One explanation for superconductivity is that the electrons that make up the current move in coordinated pairs. One of the electrons in a pair may electrically distort the molecular structure of the superconducting material as it moves through, creating nearby a short-lived concentration of positive charge. The other electron in the pair may then be attracted toward this positive charge. According to the theory, such coordination between electrons would prevent them from colliding with the molecules of the material and thus would eliminate electrical resistance. The theory worked well to explain the pre-1986, lower temperature superconductors, but new theories appear to be needed for the newer, higher temperature superconductors.

## REVIEW \& SUMMARY

Current An electric current $i$ in a conductor is defined by

$$
\begin{equation*}
i=\frac{d q}{d t} \tag{26-1}
\end{equation*}
$$

Here $d q$ is the amount of (positive) charge that passes in time $d t$ through a hypothetical surface that cuts across the conductor. By convention, the direction of electric current is taken as the direction in which positive charge carriers would move. The SI unit of electric current is the ampere (A): $1 \mathrm{~A}=1 \mathrm{C} / \mathrm{s}$.

Current Density Current (a scalar) is related to current density $\vec{J}$ (a vector) by

$$
\begin{equation*}
i=\int \vec{J} \cdot d \vec{A} \tag{26-4}
\end{equation*}
$$

where $d \vec{A}$ is a vector perpendicular to a surface element of area $d A$ and the integral is taken over any surface cutting across the conductor. $\vec{J}$ has the same direction as the velocity of the moving charges if they are positive and the opposite direction if they are negative.

Drift Speed of the Charge Carriers When an electric field $\vec{E}$ is established in a conductor, the charge carriers (assumed positive) acquire a drift speed $v_{d}$ in the direction of $\vec{E}$; the velocity $\vec{v}_{d}$ is related to the current density by

$$
\begin{equation*}
\vec{J}=(n e) \vec{v}_{d}, \tag{26-7}
\end{equation*}
$$

where $n e$ is the carrier charge density.
Resistance of a Conductor The resistance $R$ of a conductor is defined as

$$
\begin{equation*}
R=\frac{V}{i} \quad(\text { definition of } R), \tag{26-8}
\end{equation*}
$$

where $V$ is the potential difference across the conductor and $i$ is the current. The SI unit of resistance is the $\mathbf{o h m}(\Omega): 1 \Omega=1 \mathrm{~V} / \mathrm{A}$. Similar equations define the resistivity $\rho$ and conductivity $\sigma$ of a material:

$$
\begin{equation*}
\rho=\frac{1}{\sigma}=\frac{E}{J} \quad(\text { definitions of } \rho \text { and } \sigma), \tag{26-12,26-10}
\end{equation*}
$$

where $E$ is the magnitude of the applied electric field. The SI unit of resistivity is the ohm-meter $(\Omega \cdot \mathrm{m})$. Equation $26-10$ corresponds to the vector equation

$$
\begin{equation*}
\vec{E}=\rho \vec{J} . \tag{26-11}
\end{equation*}
$$

The resistance $R$ of a conducting wire of length $L$ and uniform cross section is

$$
\begin{equation*}
R=\rho \frac{L}{A} \tag{26-16}
\end{equation*}
$$

where $A$ is the cross-sectional area.

Change of $\rho$ with Temperature The resistivity $\rho$ for most materials changes with temperature. For many materials, including metals, the relation between $\rho$ and temperature $T$ is approximated by the equation

$$
\begin{equation*}
\rho-\rho_{0}=\rho_{0} \alpha\left(T-T_{0}\right) . \tag{26-17}
\end{equation*}
$$

Here $T_{0}$ is a reference temperature, $\rho_{0}$ is the resistivity at $T_{0}$, and $\alpha$ is the temperature coefficient of resistivity for the material.

Ohm's Law A given device (conductor, resistor, or any other electrical device) obeys Ohm's law if its resistance R, defined by Eq. 26-8 as $V / i$, is independent of the applied potential difference $V$. A given material obeys Ohm's law if its resistivity, defined by Eq. 26-10, is independent of the magnitude and direction of the applied electric field $\vec{E}$.

