}$. See Table 18–3.

TABLE 18–3 Summary of Units

Current	$1\,\text{A} = 1\,\text{C/s}$
Potential difference	$1\,\text{V} = 1\,\text{J/C}$
Power	$1\,\text{W} = 1\,\text{J/s}$
Resistance	$1\,\Omega = 1\,\text{V/A}$

The resistance R of a wire is inversely proportional to its cross-sectional area A, and directly proportional to its length L and to a property of the material called its resistivity:

$$R = \frac{\rho L}{A}. \quad (18\text{–}3)$$

The **resistivity**, ρ, increases with temperature for metals, but for semiconductors it may decrease.

The rate at which energy is transformed in a resistance R from electric to other forms of energy (such as heat and light) is equal to the product of current and voltage. That is, the **power** transformed, measured in watts, is given by

$$P = IV, \quad (18\text{–}5)$$

which for resistors can be written as

$$P = I^2R = \frac{V^2}{R}. \quad (18\text{–}6)$$

The SI unit of power is the **watt** ($1\,\text{W} = 1\,\text{J/s}$).

The total electric energy transformed in any device equals the product of the power and the time during which the device is operated. In SI units, energy is given in joules ($1\,\text{J} = 1\,\text{W}\cdot\text{s}$), but electric companies use a larger unit, the **kilowatt-hour** ($1\,\text{kWh} = 3.6 \times 10^6\,\text{J}$).

Electric current can be **direct current (dc)**, in which the current is steady in one direction; or it can be **alternating current (ac)**, in which the current reverses direction at a particular frequency f, typically 60 Hz. Alternating currents are typically sinusoidal in time,

$$I = I_0 \sin \omega t, \quad (18\text{–}7)$$

where $\omega = 2\pi f$, and are produced by an alternating voltage.

The **rms** values of sinusoidally alternating currents and voltages are given by

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \quad \text{and} \quad V_{\text{rms}} = \frac{V_0}{\sqrt{2}}, \quad (18\text{–}8)$$

respectively, where I_0 and V_0 are the **peak** values. The power relationship, $P = IV = I^2R = V^2/R$, is valid for the average power in alternating currents when the rms values of V and I are used.

[*The current in a wire, at the microscopic level, is considered to be a slow **drift speed** of electrons, v_d. The current I is given by

$$I = neAv_d, \quad (18\text{–}10)$$

where n is the number of free electrons per unit volume, e is the charge on an electron, and A is the cross-sectional area of the wire.]

[*At very low temperatures certain materials become **superconducting**, which means their electrical resistance becomes zero.]

[*The human nervous system operates via electrical conduction: when a nerve "fires," an electrical signal travels as a voltage pulse known as an **action potential**.]

Questions

1. What quantity is measured by a battery rating given in ampere-hours ($\text{A}\cdot\text{h}$)?
2. When an electric cell is connected to a circuit, electrons flow away from the negative terminal in the circuit. But within the cell, electrons flow *to* the negative terminal. Explain.
3. When a flashlight is operated, what is being used up: battery current, battery voltage, battery energy, battery power, or battery resistance? Explain.
4. One terminal of a car battery is said to be connected to "ground." Since it is not really connected to the ground, what is meant by this expression?
5. When you turn on a water faucet, the water usually flows immediately. You don't have to wait for water to flow from the faucet valve to the spout. Why not? Is the same thing true when you connect a wire to the terminals of a battery?

6. Can a copper wire and an aluminum wire of the same length have the same resistance? Explain.

7. If the resistance of a small immersion heater (to heat water for tea or soup, Fig. 18–32) was increased, would it speed up or slow down the heating process? Explain.

