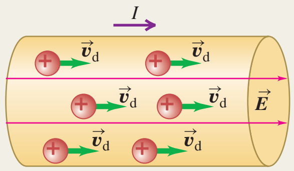
# CHAPTER 25 SUMMARY

**Current and current density:** Current is the amount of charge flowing through a specified area, per unit time. The SI unit of current is the ampere $(1\text{ A} = 1\text{ C/s})$. The current $I$ through an area $A$ depends on the concentration $n$ and charge $q$ of the charge carriers, as well as on the magnitude of their drift velocity $\vec{v}_d$. The current density is current per unit cross-sectional area. Current is usually described in terms of a flow of positive charge, even when the charges are actually negative or of both signs. (See Example 25.1.)

$$I = \frac{dQ}{dt} = n|q|v_d A \qquad (25.2)$$

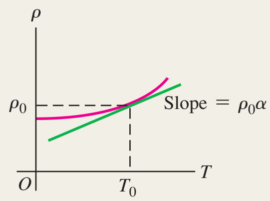
$$\vec{J} = nq\vec{v}_d \qquad (25.4)$$




**Resistivity:** The resistivity $\rho$ of a material is the ratio of the magnitudes of electric field and current density. Good conductors have small resistivity; good insulators have large resistivity. Ohm's law, obeyed approximately by many materials, states that $\rho$ is a constant independent of the value of $E$. Resistivity usually increases with temperature; for small temperature changes this variation is represented approximately by Eq. (25.6), where $\alpha$ is the temperature coefficient of resistivity.

$$\rho = \frac{E}{J} \qquad (25.5)$$

$$\rho(T) = \rho_0[1 + \alpha(T - T_0)] \qquad (25.6)$$

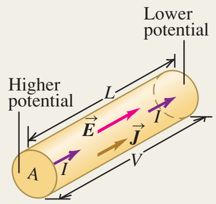



Metal: $\rho$ increases with increasing $T$.

**Resistors:** The potential difference $V$ across a sample of material that obeys Ohm's law is proportional to the current $I$ through the sample. The ratio $V/I = R$ is the resistance of the sample. The SI unit of resistance is the ohm $(1\ \Omega = 1\text{ V/A})$. The resistance of a cylindrical conductor is related to its resistivity $\rho$, length $L$, and cross-sectional area $A$. (See Examples 25.2 and 25.3.)

$$V = IR \qquad (25.11)$$

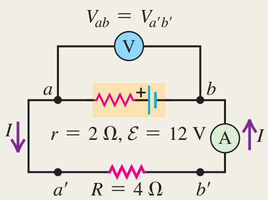
$$R = \frac{\rho L}{A} \qquad (25.10)$$




**Circuits and emf:** A complete circuit has a continuous current-carrying path. A complete circuit carrying a steady current must contain a source of electromotive force (emf) $\mathcal{E}$. The SI unit of electromotive force is the volt (1 V). Every real source of emf has some internal resistance $r$, so its terminal potential difference $V_{ab}$ depends on current. (See Examples 25.4–25.7.)

$$V_{ab} = \mathcal{E} - Ir \qquad (25.15)$$

(source with internal resistance)



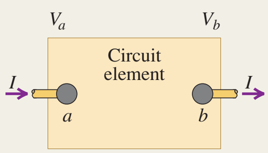

**Energy and power in circuits:** A circuit element with a potential difference $V_a - V_b = V_{ab}$ and a current $I$ puts energy into a circuit if the current direction is from lower to higher potential in the device, and it takes energy out of the circuit if the current is opposite. The power $P$ equals the product of the potential difference and the current. A resistor always takes electrical energy out of a circuit. (See Examples 25.8–25.10.)

$$P = V_{ab}I \qquad (25.17)$$

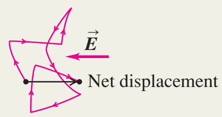
(general circuit element)

$$P = V_{ab}I = I^2R = \frac{V_{ab}^2}{R} \qquad (25.18)$$

(power into a resistor)




**Conduction in metals:** The microscopic basis of conduction in metals is the motion of electrons that move freely through the metallic crystal, bumping into ion cores in the crystal. In a crude classical model of this motion, the resistivity of the material can be related to the electron mass, charge, speed of random motion, density, and mean free time between collisions. (See Example 25.11.)



## BRIDGING PROBLEM Resistivity, Temperature, and Power

A toaster using a Nichrome heating element operates on 120 V. When it is switched on at 20°C, the heating element carries an initial current of 1.35 A. A few seconds later the current reaches the steady value of 1.23 A. (a) What is the final temperature of the element? The average value of the temperature coefficient of resistivity for Nichrome over the relevant temperature range is $4.5 \times 10^{-4}\ (\text{C}°)^{-1}$. (b) What is the power dissipated in the heating element initially and when the current reaches 1.23 A?

### SOLUTION GUIDE

See MasteringPhysics® study area for a Video Tutor solution.

### IDENTIFY and SET UP

1. A heating element acts as a resistor that converts electrical energy into thermal energy. The resistivity ρ of Nichrome depends on temperature, and hence so does the resistance $R = \rho L/A$ of the heating element and the current $I = V/R$ that it carries.
2. We are given $V = 120$ V and the initial and final values of $I$. Select an equation that will allow you to find the initial and final values of resistance, and an equation that relates resistance to temperature [the target variable in part (a)].
3. The power $P$ dissipated in the heating element depends on $I$ and $V$. Select an equation that will allow you to calculate the initial and final values of $P$.

### EXECUTE

4. Combine your equations from step 2 to give a relationship between the initial and final values of $I$ and the initial and final temperatures (20°C and $T_{\text{final}}$).
5. Solve your expression from step 4 for $T_{\text{final}}$.
6. Use your equation from step 3 to find the initial and final powers.

### EVALUATE

7. Is the final temperature greater than or less than 20°C? Does this make sense?
8. Is the final resistance greater than or less than the initial resistance? Again, does this make sense?
9. Is the final power greater than or less than the initial power? Does this agree with your observations in step 8?

## Problems

For instructor-assigned homework, go to www.masteringphysics.com

•, ••, •••: Problems of increasing difficulty. **CP**: Cumulative problems incorporating material from earlier chapters. **CALC**: Problems requiring calculus. **BIO**: Biosciences problems.

### DISCUSSION QUESTIONS

**Q25.1** The definition of resistivity ($\rho = E/J$) implies that an electric field exists inside a conductor. Yet we saw in Chapter 21 that there can be no electric field inside a conductor. Is there a contradiction here? Explain.

**Q25.2** A cylindrical rod has resistance $R$. If we triple its length and diameter, what is its resistance, in terms of $R$?

**Q25.3** A cylindrical rod has resistivity $\rho$. If we triple its length and diameter, what is its resistivity, in terms of $\rho$?

**Q25.4** Two copper wires with different diameters are joined end to end. If a current flows in the wire combination, what happens to electrons when they move from the larger-diameter wire into the smaller-diameter wire? Does their drift speed increase, decrease, or stay the same? If the drift speed changes, what is the force that causes the change? Explain your reasoning.