Resistivity of a Metal By assuming that the conduction electrons in a metal are free to move like the molecules of a gas, it is possible to derive an expression for the resistivity of a metal:

$$
\begin{equation*}
\rho=\frac{m}{e^{2} n \tau} \tag{26-22}
\end{equation*}
$$

Here $n$ is the number of free electrons per unit volume and $\tau$ is the mean time between the collisions of an electron with the atoms of the metal. We can explain why metals obey Ohm's law by pointing out that $\tau$ is essentially independent of the magnitude $E$ of any electric field applied to a metal.

Power The power $P$, or rate of energy transfer, in an electrical device across which a potential difference $V$ is maintained is

$$
\begin{equation*}
P=i V \quad \text { (rate of electrical energy transfer). } \tag{26-26}
\end{equation*}
$$

Resistive Dissipation If the device is a resistor, we can write Eq. 26-26 as

$$
P=i^{2} R=\frac{V^{2}}{R} \quad \text { (resistive dissipation). }
$$

(26-27, 26-28)
In a resistor, electric potential energy is converted to internal thermal energy via collisions between charge carriers and atoms.

Semiconductors Semiconductors are materials that have few conduction electrons but can become conductors when they are doped with other atoms that contribute free electrons.

Superconductors Superconductors are materials that lose all electrical resistance at low temperatures. Recent research has discovered materials that are superconducting at surprisingly high temperatures.

## Q U ESTIONS

1 Figure 26-15 shows cross sections through three long conductors of the same length and material, with square cross sections of edge lengths as shown. Conductor $B$ fits snugly within conductor $A$, and conductor $C$ fits snugly within conductor $B$. Rank the following according to their end-to-end resistances, greatest first: the individual conductors and the combinations of $A+B$ ( $B$ inside $A), B+C(C$ inside $B)$, and $A+B+C(B$ inside $A$ inside $C)$.


Fig. 26-15 Question 1.
2 Figure 26-16 shows cross sections through three wires of identical length and material; the sides are given in millimeters. Rank the wires according to their resistance (measured end to end along each wire's length), greatest first.


Fig. 26-16 Question 2.
3 Figure 26-17 shows a rectangular solid conductor of edge lengths $L, 2 L$, and $3 L$. A potential difference $V$ is to be applied uniformly between pairs of opposite faces of the conductor as in Fig. 26-8b. First $V$ is applied between the left-right


Fig. 26-17 Question 3. faces, then between the top-bottom faces, and then between the front-back faces. Rank those pairs, greatest first, according to the following (within the conductor): (a) the magnitude of the electric field, (b) the current density, (c) the current, and (d) the drift speed of the electrons.
4 Figure 26-18 shows plots of the current $i$ through a certain cross section of a wire over four different time periods. Rank the periods according to the net charge that passes through the cross section during the period, greatest first.


Fig. 26-18 Question 4.

5 Figure 26-19 shows four situations in which positive and negative charges move horizontally and gives the rate at which each charge moves. Rank the situations according to the effective current through the regions, greatest first.


Fig. 26-19 Question 5.

6 In Fig. 26-20, a wire that carries a current consists of three sections with different radii. Rank the sections according to the following quantities, greatest first: (a) current, (b) magnitude of current density, and (c) magnitude of electric field.
7 Figure 26-21 gives the electric potential $V(x)$ versus position $x$ along a copper wire carrying current. The wire consists of three sections that differ in radius. Rank the three sections according to the magnitude of the (a) electric field and (b) current density, greatest first.

8 The following table gives the lengths of three copper rods, their diameters, and the potential differences between their ends. Rank the rods according to (a) the magnitude of the electric field within them, (b) the current density within them, and (c) the drift speed of electrons through them, greatest first.

| Rod | Length | Diameter | Potential Difference |
| :---: | :---: | :---: | :---: |
| 1 | $L$ | $3 d$ | $V$ |
| 2 | $2 L$ | $d$ | $2 V$ |
| 3 | $3 L$ | $2 d$ | $2 V$ |

9 Figure 26-22 gives the drift speed $v_{d}$ of conduction electrons in a copper wire versus position $x$ along the wire. The wire consists of three sections that differ in radius. Rank the three sections according to the following quantities, greatest first: (a)