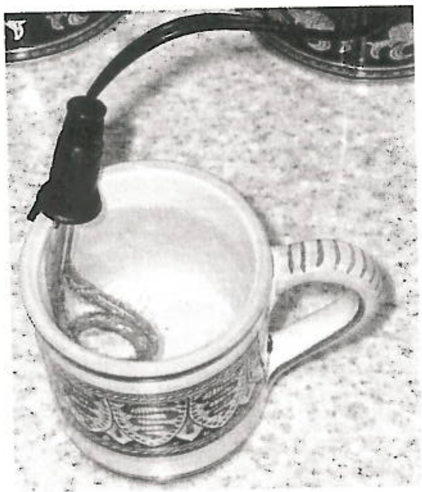

FIGURE 18–32 Question 7.

8. If a rectangular solid made of carbon has sides of lengths a, $2a$, and $3a$, how would you connect the wires from a battery so as to obtain (a) the least resistance, (b) the greatest resistance?

9. The equation $P = V^2/R$ indicates that the power dissipated in a resistor decreases if the resistance is increased, whereas the equation $P = I^2R$ implies the opposite. Is there a contradiction here? Explain.

10. What happens when a lightbulb burns out?

11. Explain why lightbulbs almost always burn out just as they are turned on and not after they have been on for some time.

12. Which draws more current, a 100-W lightbulb or a 75-W bulb? Which has the higher resistance?

13. Electric power is transferred over large distances at very high voltages. Explain how the high voltage reduces power losses in the transmission lines.

14. A 15-A fuse blows repeatedly. Why is it dangerous to replace this fuse with a 25-A fuse?

15. When electric lights are operated on low-frequency ac (say, 5 Hz), they flicker noticeably. Why?

16. Driven by ac power, the same electrons pass back and forth through your reading lamp over and over again. Explain why the light stays lit instead of going out after the first pass of electrons.

17. The heating element in a toaster is made of Nichrome wire. Immediately after the toaster is turned on, is the current (I_{rms}) in the wire increasing, decreasing, or staying constant? Explain.

18. Is current used up in a resistor? Explain.

19. Different lamps might have batteries connected in either of the two arrangements shown in Fig. 18–33. What would be the advantages of each scheme?

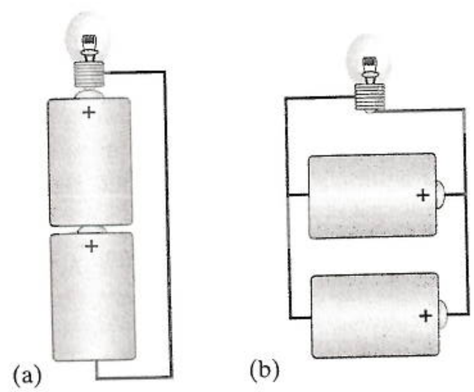

FIGURE 18–33 Question 19.

Problems

18–2 and 18–3 Electric Current, Resistance, Ohms' Law

(*Note:* The charge on one electron is 1.60×10^{-19} C).

1. (I) A current of 1.30 A flows in a wire. How many electrons are flowing past any point in the wire per second?

2. (I) A service station charges a battery using a current of 6.7 A for 5.0 h. How much charge passes through the battery?

3. (I) What is the current in amperes if 1200 Na^+ ions flow across a cell membrane in 3.5 μs? The charge on the sodium is the same as on an electron, but positive.

4. (I) What is the resistance of a toaster if 120 V produces a current of 4.2 A?

5. (I) What voltage will produce 0.25 A of current through a 3800-Ω resistor?

6. (II) A hair dryer draws 7.5 A when plugged into a 120-V line. (a) What is its resistance? (b) How much charge passes through it in 15 min? (Assume direct current.)

7. (II) An electric clothes dryer has a heating element with a resistance of 9.6 Ω. (a) What is the current in the element when it is connected to 240 V? (b) How much charge passes through the element in 50 min?

8. (II) A 9.0-V battery is connected to a bulb whose resistance is 1.6 Ω. How many electrons leave the battery per minute?

9. (II) A bird stands on a dc electric transmission line carrying 2800 A (Fig. 18–34). The line has $2.5 \times 10^{-5}\,\Omega$ resistance per meter, and the bird's feet are 4.0 cm apart. What is the potential difference between the bird's feet?