**Q25.5** When is a 1.5-V AAA battery *not* actually a 1.5-V battery? That is, when do its terminals provide a potential difference of less than 1.5 V?

**Q25.6** Can the potential difference between the terminals of a battery ever be opposite in direction to the emf? If it can, give an example. If it cannot, explain why not.

**Q25.7** A rule of thumb used to determine the internal resistance of a source is that it is the open-circuit voltage divided by the short-circuit current. Is this correct? Why or why not?

**Q25.8** Batteries are always labeled with their emf; for instance, an AA flashlight battery is labeled "1.5 volts." Would it also be appropriate to put a label on batteries stating how much current they provide? Why or why not?

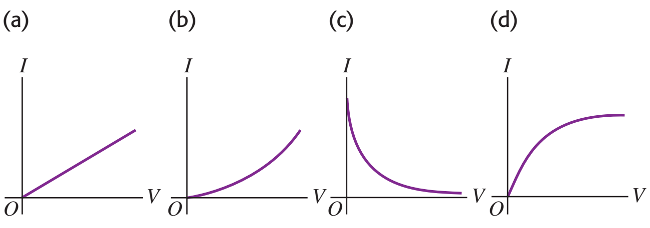
**Q25.9** We have seen that a coulomb is an enormous amount of charge; it is virtually impossible to place a charge of 1 C on an object. Yet, a current of 10 A, 10 C/s, is quite reasonable. Explain this apparent discrepancy.

**Q25.10** Electrons in an electric circuit pass through a resistor. The wire on either side of the resistor has the same diameter. (a) How does the drift speed of the electrons before entering the resistor compare to the speed after leaving the resistor? Explain your reasoning. (b) How does the potential energy for an electron before entering the resistor compare to the potential energy after leaving the resistor? Explain your reasoning.

**Q25.11** Current causes the temperature of a real resistor to increase. Why? What effect does this heating have on the resistance? Explain.

**Q25.12** Which of the graphs in Fig. Q25.12 best illustrates the current $I$ in a real resistor as a function of the potential difference $V$ across it? Explain. (*Hint*: See Discussion Question Q25.11.)

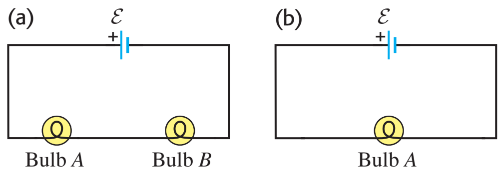
Figure **Q25.12**



**Q25.13** Why does an electric light bulb nearly always burn out just as you turn on the light, almost never while the light is shining?

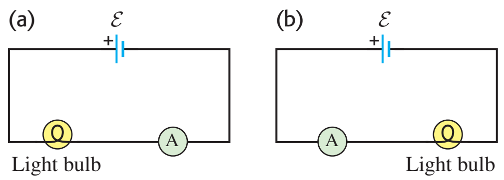
**Q25.14** A light bulb glows because it has resistance. The brightness of a light bulb increases with the electrical power dissipated in the bulb. (a) In the circuit shown in Fig. Q25.14a, the two bulbs *A* and *B* are identical. Compared to bulb *A*, does bulb *B* glow more brightly, just as brightly, or less brightly? Explain your reasoning. (b) Bulb *B* is removed from the circuit and the circuit is completed as shown in Fig. Q25.14b. Compared to the brightness of bulb *A* in Fig. Q25.14a, does bulb *A* now glow more brightly, just as brightly, or less brightly? Explain your reasoning.

Figure **Q25.14**



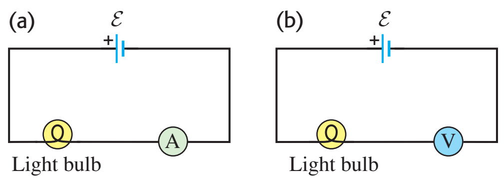

**Q25.15** (See Discussion Question Q25.14.) An ideal ammeter A is placed in a circuit with a battery and a light bulb as shown in Fig. Q25.15a, and the ammeter reading is noted. The circuit is then reconnected as in Fig. Q25.15b, so that the positions of the ammeter and light bulb are reversed. (a) How does the ammeter reading in the situation shown in Fig. Q25.15a compare to the reading in the situation shown in Fig. Q25.15b? Explain your reasoning. (b) In which situation does the light bulb glow more brightly? Explain your reasoning.

Figure **Q25.15**




**Q25.16** (See Discussion Question Q25.14.) Will a light bulb glow more brightly when it is connected to a battery as shown in Fig. Q25.16a, in which an ideal ammeter A is placed in the circuit, or when it is connected as shown in Fig. 25.16b, in which an ideal voltmeter *V* is placed in the circuit? Explain your reasoning.

Figure **Q25.16**




**Q25.17** The energy that can be extracted from a storage battery is always less than the energy that goes into it while it is being charged. Why?

**Q25.18** Eight flashlight batteries in series have an emf of about 12 V, similar to that of a car battery. Could they be used to start a car with a dead battery? Why or why not?

**Q25.19** Small aircraft often have 24-V electrical systems rather than the 12-V systems in automobiles, even though the electrical power requirements are roughly the same in both applications. The explanation given by aircraft designers is that a 24-V system weighs less than a 12-V system because thinner wires can be used. Explain why this is so.

**Q25.20** Long-distance, electric-power, transmission lines always operate at very high voltage, sometimes as much as 750 kV. What are the advantages of such high voltages? What are the disadvantages?

**Q25.21** Ordinary household electric lines in North America usually operate at 120 V. Why is this a desirable voltage, rather than a value considerably larger or smaller? On the other hand, automobiles usually have 12-V electrical systems. Why is this a desirable voltage?

**Q25.22** A fuse is a device designed to break a circuit, usually by melting when the current exceeds a certain value. What characteristics should the material of the fuse have?

**Q25.23** High-voltage power supplies are sometimes designed intentionally to have rather large internal resistance as a safety precaution. Why is such a power supply with a large internal resistance safer than a supply with the same voltage but lower internal resistance?

**Q25.24** The text states that good thermal conductors are also good electrical conductors. If so, why don't the cords used to connect toasters, irons, and similar heat-producing appliances get hot by conduction of heat from the heating element?

## EXERCISES

### Section 25.1 Current

**25.1** • **Lightning Strikes.** During lightning strikes from a cloud to the ground, currents as high as 25,000 A can occur and last for about 40 $\mu$s. How much charge is transferred from the cloud to the earth during such a strike?

**25.2** • A silver wire 2.6 mm in diameter transfers a charge of 420 C in 80 min. Silver contains $5.8 \times 10^{28}$ free electrons per cubic meter. (a) What is the current in the wire? (b) What is the magnitude of the drift velocity of the electrons in the wire?

**25.3** • A 5.00-A current runs through a 12-gauge copper wire (diameter 2.05 mm) and through a light bulb. Copper has $8.5 \times 10^{28}$ free electrons per cubic meter. (a) How many electrons pass through the light bulb each second? (b) What is the current density in the wire? (c) At what speed does a typical electron pass by any given point in the wire? (d) If you were to use wire of twice the diameter, which of the above answers would change? Would they increase or decrease?