Fig. 26-22 Question 9. radius, (b) number of conduction electrons per cubic meter, (c) magnitude of electric field, (d) conductivity.
10 Three wires, of the same diameter, are connected in turn between two points maintained at a constant potential difference. Their resistivities and lengths are $\rho$ and $L$ (wire $A$ ), $1.2 \rho$ and $1.2 L$ (wire $B$ ), and $0.9 \rho$ and $L$ (wire $C$ ). Rank the wires according to the rate at which energy is transferred to thermal energy, greatest first.

```
(c) Tutoring problem available (at instructor's discretion) in WileyPLUS and WebAssign
SSM Worked-out solution available in Student Solutions Manual WWW Worked-out solution is a
--.00 Number of dots indicates level of problem difficulty ILW Interactive solution is at
#W Additional information available in The Flying Circus of Physics and at flyingcircusofphysics.com
```


## sec. 26-2 Electric Current

-1 During the 4.0 min a 5.0 A current is set up in a wire, how many (a) coulombs and (b) electrons pass through any cross section across the wire's width?
$\bullet 2$ An isolated conducting sphere has a 10 cm radius. One wire carries a current of 1.0000020 A into it. Another wire carries a current of 1.0000000 A out of it. How long would it take for the sphere to increase in potential by 1000 V ?
-3 A charged belt, 50 cm wide, travels at $30 \mathrm{~m} / \mathrm{s}$ between a source of charge and a sphere. The belt carries charge into the sphere at a rate corresponding to $100 \mu \mathrm{~A}$. Compute the surface charge density on the belt.

## sec. 26-3 Current Density

-4 The (United States) National Electric Code, which sets maximum safe currents for insulated copper wires of various diameters, is given (in part) in the table. Plot the safe current density as a function of diameter. Which wire gauge has the maximum safe current density? ("Gauge" is a way of identifying wire diameters, and $1 \mathrm{mil}=10^{-3} \mathrm{in}$.)

| Gauge | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| Diameter, mils | 204 | 162 | 129 | 102 | 81 | 64 | 51 | 40 |
| Safe current, A | 70 | 50 | 35 | 25 | 20 | 15 | 6 | 3 |

-5 SSM www A beam contains $2.0 \times 10^{8}$ doubly charged positive ions per cubic centimeter, all of which are moving north with a speed of $1.0 \times 10^{5} \mathrm{~m} / \mathrm{s}$. What are the (a) magnitude and (b) direction of the current density $\vec{J}$ ? (c) What additional quantity do you need to calculate the total current $i$ in this ion beam?
-6 A certain cylindrical wire carries current. We draw a circle of radius $r$ around its central axis in Fig. 26-23a to determine the current $i$ within the circle. Figure $26-23 b$ shows current $i$ as a function of $r^{2}$. The vertical scale is set by $i_{s}=$ 4.0 mA , and the horizontal scale is set by $r_{s}^{2}=4.0 \mathrm{~mm}^{2}$. (a) Is the current density uniform? (b) If so, what is its magnitude?
-7 A fuse in an electric circuit is a wire that is designed to melt, and thereby open the circuit, if the current exceeds a predetermined value. Suppose that the material to be used in a fuse melts when the current density rises to $440 \mathrm{~A} / \mathrm{cm}^{2}$. What diameter of cylindrical wire should be used to make a fuse that will limit the current to 0.50 A ?
-8 A small but measurable current of $1.2 \times 10^{-10} \mathrm{~A}$ exists in a copper wire whose diameter is 2.5 mm . The number of charge carriers per unit volume is $8.49 \times 10^{28} \mathrm{~m}^{-3}$. Assuming the current is uniform, calculate the (a) current density and (b) electron drift speed.