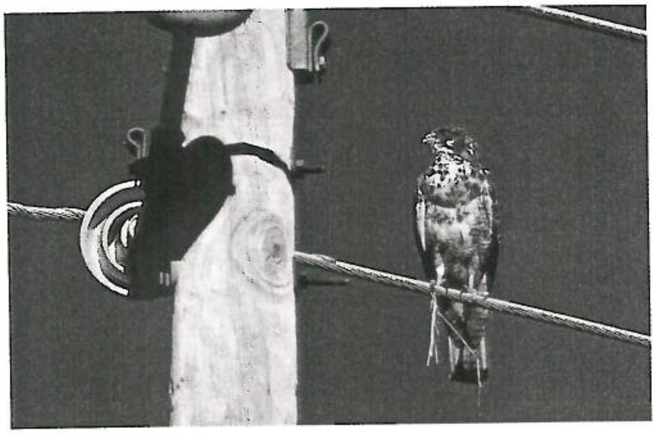

FIGURE 18–34 Problem 9.

10. (II) An electric device draws 6.50 A at 240 V. (*a*) If the voltage drops by 15%, what will be the current, assuming nothing else changes? (*b*) If the resistance of the device were reduced by 15%, what current would be drawn at 240 V?

11. (II) A 12-V battery causes a current of 0.60 A through a resistor. (*a*) What is its resistance, and (*b*) how many joules of energy does the battery lose in a minute?

18–4 Resistivity

12. (I) What is the diameter of a 1.00-m length of tungsten wire whose resistance is $0.32\,\Omega$?

13. (I) What is the resistance of a 3.5-m length of copper wire 1.5 mm in diameter?

14. (II) Calculate the ratio of the resistance of 10.0 m of aluminum wire 2.0 mm in diameter, to 20.0 m of copper wire 2.5 mm in diameter.

15. (II) Can a 2.5-mm-diameter copper wire have the same resistance as a tungsten wire of the same length? Give numerical details.

16. (II) A certain copper wire has a resistance of $10.0\,\Omega$. At what point along its length must the wire be cut so that the resistance of one piece is 4.0 times the resistance of the other? What is the resistance of each piece?

* 17. (II) How much would you have to raise the temperature of a copper wire (originally at 20°C) to increase its resistance by 15%?

* 18. (II) Estimate at what temperature copper will have the same resistivity as tungsten does at 20°C.

* 19. (II) A 100-W lightbulb has a resistance of about $12\,\Omega$ when cold (20°C) and $140\,\Omega$ when on (hot). Estimate the temperature of the filament when hot assuming an average temperature coefficient of resistivity $\alpha = 0.0060\,(\mathrm{C}^\circ)^{-1}$.

20. (II) Compute the voltage drop along a 26-m length of household no. 14 copper wire (used in 15-A circuits). The wire has diameter 1.628 mm and carries a 12-A current.

21. (II) A rectangular solid made of carbon has sides of lengths 1.0 cm, 2.0 cm, and 4.0 cm, lying along the *x*, *y*, and *z* axes, respectively (Fig. 18–35). Determine the resistance for current that passes through the solid in (*a*) the *x* direction, (*b*) the *y* direction, and (*c*) the *z* direction. Assume the resistivity is $\rho = 3.0 \times 10^{-5}\,\Omega\cdot\mathrm{m}$.

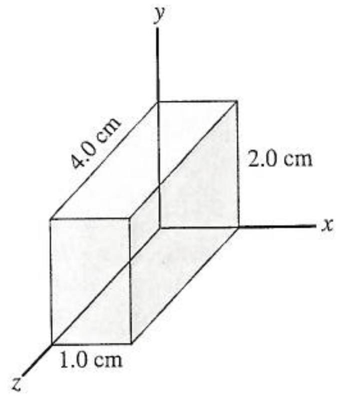

FIGURE 18–35 Problem 21.

22. (II) Two aluminum wires have the same resistance. If one has twice the length of the other, what is the ratio of the diameter of the longer wire to the diameter of the shorter wire?