**25.4** • An 18-gauge copper wire (diameter 1.02 mm) carries a current with a current density of $1.50 \times 10^6\ \text{A/m}^2$. The density of free electrons for copper is $8.5 \times 10^{28}$ electrons per cubic meter. Calculate (a) the current in the wire and (b) the drift velocity of electrons in the wire.

**25.5** •• Copper has $8.5 \times 10^{28}$ free electrons per cubic meter. A 71.0-cm length of 12-gauge copper wire that is 2.05 mm in diameter carries 4.85 A of current. (a) How much time does it take for an electron to travel the length of the wire? (b) Repeat part (a) for 6-gauge copper wire (diameter 4.12 mm) of the same length that carries the same current. (c) Generally speaking, how does changing the diameter of a wire that carries a given amount of current affect the drift velocity of the electrons in the wire?

**25.6** • Consider the 18-gauge wire in Example 25.1. How many atoms are in 1.00 $\text{m}^3$ of copper? With the density of free electrons given in the example, how many free electrons are there per copper atom?

**25.7** • **CALC** The current in a wire varies with time according to the relationship $I = 55\text{ A} - (0.65\text{ A/s}^2)t^2$. (a) How many coulombs of charge pass a cross section of the wire in the time interval between $t = 0$ and $t = 8.0$ s? (b) What constant current would transport the same charge in the same time interval?

**25.8** • Current passes through a solution of sodium chloride. In 1.00 s, $2.68 \times 10^{16}$ $Na^+$ ions arrive at the negative electrode and $3.92 \times 10^{16}$ $Cl^-$ ions arrive at the positive electrode. (a) What is the current passing between the electrodes? (b) What is the direction of the current?

**25.9** • **BIO** **Transmission of Nerve Impulses.** Nerve cells transmit electric signals through their long tubular axons. These signals propagate due to a sudden rush of $Na^+$ ions, each with charge $+e$, into the axon. Measurements have revealed that typically about $5.6 \times 10^{11}$ $Na^+$ ions enter each meter of the axon during a time of 10 ms. What is the current during this inflow of charge in a meter of axon?

## Section 25.2 Resistivity and Section 25.3 Resistance

**25.10** • (a) At room temperature what is the strength of the electric field in a 12-gauge copper wire (diameter 2.05 mm) that is needed to cause a 2.75-A current to flow? (b) What field would be needed if the wire were made of silver instead?

**25.11** •• A 1.50-m cylindrical rod of diameter 0.500 cm is connected to a power supply that maintains a constant potential difference of 15.0 V across its ends, while an ammeter measures the current through it. You observe that at room temperature (20.0°C) the ammeter reads 18.5 A, while at 92.0°C it reads 17.2 A. You can ignore any thermal expansion of the rod. Find (a) the resistivity at 20.0°C and (b) the temperature coefficient of resistivity at 20°C for the material of the rod.

**25.12** • A copper wire has a square cross section 2.3 mm on a side. The wire is 4.0 m long and carries a current of 3.6 A. The density of free electrons is $8.5 \times 10^{28}/\text{m}^3$. Find the magnitudes of (a) the current density in the wire and (b) the electric field in the wire. (c) How much time is required for an electron to travel the length of the wire?

**25.13** • A 14-gauge copper wire of diameter 1.628 mm carries a current of 12.5 mA. (a) What is the potential difference across a 2.00-m length of the wire? (b) What would the potential difference in part (a) be if the wire were silver instead of copper, but all else were the same?

**25.14** •• A wire 6.50 m long with diameter of 2.05 mm has a resistance of 0.0290 Ω. What material is the wire most likely made of?

**25.15** •• A cylindrical tungsten filament 15.0 cm long with a diameter of 1.00 mm is to be used in a machine for which the temperature will range from room temperature (20°C) up to 120°C. It will carry a current of 12.5 A at all temperatures (consult Tables 25.1 and 25.2). (a) What will be the maximum electric field in this filament, and (b) what will be its resistance with that field? (c) What will be the maximum potential drop over the full length of the filament?

**25.16** •• A ductile metal wire has resistance $R$. What will be the resistance of this wire in terms of $R$ if it is stretched to three times its original length, assuming that the density and resistivity of the material do not change when the wire is stretched? (*Hint:* The amount of metal does not change, so stretching out the wire will affect its cross-sectional area.)

**25.17** • In household wiring, copper wire 2.05 mm in diameter is often used. Find the resistance of a 24.0-m length of this wire.

**25.18** •• What diameter must a copper wire have if its resistance is to be the same as that of an equal length of aluminum wire with diameter 3.26 mm?

**25.19** • You need to produce a set of cylindrical copper wires 3.50 m long that will have a resistance of 0.125 Ω each. What will be the mass of each of these wires?

**25.20** • A tightly coiled spring having 75 coils, each 3.50 cm in diameter, is made of insulated metal wire 3.25 mm in diameter. An ohmmeter connected across its opposite ends reads 1.74 Ω. What is the resistivity of the metal?

**25.21** • An aluminum cube has sides of length 1.80 m. What is the resistance between two opposite faces of the cube?

**25.22** • You apply a potential difference of 4.50 V between the ends of a wire that is 2.50 m in length and 0.654 mm in radius. The resulting current through the wire is 17.6 A. What is the resistivity of the wire?

**25.23** • A current-carrying gold wire has diameter 0.84 mm. The electric field in the wire is 0.49 V/m. What are (a) the current carried by the wire; (b) the potential difference between two points in the wire 6.4 m apart; (c) the resistance of a 6.4-m length of this wire?

**25.24** • A hollow aluminum cylinder is 2.50 m long and has an inner radius of 3.20 cm and an outer radius of 4.60 cm. Treat each surface (inner, outer, and the two end faces) as an equipotential surface. At room temperature, what will an ohmmeter read if it is connected between (a) the opposite faces and (b) the inner and outer surfaces?

**25.25** • (a) What is the resistance of a Nichrome wire at 0.0°C if its resistance is 100.00 Ω at 11.5°C? (b) What is the resistance of a carbon rod at 25.8°C if its resistance is 0.0160 Ω at 0.0°C?

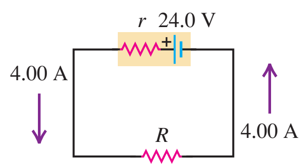
**25.26** • A carbon resistor is to be used as a thermometer. On a winter day when the temperature is 4.0°C, the resistance of the carbon resistor is 217.3 Ω. What is the temperature on a spring day when the resistance is 215.8 Ω? (Take the reference temperature $T_0$ to be 4.0°C.)

**25.27** • A strand of wire has resistance 5.60 μΩ. Find the net resistance of 120 such strands if they are (a) placed side by side to form a cable of the same length as a single strand, and (b) connected end to end to form a wire 120 times as long as a single strand.

## Section 25.4 Electromotive Force and Circuits

**25.28** • Consider the circuit shown in Fig. E25.28. The terminal voltage of the 24.0-V battery is 21.2 V. What are (a) the internal resistance $r$ of the battery and (b) the resistance $R$ of the circuit resistor?