-18 A wire 4.00 m long and 6.00 mm in diameter has a resistance of $15.0 \mathrm{~m} \Omega$. A potential difference of 23.0 V is applied between the ends. (a) What is the current in the wire? (b) What is the magnitude of the current density? (c) Calculate the resistivity of the wire material. (d) Using Table 26-1, identify the material.
-19 SSM What is the resistivity of a wire of 1.0 mm diameter, 2.0 m length, and $50 \mathrm{~m} \Omega$ resistance?
-20 A certain wire has a resistance $R$. What is the resistance of a second wire, made of the same material, that is half as long and has half the diameter?
-221 ILW A common flashlight bulb is rated at 0.30 A and 2.9 V (the values of the current and voltage under operating conditions). If the resistance of the tungsten bulb filament at room temperature $\left(20^{\circ} \mathrm{C}\right)$ is $1.1 \Omega$, what is the temperature of the filament when the bulb is on?
$\bullet 22 \Longrightarrow$ Kiting during a storm. The legend that Benjamin Franklin flew a kite as a storm approached is only a legend-he was neither stupid nor suicidal. Suppose a kite string of radius 2.00 mm extends directly upward by 0.800 km and is coated with a 0.500 mm layer of water having resistivity $150 \Omega \cdot \mathrm{~m}$. If the potential difference between the two ends of the string is 160 MV , what is the current through the water layer? The danger is not this current but the chance that the string draws a lightning strike, which can have a current as large as 500000 A (way beyond just being lethal).
$\bullet 23$ When 115 V is applied across a wire that is 10 m long and has a 0.30 mm radius, the magnitude of the current density is $1.4 \times$ $10^{4} \mathrm{~A} / \mathrm{m}^{2}$. Find the resistivity of the wire.
$\bullet 24$ Figure 26-24a gives the magnitude $E(x)$ of the electric fields that have been set up by a battery along a resistive rod of length 9.00 mm (Fig. 26-24b). The vertical scale is set by $E_{s}=4.00 \times 10^{3}$ $\mathrm{V} / \mathrm{m}$. The rod consists of three sections of the same material but with different radii. (The schematic diagram of Fig. 26-24b does not indicate the different radii.) The radius of section 3 is 2.00 mm . What is the radius of (a) section 1 and (b) section 2?


Fig. 26-24 Problem 24.
-25 SSM ILW A wire with a resistance of $6.0 \Omega$ is drawn out through a die so that its new length is three times its original length. Find the resistance of the longer wire, assuming that the resistivity and density of the material are unchanged.
-•26 In Fig. 26-25a, a 9.00 V battery is connected to a resistive


Fig. 26-25 Problem 26.
strip that consists of three sections with the same cross-sectional areas but different conductivities. Figure $26-25 b$ gives the electric potential $V(x)$ versus position $x$ along the strip. The horizontal scale is set by $x_{s}=8.00 \mathrm{~mm}$. Section 3 has conductivity $3.00 \times 10^{7}$ $(\Omega \cdot \mathrm{m})^{-1}$. What is the conductivity of section (a) 1 and (b) 2 ?
$\bullet 27$ SSM Www Two conductors are made of the same material and have the same length. Conductor $A$ is a solid wire of diameter 1.0 mm . Conductor $B$ is a hollow tube of outside diameter 2.0 mm and inside diameter 1.0 mm . What is the resistance ratio $R_{A} / R_{B}$, measured between their ends?
$\bullet 28$ ©o Figure 26-26 gives the electric potential $V(x)$ along a copper wire carrying uniform current, from a point of higher potential $V_{s}=12.0 \mu \mathrm{~V}$ at $x=0$ to a point of zero potential at $x_{s}=3.00 \mathrm{~m}$. The wire has a radius of 2.00 mm . What is the current in the wire?
$\bullet 29$ A potential difference of 3.00 nV is set up across a 2.00 cm


Fig. 26-26 Problem 28. length of copper wire that has a radius of 2.00 mm . How much charge drifts through a cross section in 3.00 ms ?
$\bullet 30$ If the gauge number of a wire is increased by 6 , the diameter is halved; if a gauge number is increased by 1 , the diameter decreases by the factor $2^{1 / 6}$ (see the table in Problem 4). Knowing this, and knowing that 1000 ft of 10-gauge copper wire has a resistance of approximately $1.00 \Omega$, estimate the resistance of 25 ft of 22gauge copper wire.
-•31 An electrical cable consists of 125 strands of fine wire, each having $2.65 \mu \Omega$ resistance. The same potential difference is applied between the ends of all the strands and results in a total current of 0.750 A. (a) What is the current in each strand? (b) What is the applied potential difference? (c) What is the resistance of the cable?
-•32 Earth's lower atmosphere contains negative and positive ions that are produced by radioactive elements in the soil and cosmic rays from space. In a certain region, the atmospheric electric field strength is $120 \mathrm{~V} / \mathrm{m}$ and the field is directed vertically down. This field causes singly charged positive ions, at a density of $620 \mathrm{~cm}^{-3}$, to drift downward and singly charged negative ions, at a density of $550 \mathrm{~cm}^{-3}$, to drift upward (Fig. 26-27). The measured conductivity of the air in that region is $2.70 \times 10^{-14}$ $(\Omega \cdot \mathrm{m})^{-1}$. Calculate (a) the magnitude of the current density and (b) the ion drift speed, assumed to be the same for positive and negative ions.