* 23. (II) A length of aluminum wire is connected to a precision 10.00-V power supply, and a current of 0.4212 A is precisely measured at 20.0°C. The wire is placed in a new environment of unknown temperature where the measured current is 0.3618 A. What is the unknown temperature?

24. (III) A 10.0-m length of wire consists of 5.0 m of copper followed by 5.0 m of aluminum, both of diameter 1.0 mm. A voltage difference of 85 mV is placed across the composite wire. (*a*) What is the total resistance (sum) of the two wires? (*b*) What is the current through the wire? (*c*) What are the voltages across the aluminum part and across the copper part?

* 25. (III) For some applications, it is important that the value of a resistance not change with temperature. For example, suppose you made a $4.70\text{-k}\Omega$ resistor from a carbon resistor and a Nichrome wire-wound resistor connected together so the total resistance is the sum of their separate resistances. What value should each of these resistors have (at 0°C) so that the combination is temperature independent?

18–5 and 18–6 Electric Power

26. (I) The heating element of an electric oven is designed to produce 3.3 kW of heat when connected to a 240-V source. What must be the resistance of the element?

27. (I) What is the maximum power consumption of a 3.0-V portable CD player that draws a maximum of 320 mA of current?

28. (I) What is the maximum voltage that can be applied across a $2.7\text{-k}\Omega$ resistor rated at $\frac{1}{4}$ watt?

29. (I) (*a*) Determine the resistance of, and current through, a 75-W lightbulb connected to its proper source voltage of 120 V. (*b*) Repeat for a 440-W bulb.

30. (II) A 115-V fish-tank heater is rated at 110 W. Calculate (*a*) the current through the heater when it is operating, and (*b*) its resistance?

31. (II) A 120-V hair dryer has two settings: 850 W and 1250 W. (*a*) At which setting do you expect the resistance to be higher? After making a guess, determine the resistance at (*b*) the lower setting; and (*c*) the higher setting.

32. (II) You buy a 75-W lightbulb in Europe, where electricity is delivered to homes at 240 V. If you use the lightbulb in the United States at 120 V (assume its resistance does not change), how bright will it be relative to 75-W 120-V bulbs? [*Hint*: assume roughly that brightness is proportional to power consumed.]

33. (II) How many kWh of energy does a 550-W toaster use in the morning if it is in operation for a total of 15 min? At a cost of 9.0 cents/kWh, estimate how much this would add to your monthly electric energy bill if you made toast four mornings per week.

34. (II) At $0.095 per kWh, what does it cost to leave a 25-W porch light on day and night for a year?

35. (II) An ordinary flashlight uses two D-cell 1.5-V batteries connected in series as in Fig. 18–4b (Fig. 18–36). The bulb draws 450 mA when turned on. (*a*) Calculate the resistance of the bulb and the power dissipated. (*b*) By what factor would the power increase if four D-cells in series were used with the same bulb? (Neglect heating effects of the filament.) Why shouldn't you try this?

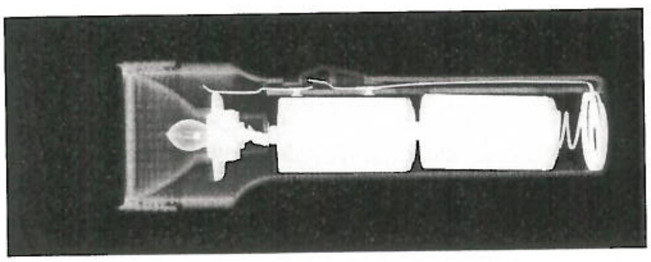

FIGURE 18–36 Problem 35.

36. (II) What is the total amount of energy stored in a 12-V, 85-A·h car battery when it is fully charged?

37. (II) How many 100-W lightbulbs, connected to 120 V as in Fig. 18–20, can be used without blowing a 15-A fuse?