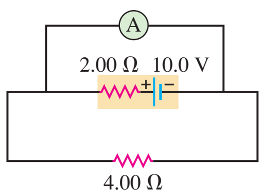
Figure **E25.28**




**25.29** • A copper transmission cable 100 km long and 10.0 cm in diameter carries a current of 125 A. (a) What is the potential drop across the cable? (b) How much electrical energy is dissipated as thermal energy every hour?

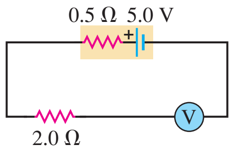
**25.30** • An idealized ammeter is connected to a battery as shown in Fig. E25.30. Find (a) the reading of the ammeter, (b) the current through the 4.00-Ω resistor, (c) the terminal voltage of the battery.

Figure **E25.30**



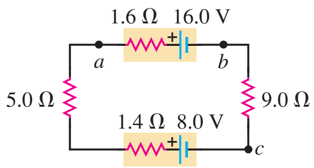
**25.31** • An ideal voltmeter V is connected to a 2.0-Ω resistor and a battery with emf 5.0 V and internal resistance 0.5 Ω as shown in Fig. E25.31. (a) What is the current in the 2.0-Ω resistor? (b) What is the terminal voltage of the battery? (c) What is the reading on the voltmeter? Explain your answers.

Figure **E25.31**



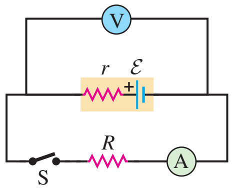

**25.32** • The circuit shown in Fig. E25.32 contains two batteries, each with an emf and an internal resistance, and two resistors. Find (a) the current in the circuit (magnitude *and* direction); (b) the terminal voltage $V_{ab}$ of the 16.0-V battery; (c) the potential difference $V_{ac}$ of point *a* with respect to point *c*. (d) Using Fig. 25.20 as a model, graph the potential rises and drops in this circuit.

Figure **E25.32**




**25.33** • When switch S in Fig. E25.33 is open, the voltmeter V of the battery reads 3.08 V. When the switch is closed, the voltmeter reading drops to 2.97 V, and the ammeter A reads 1.65 A. Find the emf, the internal resistance of the battery, and the circuit resistance *R*. Assume that the two meters are ideal, so they don't affect the circuit.

Figure **E25.33**




**25.34** • In the circuit of Fig. E25.32, the 5.0-Ω resistor is removed and replaced by a resistor of unknown resistance *R*. When this is done, an ideal voltmeter connected across the points *b* and *c* reads 1.9 V. Find (a) the current in the circuit and (b) the resistance *R*. (c) Graph the potential rises and drops in this circuit (see Fig. 25.20).

**25.35** • In the circuit shown in Fig. E25.32, the 16.0-V battery is removed and reinserted with the opposite polarity, so that its negative terminal is now next to point *a*. Find (a) the current in the circuit (magnitude *and* direction); (b) the terminal voltage $V_{ba}$ of the 16.0-V battery; (c) the potential difference $V_{ac}$ of point *a* with respect to point *c*. (d) Graph the potential rises and drops in this circuit (see Fig. 25.20).

**25.36** • The following measurements were made on a Thyrite resistor:

| | | | | |
|---|---|---|---|---|
| ***I*** **(A)** | 0.50 | 1.00 | 2.00 | 4.00 |
| $V_{ab}$ **(V)** | 2.55 | 3.11 | 3.77 | 4.58 |

(a) Graph $V_{ab}$ as a function of *I*. (b) Does Thyrite obey Ohm's law? How can you tell? (c) Graph the resistance $R = V_{ab}/I$ as a function of *I*.

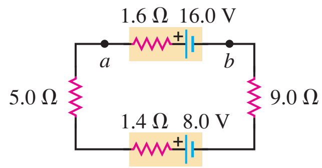
**25.37** • The following measurements of current and potential difference were made on a resistor constructed of Nichrome wire:

| | | | | |
|---|---|---|---|---|
| ***I*** **(A)** | 0.50 | 1.00 | 2.00 | 4.00 |
| $V_{ab}$ **(V)** | 1.94 | 3.88 | 7.76 | 15.52 |

(a) Graph $V_{ab}$ as a function of *I*. (b) Does Nichrome obey Ohm's law? How can you tell? (c) What is the resistance of the resistor in ohms?

**25.38** •• The circuit shown in Fig. E25.38 contains two batteries, each with an emf and an internal resistance, and two resistors. Find (a) the current in the circuit (magnitude and direction) and (b) the terminal voltage $V_{ab}$ of the 16.0-V battery.

Figure **E25.38**




## Section 25.5 Energy and Power in Electric Circuits

**25.39** • **Light Bulbs.** The power rating of a light bulb (such as a 100-W bulb) is the power it dissipates when connected across a 120-V potential difference. What is the resistance of (a) a 100-W bulb and (b) a 60-W bulb? (c) How much current does each bulb draw in normal use?

**25.40** • If a "75-W" bulb (see Problem 25.39) is connected across a 220-V potential difference (as is used in Europe), how much power does it dissipate?

**25.41** • **European Light Bulb.** In Europe the standard voltage in homes is 220 V instead of the 120 V used in the United States. Therefore a "100-W" European bulb would be intended for use with a 220-V potential difference (see Problem 25.40). (a) If you bring a "100-W" European bulb home to the United States, what should be its U.S. power rating? (b) How much current will the 100-W European bulb draw in normal use in the United States?

**25.42** • A battery-powered global positioning system (GPS) receiver operating on 9.0 V draws a current of 0.13 A. How much electrical energy does it consume during 1.5 h?

**25.43** • Consider a resistor with length *L*, uniform cross-sectional area *A*, and uniform resistivity $\rho$ that is carrying a current with uniform current density *J*. Use Eq. (25.18) to find the electrical power dissipated per unit volume, *p*. Express your result in terms of (a) *E* and *J*; (b) *J* and $\rho$; (c) *E* and $\rho$.

**25.44** • BIO **Electric Eels.** Electric eels generate electric pulses along their skin that can be used to stun an enemy when they come into contact with it. Tests have shown that these pulses can be up to 500 V and produce currents of 80 mA (or even larger). A typical pulse lasts for 10 ms. What power and how much energy are delivered to the unfortunate enemy with a single pulse, assuming a steady current?

**25.45** • BIO **Treatment of Heart Failure.** A heart defibrillator is used to enable the heart to start beating if it has stopped. This is done by passing a large current of 12 A through the body at 25 V for a very short time, usually about 3.0 ms. (a) What power does the defibrillator deliver to the body, and (b) how much energy is transferred?

**25.46** • Consider the circuit of Fig. E25.32. (a) What is the total rate at which electrical energy is dissipated in the 5.0-Ω and 9.0-Ω resistors? (b) What is the power output of the 16.0-V battery? (c) At what rate is electrical energy being converted to other forms in the 8.0-V battery? (d) Show that the power output of the 16.0-V battery equals the overall rate of dissipation of electrical energy in the rest of the circuit.