Fig. 26-27 Problem 32.
-•33 A block in the shape of a rectangular solid has a cross-sectional area of $3.50 \mathrm{~cm}^{2}$ across its width, a front-to-rear length of 15.8 cm , and a resistance of $935 \Omega$. The block's material contains $5.33 \times 10^{22}$ conduction electrons $/ \mathrm{m}^{3}$. A potential difference of 35.8 V is maintained between its front and rear faces. (a) What is the current in the block? (b) If the current density is uniform, what is its magnitude? What are (c) the drift velocity of the conduction electrons and (d) the magnitude of the electric field in the block?
-0034 ©0 Figure 26-28 shows wire section 1 of diameter $D_{1}=4.00 \mathrm{R}$ and wire section 2 of diameter $D_{2}=2.00 R$, connected by a tapered section. The wire is copper and carries a current. Assume that the cur-


Fig. 26-28 Problem 34. rent is uniformly distributed across any cross-sectional area through the wire's width. The electric potential change $V$ along the length $L=2.00 \mathrm{~m}$ shown in section 2 is $10.0 \mu \mathrm{~V}$. The number of charge carriers per unit volume is $8.49 \times 10^{28} \mathrm{~m}^{-3}$. What is the drift speed of the conduction electrons in section 1?
*o035 In Fig. 26-29, current is set up through a truncated right circular cone of resistivity $731 \Omega \cdot \mathrm{~m}$, left radius $a=2.00 \mathrm{~mm}$, right radius $b=2.30 \mathrm{~mm}$, and length $L=1.94 \mathrm{~cm}$. Assume that the current density is uniform across any cross section taken perpendicular to the length. What is the resistance of the cone?


Fig. 26-29 Problem 35.
$0036 \Longrightarrow$ Swimming during a storm. Figure 26-30 shows a swimmer at distance $D=35.0 \mathrm{~m}$ from a lightning strike to the water, with current $I=78 \mathrm{kA}$. The water has resistivity $30 \Omega \cdot \mathrm{~m}$, the width of the swimmer along a radial line from the strike is 0.70 m , and his resistance across that width is $4.00 \mathrm{k} \Omega$. Assume that the current spreads through the water over a hemisphere centered on the strike point. What is the current through the swimmer?


Fig. 26-30 Problem 36.

## sec. 26-6 A Microscopic View of Ohm's Law

$\because 37$ Show that, according to the free-electron model of electrical conduction in metals and classical physics, the resistivity of metals should be proportional to $\sqrt{T}$, where $T$ is the temperature in kelvins. (See Eq. 19-31.)

## sec. 26-7 Power in Electric Circuits

-38 In Fig. 26-31a, a $20 \Omega$ resistor is connected to a battery. Figure
$26-31 b$ shows the increase of thermal energy $E_{\text {th }}$ in the resistor as a function of time $t$. The vertical scale is set by $E_{\mathrm{th}, s}=2.50 \mathrm{~mJ}$, and the horizontal scale is set by $t_{s}=4.0 \mathrm{~s}$. What is the electric potential across the battery?
-39 A certain brand of hot-dog cooker works by applying a potential difference of 120 V across opposite ends of a hot dog and allowing it to cook by means of the thermal energy produced. The current is 10.0 A , and the energy required to cook one hot dog is 60.0 kJ . If the rate at which energy is supplied is unchanged, how long will it take to cook three hot dogs simultaneously?
-40 Thermal energy is produced in a resistor at a rate of 100 W when the current is 3.00 A . What is the resistance?
-41 SSM A 120 V potential difference is applied to a space heater whose resistance is $14 \Omega$ when hot. (a) At what rate is electrical energy transferred to thermal energy? (b) What is the cost for 5.0 h at $\mathrm{US} \$ 0.05 / \mathrm{kW} \cdot \mathrm{h}$ ?
-42 In Fig. 26-32, a battery of potential difference $V=12 \mathrm{~V}$ is connected to a resistive strip of resistance $R=6.0 \Omega$. When an electron moves through the strip from one end to the other, (a) in which direction in the figure does the electron move, (b) how much work is done on the electron by the electric field in the strip, and (c) how much energy is