38. (II) An extension cord made of two wires of diameter 0.129 cm (no. 16 copper wire) and of length 2.7 m (9 ft) is connected to an electric heater which draws 15.0 A on a 120-V line. How much power is dissipated in the cord?

39. (II) A power station delivers 620 kW of power at 12,000 V to a factory through wires with total resistance 3.0 Ω. How much less power is wasted if the electricity is delivered at 50,000 V rather than 12,000 V?

40. (III) The current in an electromagnet connected to a 240-V line is 17.5 A. At what rate must cooling water pass over the coils if the water temperature is to rise by no more than 7.50 C°?

41. (III) A small immersion heater can be used in a car to heat a cup of water for coffee or tea. If the heater can heat 120 mL of water from 25°C to 95°C in 8.0 min, (*a*) approximately how much current does it draw from the car's 12-V battery, and (*b*) what is its resistance? Assume the manufacturer's claim of 60% efficiency.

18–7 Alternating Current

42. (I) Calculate the peak current in a 2.2-kΩ resistor connected to a 220-V rms ac source.

43. (I) An ac voltage, whose peak value is 180 V, is across a 330-Ω resistor. What are the rms and peak currents in the resistor?

44. (II) Estimate the resistance of the 120-V_{rms} circuits in your house as seen by the power company, when (*a*) everything electrical is unplugged, and (*b*) there is a lone 75-W lightbulb burning.

45. (II) The peak value of an alternating current in a 1500-W device is 5.4 A. What is the rms voltage across it?

46. (II) An 1800-W arc welder is connected to a 660-V_{rms} ac line. Calculate (*a*) the peak voltage and (*b*) the peak current.

47. (II) (*a*) What is the maximum instantaneous power dissipated by a 3.0-hp pump connected to a 240-V_{rms} ac power source? (*b*) What is the maximum current passing through the pump?

48. (II) A heater coil connected to a 240-V_{rms} ac line has a resistance of 34 Ω. (*a*) What is the average power used? (*b*) What are the maximum and minimum values of the instantaneous power?

* 18–8 Microscopic View of Electric Current

* 49. (II) A 0.65-mm-diameter copper wire carries a tiny current of 2.3 μA. What is the electron drift speed in the wire?

* 50. (II) A 5.80-m length of 2.0-mm-diameter wire carries a 750-mA current when 22.0 mV is applied to its ends. If the drift speed is 1.7×10^{-5} m/s, determine (*a*) the resistance R of the wire, (*b*) the resistivity ρ, and (*c*) the number n of free electrons per unit volume.

* 51. (III) At a point high in the Earth's atmosphere, He^{2+} ions in a concentration of $2.8 \times 10^{12}/m^3$ are moving due north at a speed of 2.0×10^6 m/s. Also, a $7.0 \times 10^{11}/m^3$ concentration of O_2^- ions is moving due south at a speed of 7.2×10^6 m/s. Determine the magnitude and direction of the net current passing through unit area (A/m^2).

* 18–10 Nerve Conduction

* 52. (I) What is the magnitude of the electric field across an axon membrane 1.0×10^{-8} m thick if the resting potential is −70 mV?

* 53. (II) A neuron is stimulated with an electric pulse. The action potential is detected at a point 3.40 cm down the axon 0.0052 s later. When the action potential is detected 7.20 cm from the point of stimulation, the time required is 0.0063 s. What is the speed of the electric pulse along the axon? (Why are two measurements needed instead of only one?)

* 54. (III) Estimate how much energy is required to transmit one action potential along the axon of Example 18–15. [*Hint*: the energy to transmit one pulse is equivalent to the energy stored by charging the axon capacitance; see Section 17–9]. What minimum average power is required for 10^4 neurons each transmitting 100 pulses per second?

* 55. (III) During an action potential, Na^+ ions move into the cell at a rate of about 3×10^{-7} mol/m²·s. How much power must be produced by the "active Na^+ pumping" system to produce this flow against a +30-mV potential difference? Assume that the axon is 10 cm long and 20 μm in diameter.