**25.47** •• The capacity of a storage battery, such as those used in automobile electrical systems, is rated in ampere-hours $(\mathrm{A \cdot h})$. A 50-A·h battery can supply a current of 50 A for 1.0 h, or 25 A for 2.0 h, and so on. (a) What total energy can be supplied by a 12-V, 60-A·h battery if its internal resistance is negligible? (b) What volume (in liters) of gasoline has a total heat of combustion equal to the energy obtained in part (a)? (See Section 17.6; the density of gasoline is 900 $kg/m^3$.) (c) If a generator with an average electrical power output of 0.45 kW is connected to the battery, how much time will be required for it to charge the battery fully?

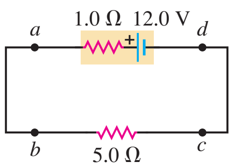
**25.48** • In the circuit analyzed in Example 25.8 the 4.0-$\Omega$ resistor is replaced by a 8.0-$\Omega$ resistor, as in Example 25.9. (a) Calculate the rate of conversion of chemical energy to electrical energy in the battery. How does your answer compare to the result calculated in Example 25.8? (b) Calculate the rate of electrical energy dissipation in the internal resistance of the battery. How does your answer compare to the result calculated in Example 25.8? (c) Use the results of parts (a) and (b) to calculate the net power output of the battery. How does your result compare to the electrical power dissipated in the 8.0-$\Omega$ resistor as calculated for this circuit in Example 25.9?

**25.49** •• A 25.0-$\Omega$ bulb is connected across the terminals of a 12.0-V battery having 3.50 $\Omega$ of internal resistance. What percentage of the power of the battery is dissipated across the internal resistance and hence is not available to the bulb?

**25.50** • An idealized voltmeter is connected across the terminals of a 15.0-V battery, and a 75.0-$\Omega$ appliance is also connected across its terminals. If the voltmeter reads 11.3 V: (a) how much power is being dissipated by the appliance, and (b) what is the internal resistance of the battery?

**25.51** • In the circuit in Fig. E25.51, find (a) the rate of conversion of internal (chemical) energy to electrical energy within the battery; (b) the rate of dissipation of electrical energy in the battery; (c) the rate of dissipation of electrical energy in the external resistor.

Figure **E25.51**




**25.52** •• A typical small flashlight contains two batteries, each having an emf of 1.5 V, connected in series with a bulb having resistance 17 $\Omega$. (a) If the internal resistance of the batteries is negligible, what power is delivered to the bulb? (b) If the batteries last for 5.0 h, what is the total energy delivered to the bulb? (c) The resistance of real batteries increases as they run down. If the initial internal resistance is negligible, what is the combined internal resistance of both batteries when the power to the bulb has decreased to half its initial value? (Assume that the resistance of the bulb is constant. Actually, it will change somewhat when the current through the filament changes, because this changes the temperature of the filament and hence the resistivity of the filament wire.)

**25.53** • A "540-W" electric heater is designed to operate from 120-V lines. (a) What is its resistance? (b) What current does it draw? (c) If the line voltage drops to 110 V, what power does the heater take? (Assume that the resistance is constant. Actually, it will change because of the change in temperature.) (d) The heater coils are metallic, so that the resistance of the heater decreases with decreasing temperature. If the change of resistance with temperature is taken into account, will the electrical power consumed by the heater be larger or smaller than what you calculated in part (c)? Explain.

## Section 25.6 Theory of Metallic Conduction

**25.54** •• Pure silicon contains approximately $1.0 \times 10^{16}$ free electrons per cubic meter. (a) Referring to Table 25.1, calculate the mean free time $\tau$ for silicon at room temperature. (b) Your answer in part (a) is much greater than the mean free time for copper given in Example 25.11. Why, then, does pure silicon have such a high resistivity compared to copper?

## PROBLEMS

**25.55** • An electrical conductor designed to carry large currents has a circular cross section 2.50 mm in diameter and is 14.0 m long. The resistance between its ends is 0.104 $\Omega$. (a) What is the resistivity of the material? (b) If the electric-field magnitude in the conductor is 1.28 V/m, what is the total current? (c) If the material has $8.5 \times 10^{28}$ free electrons per cubic meter, find the average drift speed under the conditions of part (b).

**25.56** •• A plastic tube 25.0 m long and 3.00 cm in diameter is dipped into a silver solution, depositing a layer of silver 0.100 mm thick uniformly over the outer surface of the tube. If this coated tube is then connected across a 12.0-V battery, what will be the current?

**25.57** •• On your first day at work as an electrical technician, you are asked to determine the resistance per meter of a long piece of wire. The company you work for is poorly equipped. You find a battery, a voltmeter, and an ammeter, but no meter for directly measuring resistance (an ohmmeter). You put the leads from the voltmeter across the terminals of the battery, and the meter reads 12.6 V. You cut off a 20.0-m length of wire and connect it to the battery, with an ammeter in series with it to measure the current in the wire. The ammeter reads 7.00 A. You then cut off a 40.0-m length of wire and connect it to the battery, again with the ammeter in series to measure the current. The ammeter reads 4.20 A. Even though the equipment you have available to you is limited, your boss assures you of its high quality: The ammeter has very small resistance, and the voltmeter has very large resistance. What is the resistance of 1 meter of wire?

**25.58** • A 2.0-mm length of wire is made by welding the end of a 120-cm-long silver wire to the end of an 80-cm-long copper wire. Each piece of wire is 0.60 mm in diameter. The wire is at room temperature, so the resistivities are as given in Table 25.1. A potential difference of 5.0 V is maintained between the ends of the 2.0-m composite wire. (a) What is the current in the copper section? (b) What is the current in the silver section? (c) What is the magnitude of $\vec{E}$ in the copper? (d) What is the magnitude of $\vec{E}$ in the silver? (e) What is the potential difference between the ends of the silver section of wire?

**25.59** • A 3.00-m length of copper wire at 20°C has a 1.20-m-long section with diameter 1.60 mm and a 1.80-m-long section with diameter 0.80 mm. There is a current of 2.5 mA in the 1.60-mm-diameter section. (a) What is the current in the 0.80-mm-diameter section? (b) What is the magnitude of $\vec{E}$ in the 1.60-mm-diameter section? (c) What is the magnitude of $\vec{E}$ in the 0.80-mm-diameter section? (d) What is the potential difference between the ends of the 3.00-m length of wire?

**25.60** • **Critical Current Density in Superconductors.** One problem with some of the newer high-temperature superconductors is getting a large enough current density for practical use without causing the resistance to reappear. The maximum current density for which the material will remain a superconductor is called the critical current density of the material. In 1987, IBM research labs had produced thin films with critical current densities of $1.0 \times 10^5$ $A/cm^2$. (a) How much current could an 18-gauge wire (see Example 25.1 in Section 25.1) of this material carry and still remain superconducting? (b) Researchers are trying to develop superconductors with critical current densities of $1.0 \times 10^6$ $A/cm^2$. What diameter cylindrical wire of such a material would be needed to carry 1000 A without losing its superconductivity?