Fig. 26-32 Problem 42. transferred to the thermal energy of the strip by the electron?
-43 ILW An unknown resistor is connected between the terminals of a 3.00 V battery. Energy is dissipated in the resistor at the rate of 0.540 W . The same resistor is then connected between the terminals of a 1.50 V battery. At what rate is energy now dissipated?
-44 A student kept his $9.0 \mathrm{~V}, 7.0 \mathrm{~W}$ radio turned on at full volume from 9:00 p.m. until 2:00 A.m. How much charge went through it?
$\bullet 45$ SSM ILW A 1250 W radiant heater is constructed to operate at 115 V . (a) What is the current in the heater when the unit is operating? (b) What is the resistance of the heating coil? (c) How much thermal energy is produced in 1.0 h ?
-046 (60 A copper wire of cross-sectional area $2.00 \times 10^{-6} \mathrm{~m}^{2}$ and length 4.00 m has a current of 2.00 A uniformly distributed across that area. (a) What is the magnitude of the electric field along the wire? (b) How much electrical energy is transferred to thermal energy in 30 min ?
-•47 A heating element is made by maintaining a potential difference of 75.0 V across the length of a Nichrome wire that has a $2.60 \times$ $10^{-6} \mathrm{~m}^{2}$ cross section. Nichrome has a resistivity of $5.00 \times 10^{-7} \Omega \cdot \mathrm{~m}$. (a) If the element dissipates 5000 W , what is its length? (b) If 100 V is used to obtain the same dissipation rate, what should the length be? $\bullet 48 \Longrightarrow$ Exploding shoes. The rain-soaked shoes of a person may explode if ground current from nearby lightning vaporizes the water. The sudden conversion of water to water vapor causes a dramatic expansion that can rip apart shoes. Water has density 1000
$\mathrm{kg} / \mathrm{m}^{3}$ and requires $2256 \mathrm{~kJ} / \mathrm{kg}$ to be vaporized. If horizontal current lasts 2.00 ms and encounters water with resistivity $150 \Omega \cdot \mathrm{~m}$, length 12.0 cm , and vertical cross-sectional area $15 \times 10^{-5} \mathrm{~m}^{2}$, what average current is required to vaporize the water?
$\bullet 49$ A 100 W lightbulb is plugged into a standard 120 V outlet. (a) How much does it cost per 31-day month to leave the light turned on continuously? Assume electrical energy costs US $\$ 0.06 / \mathrm{kW} \cdot \mathrm{h}$. (b) What is the resistance of the bulb? (c) What is the current in the bulb?
$\bullet 50$ The current through the battery and resistors 1 and 2 in Fig. 26-33a is 2.00 A . Energy is transferred from the current to thermal energy $E_{\mathrm{th}}$ in both resistors. Curves 1 and 2 in Fig. 26-33b give that thermal energy $E_{\mathrm{th}}$ for resistors 1 and 2, respectively, as a function of time $t$. The vertical scale is set by $E_{\mathrm{th}, s}=40.0 \mathrm{~mJ}$, and the horizontal scale is set by $t_{s}=5.00 \mathrm{~s}$. What is the power of the battery?
(a)


(b)
$t$ (s)

Fig. 26-33 Problem 50.

- 51 ssm www Wire $C$ and wire $D$ are made from different materials and have length $L_{C}=$ $L_{D}=1.0 \mathrm{~m}$. The resistivity and diameter of wire $C$ are $2.0 \times 10^{-6}$ $\Omega \cdot \mathrm{m}$ and 1.00 mm , and those of wire $D$ are $1.0 \times 10^{-6} \Omega \cdot \mathrm{~m}$ and


Fig. 26-34 Problem 51. 0.50 mm . The wires are joined as shown in Fig. 26-34, and a current of 2.0 A is set up in them. What is the electric potential difference between (a) points 1 and 2 and (b) points 2 and 3 ? What is the rate at which energy is dissipated between (c) points 1 and 2 and (d) points 2 and 3 ?

- 52 so The current-density magnitude in a certain circular wire is $J=\left(2.75 \times 10^{10} \mathrm{~A} / \mathrm{m}^{4}\right) r^{2}$, where $r$ is the radial distance out to the wire's radius of 3.00 mm . The potential applied to the wire (end to end) is 60.0 V . How much energy is converted to thermal energy in 1.00 h ?
$\bullet 53$ A 120 V potential difference is applied to a space heater that dissipates 500 W during operation. (a) What is its resistance during operation? (b) At what rate do electrons flow through any cross section of the heater element?
$\bullet \bullet 54$ Figure 26-35a shows a rod of resistive material. The resistance per unit length of the rod increases in the positive direction of the $x$ axis. At any position $x$ along the rod, the resistance $d R$ of a narrow (differential) section of width $d x$ is given by $d R=5.00 x d x$, where $d R$ is in ohms and $x$ is in meters. Figure $26-35 b$ shows such a narrow section. You are to slice off


Fig. 26-35 Problem 54.
a length of the rod between $x=0$ and some position $x=L$ and then connect that length to a battery with potential difference $V=$ 5.0 V (Fig. 26-35c). You want the current in the length to transfer energy to thermal energy at the rate of 200 W . At what position $x=$ $L$ should you cut the rod?

## Additional Problems

55 SSM A Nichrome heater dissipates 500 W when the applied potential difference is 110 V and the wire temperature is $800^{\circ} \mathrm{C}$. What would be the dissipation rate if the wire temperature were held at $200^{\circ} \mathrm{C}$ by immersing the wire in a bath of cooling oil? The applied potential difference remains the same, and $\alpha$ for Nichrome at $800^{\circ} \mathrm{C}$ is $4.0 \times 10^{-4} \mathrm{~K}^{-1}$.

56 A potential difference of 1.20 V will be applied to a 33.0 m length of 18 -gauge copper wire (diameter $=0.0400$ in.). Calculate (a) the current, (b) the magnitude of the current density, (c) the magnitude of the electric field within the wire, and (d) the rate at which thermal energy will appear in the wire.
57 An 18.0 W device has 9.00 V across it. How much charge goes through the device in 4.00 h ?
58 An aluminum rod with a square cross section is 1.3 m long and 5.2 mm on edge. (a) What is the resistance between its ends? (b) What must be the diameter of a cylindrical copper rod of length 1.3 m if its resistance is to be the same as that of the aluminum rod?
59 A cylindrical metal rod is 1.60 m long and 5.50 mm in diameter. The resistance between its two ends (at $20^{\circ} \mathrm{C}$ ) is $1.09 \times$ $10^{-3} \Omega$. (a) What is the material? (b) A round disk, 2.00 cm in diameter and 1.00 mm thick, is formed of the same material. What is the resistance between the round faces, assuming that each face is an equipotential surface?
$60 \Longrightarrow$ The chocolate crumb mystery. This story begins with Problem 60 in Chapter 23 and continues through Chapters 24 and 25. The chocolate crumb powder moved to the silo through a pipe of radius $R$ with uniform speed $v$ and uniform charge density $\rho$. (a) Find an expression for the current $i$ (the rate at which charge on the powder moved) through a perpendicular cross section of the pipe. (b) Evaluate $i$ for the conditions at the factory: pipe radius $R=5.0 \mathrm{~cm}$, speed $v=2.0 \mathrm{~m} / \mathrm{s}$, and charge density $\rho=1.1 \times$ $10^{-3} \mathrm{C} / \mathrm{m}^{3}$.

If the powder were to flow through a change $V$ in electric potential, its energy could be transferred to a spark at the rate $P=$ $i V$. (c) Could there be such a transfer within the pipe due to the radial potential difference discussed in Problem 70 of Chapter 24?

As the powder flowed from the pipe into the silo, the electric potential of the powder changed. The magnitude of that change was at least equal to the radial potential difference within the pipe (as evaluated in Problem 70 of Chapter 24). (d) Assuming that value for the potential difference and using the current found in (b) above, find the rate at which energy could have been transferred from the powder to a spark as the powder exited the pipe. (e) If a spark did occur at the exit and lasted for 0.20 s (a reasonable expectation), how much energy would have been transferred to the spark?