**25.61** •• **CP** A Nichrome heating element that has resistance 28.0 $\Omega$ is connected to a battery that has emf 96.0 V and internal resistance 1.2 $\Omega$. An aluminum cup with mass 0.130 kg contains 0.200 kg of water. The heating element is placed in the water and the electrical energy dissipated in the resistance of the heating element all goes into the cup and water. The element itself has very small mass. How much time does it take for the temperature of the cup and water to rise from 21.2°C to 34.5°C? (The change of the resistance of the Nichrome due to its temperature change can be neglected.)

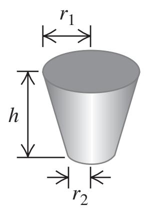
**25.62** •• A resistor with resistance $R$ is connected to a battery that has emf 12.0 V and internal resistance $r = 0.40\ \Omega$. For what two values of $R$ will the power dissipated in the resistor be 80.0 W?

**25.63** •• **CP BIO** **Struck by Lightning.** Lightning strikes can involve currents as high as 25,000 A that last for about 40 $\mu$s. If a person is struck by a bolt of lightning with these properties, the current will pass through his body. We shall assume that his mass is 75 kg, that he is wet (after all, he is in a rainstorm) and therefore has a resistance of 1.0 k$\Omega$, and that his body is all water (which is reasonable for a rough, but plausible, approximation). (a) By how many degrees Celsius would this lightning bolt increase the temperature of 75 kg of water? (b) Given that the internal body temperature is about 37°C, would the person's temperature actually increase that much? Why not? What would happen first?

**25.64** •• In the Bohr model of the hydrogen atom, the electron makes $6.0 \times 10^{15}$ rev/s around the nucleus. What is the average current at a point on the orbit of the electron?

**25.65** • **CALC** A material of resistivity $\rho$ is formed into a solid, truncated cone of height $h$ and radii $r_1$ and $r_2$ at either end (Fig. P25.65). (a) Calculate the resistance of the cone between the two flat end faces. (*Hint:* Imagine slicing the cone into very many thin disks, and calculate the resistance of one such disk.) (b) Show that your result agrees with Eq. (25.10) when $r_1 = r_2$.

Figure **P25.65**




**25.66** • **CALC** The region between two concentric conducting spheres with radii $a$ and $b$ is filled with a conducting material with resistivity $\rho$. (a) Show that the resistance between the spheres is given by

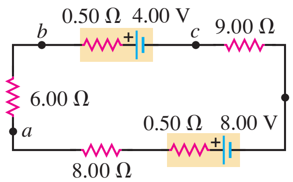
$$R = \frac{\rho}{4\pi}\left(\frac{1}{a} - \frac{1}{b}\right)$$

(b) Derive an expression for the current density as a function of radius, in terms of the potential difference $V_{ab}$ between the spheres. (c) Show that the result in part (a) reduces to Eq. (25.10) when the separation $L = b - a$ between the spheres is small.

**25.67** ••• The temperature coefficient of resistance $\alpha$ in Eq. (25.12) equals the temperature coefficient of resistivity $\alpha$ in Eq. (25.6) only if the coefficient of thermal expansion is small. A cylindrical column of mercury is in a vertical glass tube. At 20°C, the length of the mercury column is 12.0 cm. The diameter of the mercury column is 1.6 mm and doesn't change with temperature because glass has a small coefficient of thermal expansion. The coefficient of volume expansion of the mercury is given in Table 17.2, its resistivity at 20°C is given in Table 25.1, and its temperature coefficient of resistivity is given in Table 25.2. (a) At 20°C, what is the resistance between the ends of the mercury column? (b) The mercury column is heated to 60°C. What is the change in its resistivity? (c) What is the change in its length? Explain why the coefficient of volume expansion, rather than the coefficient of linear expansion, determines the change in length. (d) What is the change in its resistance? (*Hint:* Since the percentage changes in $\rho$ and $L$ are small, you may find it helpful to derive from Eq. (25.10) an equation for $\Delta R$ in terms of $\Delta\rho$ and $\Delta L$.) (e) What is the temperature coefficient of resistance $\alpha$ for the mercury column, as defined in Eq. (25.12)? How does this value compare with the temperature coefficient of resistivity? Is the effect of the change in length important?

**25.68** • (a) What is the potential difference $V_{ad}$ in the circuit of Fig. P25.68? (b) What is the terminal voltage of the 4.00-V battery? (c) A battery with emf 10.30 V and internal resistance 0.50 $\Omega$ is inserted in the circuit at $d$, with its negative terminal connected to the negative terminal of the 8.00-V battery. What is the difference of potential $V_{bc}$ between the terminals of the 4.00-V battery now?

Figure **P25.68**




**25.69** • The potential difference across the terminals of a battery is 8.40 V when there is a current of 1.50 A in the battery from the negative to the positive terminal. When the current is 3.50 A in the reverse direction, the potential difference becomes 10.20 V. (a) What is the internal resistance of the battery? (b) What is the emf of the battery?

**25.70** •• **BIO** A person with body resistance between his hands of 10 k$\Omega$ accidentally grasps the terminals of a 14-kV power supply. (a) If the internal resistance of the power supply is 2000 $\Omega$, what is the current through the person's body? (b) What is the power dissipated in his body? (c) If the power supply is to be made safe by increasing its internal resistance, what should the internal resistance be for the maximum current in the above situation to be 1.00 mA or less?

**25.71** • **BIO** The average bulk resistivity of the human body (apart from surface resistance of the skin) is about 5.0 $\Omega \cdot$m. The conducting path between the hands can be represented approximately as a cylinder 1.6 m long and 0.10 m in diameter. The skin resistance can be made negligible by soaking the hands in salt water. (a) What is the resistance between the hands if the skin resistance is negligible? (b) What potential difference between the hands is needed for a lethal shock current of 100 mA? (Note that your result shows that small potential differences produce dangerous currents when the skin is damp.) (c) With the current in part (b), what power is dissipated in the body?

**25.72** • A typical cost for electric power is \$0.120 per kilowatt-hour. (a) Some people leave their porch light on all the time. What is the yearly cost to keep a 75-W bulb burning day and night? (b) Suppose your refrigerator uses 400 W of power when it's running, and it runs 8 hours a day. What is the yearly cost of operating your refrigerator?

**25.73** •• A 12.6-V car battery with negligible internal resistance is connected to a series combination of a 3.2-$\Omega$ resistor that obeys Ohm's law and a thermistor that does not obey Ohm's law but instead has a current–voltage relationship $V = \alpha I + \beta I^2$, with $\alpha = 3.8\ \Omega$ and $\beta = 1.3\ \Omega/\text{A}$. What is the current through the 3.2-$\Omega$ resistor?

**25.74** •• A cylindrical copper cable 1.50 km long is connected across a 220.0-V potential difference. (a) What should be its diameter so that it produces heat at a rate of 75.0 W? (b) What is the electric field inside the cable under these conditions?

**25.75** •• **A Nonideal Ammeter.** Unlike the idealized ammeter described in Section 25.4, any real ammeter has a nonzero resistance. (a) An ammeter with resistance $R_\text{A}$ is connected in series with a resistor $R$ and a battery of emf $\mathcal{E}$ and internal resistance $r$. The current measured by the ammeter is $I_\text{A}$. Find the current through the circuit if the ammeter is removed so that the battery and the resistor form a complete circuit. Express your answer in terms of $I_A$, $r$, $R_A$, and $R$. The more "ideal" the ammeter, the smaller the difference between this current and the current $I_A$. (b) If $R = 3.80\ \Omega$, $\mathcal{E} = 7.50$ V, and $r = 0.45\ \Omega$, find the maximum value of the ammeter resistance $R_A$ so that $I_A$ is within 1.0% of the current in the circuit when the ammeter is absent. (c) Explain why your answer in part (b) represents a *maximum* value.

**25.76** • **CALC** A 1.50-m cylinder of radius 1.10 cm is made of a complicated mixture of materials. Its resistivity depends on the distance $x$ from the left end and obeys the formula $\rho(x) = a + bx^2$, where $a$ and $b$ are constants. At the left end, the resistivity is $2.25 \times 10^{-8}\ \Omega \cdot \text{m}$, while at the right end it is $8.50 \times 10^{-8}\ \Omega \cdot \text{m}$. (a) What is the resistance of this rod? (b) What is the electric field at its midpoint if it carries a 1.75-A current? (c) If we cut the rod into two 75.0-cm halves, what is the resistance of each half?

**25.77** •• According to the U.S. National Electrical Code, copper wire used for interior wiring of houses, hotels, office buildings, and industrial plants is permitted to carry no more than a specified maximum amount of current. The table below shows the maximum current $I_{max}$ for several common sizes of wire with varnished cambric insulation. The "wire gauge" is a standard used to describe the diameter of wires. Note that the larger the diameter of the wire, the *smaller* the wire gauge.

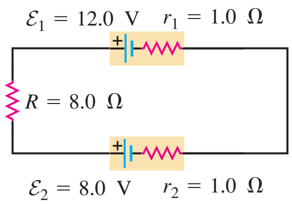
| Wire gauge | Diameter (cm) | $I_{max}$ (A) |
|---|---|---|
| 14 | 0.163 | 18 |
| 12 | 0.205 | 25 |
| 10 | 0.259 | 30 |
| 8 | 0.326 | 40 |
| 6 | 0.412 | 60 |
| 5 | 0.462 | 65 |
| 4 | 0.519 | 85 |

(a) What considerations determine the maximum current-carrying capacity of household wiring? (b) A total of 4200 W of power is to be supplied through the wires of a house to the household electrical appliances. If the potential difference across the group of appliances is 120 V, determine the gauge of the thinnest permissible wire that can be used. (c) Suppose the wire used in this house is of the gauge found in part (b) and has total length 42.0 m. At what rate is energy dissipated in the wires? (d) The house is built in a community where the consumer cost of electric energy is \$0.11 per kilowatt-hour. If the house were built with wire of the next larger diameter than that found in part (b), what would be the savings in electricity costs in one year? Assume that the appliances are kept on for an average of 12 hours a day.

**25.78** •• **Compact Fluorescent Bulbs.** Compact fluorescent bulbs are much more efficient at producing light than are ordinary incandescent bulbs. They initially cost much more, but they last far longer and use much less electricity. According to one study of these bulbs, a compact bulb that produces as much light as a 100-W incandescent bulb uses only 23 W of power. The compact bulb lasts 10,000 hours, on the average, and costs \$11.00, whereas the incandescent bulb costs only \$0.75, but lasts just 750 hours. The study assumed that electricity costs \$0.080 per kilowatt-hour and that the bulbs are on for 4.0 h per day. (a) What is the total cost (including the price of the bulbs) to run each bulb for 3.0 years? (b) How much do you save over 3.0 years if you use a compact fluorescent bulb instead of an incandescent bulb? (c) What is the resistance of a "100-W" fluorescent bulb? (Remember, it actually uses only 23 W of power and operates across 120 V.)

**25.79** • In the circuit of Fig. P25.79, find (a) the current through the 8.0-Ω resistor and (b) the total rate of dissipation of electrical energy in the 8.0-Ω resistor and in the internal resistance of the batteries. (c) In one of the batteries, chemical energy is being converted into electrical energy. In which one is this happening, and at what rate? (d) In one of the batteries, electrical energy is being converted into chemical energy. In which one is this happening, and at what rate? (e) Show that the overall rate of production of electrical energy equals the overall rate of consumption of electrical energy in the circuit.

Figure **P25.79**



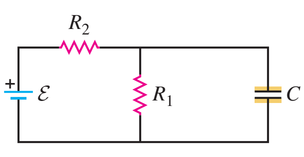

**25.80** • A lightning bolt strikes one end of a steel lightning rod, producing a 15,000-A current burst that lasts for 65 $\mu$s. The rod is 2.0 m long and 1.8 cm in diameter, and its other end is connected to the ground by 35 m of 8.0-mm-diameter copper wire. (a) Find the potential difference between the top of the steel rod and the lower end of the copper wire during the current burst. (b) Find the total energy deposited in the rod and wire by the current burst.

**25.81** • A 12.0-V battery has an internal resistance of 0.24 Ω and a capacity of 50.0 A·h (see Exercise 25.47). The battery is charged by passing a 10-A current through it for 5.0 h. (a) What is the terminal voltage during charging? (b) What total electrical energy is supplied to the battery during charging? (c) What electrical energy is dissipated in the internal resistance during charging? (d) The battery is now completely discharged through a resistor, again with a constant current of 10 A. What is the external circuit resistance? (e) What total electrical energy is supplied to the external resistor? (f) What total electrical energy is dissipated in the internal resistance? (g) Why are the answers to parts (b) and (e) not the same?

**25.82** • Repeat Problem 25.81 with charge and discharge currents of 30 A. The charging and discharging times will now be 1.7 h rather than 5.0 h. What differences in performance do you see?

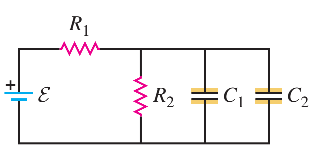
**25.83** •• **CP** Consider the circuit shown in Fig. P25.83. The emf source has negligible internal resistance. The resistors have resistances $R_1 = 6.00\ \Omega$ and $R_2 = 4.00\ \Omega$. The capacitor has capacitance $C = 9.00\ \mu$F. When the capacitor is fully charged, the magnitude of the charge on its plates is $Q = 36.0\ \mu$C. Calculate the emf $\mathcal{E}$.

Figure **P25.83**




**25.84** •• **CP** Consider the circuit shown in Fig. P25.84. The battery has emf 60.0 V and negligible internal resistance. $R_2 = 2.00\ \Omega$, $C_1 = 3.00\ \mu$F, and $C_2 = 6.00\ \mu$F. After the capacitors have attained their final charges, the charge on $C_1$ is $Q_1 = 18.0\ \mu$C. (a) What is the final charge on $C_2$? (b) What is the resistance $R_1$?

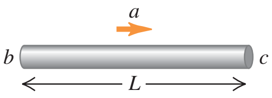
Figure **P25.84**



## CHALLENGE PROBLEMS

**25.85** ••• The *Tolman-Stewart experiment* in 1916 demonstrated that the free charges in a metal have negative charge and provided a quantitative measurement of their charge-to-mass ratio, $|q|/m$. The experiment consisted of abruptly stopping a rapidly rotating spool of wire and measuring the potential difference that this produced between the ends of the wire. In a simplified model of this experiment, consider a metal rod of length $L$ that is given a uniform acceleration $\vec{a}$ to the right. Initially the free charges in the metal lag behind the rod's motion, thus setting up an electric field $\vec{E}$ in the rod. In the steady state this field exerts a force on the free charges that makes them accelerate along with the rod. (a) Apply $\sum\vec{F} = m\vec{a}$ to the free charges to obtain an expression for $|q|/m$ in terms of the magnitudes of the induced electric field $\vec{E}$ and the acceleration $\vec{a}$. (b) If all the free charges in the metal rod have the same acceleration, the electric field $\vec{E}$ is the same at all points in the rod. Use this fact to rewrite the expression for $|q|/m$ in terms of the potential $V_{bc}$ between the ends of the rod (Fig. P25.85). (c) If the free charges have negative charge, which end of the rod, $b$ or $c$, is at higher potential? (d) If the rod is 0.50 m long and the free charges are electrons (charge $q = -1.60 \times 10^{-19}$ C, mass $9.11 \times 10^{-31}$ kg), what magnitude of acceleration is required to produce a potential difference of 1.0 mV between the ends of the rod? (e) Discuss why the actual experiment used a rotating spool of thin wire rather than a moving bar as in our simplified analysis.

Figure **P25.85**




**25.86** ••• **CALC** A source with emf $\mathcal{E}$ and internal resistance $r$ is connected to an external circuit. (a) Show that the power output of the source is maximum when the current in the circuit is one-half the short-circuit current of the source. (b) If the external circuit consists of a resistance $R$, show that the power output is maximum when $R = r$ and that the maximum power is $\mathcal{E}^2/4r$.

**25.87** ••• **CALC** The resistivity of a semiconductor can be modified by adding different amounts of impurities. A rod of semiconducting material of length $L$ and cross-sectional area $A$ lies along the $x$-axis between $x = 0$ and $x = L$. The material obeys Ohm's law, and its resistivity varies along the rod according to $\rho(x) = \rho_0 \exp(-x/L)$. The end of the rod at $x = 0$ is at a potential $V_0$ greater than the end at $x = L$. (a) Find the total resistance of the rod and the current in the rod. (b) Find the electric-field magnitude $E(x)$ in the rod as a function of $x$. (c) Find the electric potential $V(x)$ in the rod as a function of $x$. (d) Graph the functions $\rho(x)$, $E(x)$, and $V(x)$ for values of $x$ between $x = 0$ and $x = L$.

# Answers

## Chapter Opening Question ?

The current out equals the current in. In other words, charge must enter the bulb at the same rate as it exits the bulb. It is not "used up" or consumed as it flows through the bulb.

## Test Your Understanding Questions

**25.1 Answer: (v)** Doubling the diameter increases the cross-sectional area $A$ by a factor of 4. Hence the current-density magnitude $J = I/A$ is reduced to $\frac{1}{4}$ of the value in Example 25.1, and the magnitude of the drift velocity $v_d = J/n|q|$ is reduced by the same factor. The new magnitude is $v_d = (0.15\ \text{mm/s})/4 = 0.038\ \text{mm/s}$. This behavior is the same as that of an incompressible fluid, which slows down when it moves from a narrow pipe to a broader one (see Section 14.4).

**25.2 Answer: (ii)** Figure 25.6b shows that the resistivity $\rho$ of a semiconductor increases as the temperature decreases. From Eq. (25.5), the magnitude of the current density is $J = E/\rho$, so the current density decreases as the temperature drops and the resistivity increases.

**25.3 Answer: (iii)** Solving Eq. (25.11) for the current shows that $I = V/R$. If the resistance $R$ of the wire remained the same, doubling the voltage $V$ would make the current $I$ double as well. However, we saw in Example 25.3 that the resistance is *not* constant: As the current increases and the temperature increases, $R$ increases as well. Thus doubling the voltage produces a current that is *less* than double the original current. An ohmic conductor is one for which $R = V/I$ has the same value no matter what the voltage, so the wire is *nonohmic*. (In many practical problems the temperature change of the wire is so small that it can be ignored, so we can safely regard the wire as being ohmic. We do so in almost all examples in this book.)

**25.4 Answer: (iii), (ii), (i)** For circuit (i), we find the current from Eq. (25.16): $I = \mathcal{E}/(R + r) = (1.5\ \text{V})/(1.4\ \Omega + 0.10\ \Omega) = 1.0\ \text{A}$. For circuit (ii), we note that the terminal voltage $v_{ab} = 3.6\ \text{V}$ equals the voltage $IR$ across the 1.8-$\Omega$ resistor: $V_{ab} = IR$, so $I = V_{ab}/R = (3.6\ \text{V})/(1.8\ \Omega) = 2.0\ \text{A}$. For circuit (iii), we use Eq. (25.15) for the terminal voltage: $V_{ab} = \mathcal{E} - Ir$, so $I = (\mathcal{E} - V_{ab})/r = (12.0\ \text{V} - 11.0\ \text{V})/(0.20\ \Omega) = 5.0\ \text{A}$.

**25.5 Answer: (iii), (ii), (i)** These are the same circuits that we analyzed in Test Your Understanding of Section 25.4. In each case the net power output of the battery is $P = V_{ab}I$, where $V_{ab}$ is the battery terminal voltage. For circuit (i), we found that $I = 1.0\ \text{A}$, so $V_{ab} = \mathcal{E} - Ir = 1.5\ \text{V} - (1.0\ \text{A})(0.10\ \Omega) = 1.4\ \text{V}$, so $P = (1.4\ \text{V})(1.0\ \text{A}) = 1.4\ \text{W}$. For circuit (ii), we have $V_{ab} = 3.6\ \text{V}$ and found that $I = 2.0\ \text{A}$, so $P = (3.6\ \text{V})(2.0\ \text{A}) = 7.2\ \text{W}$. For circuit (iii), we have $V_{ab} = 11.0\ \text{V}$ and found that $I = 5.0\ \text{A}$, so $P = (11.0\ \text{V})(5.0\ \text{A}) = 55\ \text{A}$.

**25.6 Answer: (i)** The difficulty of producing a certain amount of current increases as the resistivity $\rho$ increases. From Eq. (25.24), $\rho = m/ne^2\tau$, so increasing the mass $m$ will increase the resistivity. That's because a more massive charged particle will respond more sluggishly to an applied electric field and hence drift more slowly. To produce the same current, a greater electric field would be needed. (Increasing $n$, $e$, or $\tau$ would decrease the resistivity and make it easier to produce a given current.)

## Bridging Problem

**Answers: (a)** 237°C **(b)** 162 W initially, 148 W at 1.23 A