Recall from Problem 60 in Chapter 23 that a minimum energy transfer of 150 mJ is needed to cause an explosion. (f) Where did the powder explosion most likely occur: in the powder cloud at the unloading bin (Problem 60 of Chapter 25), within the pipe, or at the exit of the pipe into the silo?

61 SSM A steady beam of alpha particles $(q=+2 e)$ traveling with constant kinetic energy 20 MeV carries a current of $0.25 \mu \mathrm{~A}$. (a) If the beam is directed perpendicular to a flat surface, how many alpha particles strike the surface in 3.0 s ? (b) At any instant, how many alpha particles are there in a given 20 cm length of the beam? (c) Through what potential difference is it necessary to accelerate each alpha particle from rest to bring it to an energy of 20 MeV ?
62 A resistor with a potential difference of 200 V across it transfers electrical energy to thermal energy at the rate of 3000 W . What is the resistance of the resistor?
63 A 2.0 kW heater element from a dryer has a length of 80 cm . If a 10 cm section is removed, what power is used by the now shortened element at 120 V ?

64 A cylindrical resistor of radius 5.0 mm and length 2.0 cm is made of material that has a resistivity of $3.5 \times 10^{-5} \Omega \cdot \mathrm{~m}$. What are (a) the magnitude of the current density and (b) the potential difference when the energy dissipation rate in the resistor is 1.0 W ?
65 A potential difference $V$ is applied to a wire of cross-sectional area $A$, length $L$, and resistivity $\rho$. You want to change the applied potential difference and stretch the wire so that the energy dissipation rate is multiplied by 30.0 and the current is multiplied by 4.00 . Assuming the wire's density does not change, what are (a) the ratio of the new length to $L$ and (b) the ratio of the new cross-sectional area to $A$ ?
66 The headlights of a moving car require about 10 A from the 12 V alternator, which is driven by the engine. Assume the alternator is $80 \%$ efficient (its output electrical power is $80 \%$ of its input mechanical power), and calculate the horsepower the engine must supply to run the lights.

67 A 500 W heating unit is designed to operate with an applied potential difference of 115 V . (a) By what percentage will its heat output drop if the applied potential difference drops to 110 V ? Assume no change in resistance. (b) If you took the variation of resistance with temperature into account, would the actual drop in heat output be larger or smaller than that calculated in (a)?
68 The copper windings of a motor have a resistance of $50 \Omega$ at $20^{\circ} \mathrm{C}$ when the motor is idle. After the motor has run for several hours, the resistance rises to $58 \Omega$. What is the temperature of the windings now? Ignore changes in the dimensions of the windings. (Use Table 26-1.)

69 How much electrical energy is transferred to thermal energy in 2.00 h by an electrical resistance of $400 \Omega$ when the potential applied across it is 90.0 V ?
70 A caterpillar of length 4.0 cm crawls in the direction of electron drift along a $5.2-\mathrm{mm}$-diameter bare copper wire that carries a uniform current of 12 A . (a) What is the potential difference between the two ends of the caterpillar? (b) Is its tail positive or negative relative to its head? (c) How much time does the caterpillar take to crawl 1.0 cm if it crawls at the drift speed of the electrons in the wire? (The number of charge carriers per unit volume is $8.49 \times$ $10^{28} \mathrm{~m}^{-3}$.)
71 Ssm (a) At what temperature would the resistance of a copper conductor be double its resistance at $20.0^{\circ} \mathrm{C}$ ? (Use $20.0^{\circ} \mathrm{C}$ as the reference point in Eq. 26-17; compare your answer with Fig. 26-10.) (b) Does this same "doubling temperature" hold for all copper conductors, regardless of shape or size?
72 A steel trolley-car rail has a cross-sectional area of $56.0 \mathrm{~cm}^{2}$. What is the resistance of 10.0 km of rail? The resistivity of the steel is $3.00 \times 10^{-7} \Omega \cdot \mathrm{~m}$.
73 A coil of current-carrying Nichrome wire is immersed in a liquid. (Nichrome is a nickel-chromium-iron alloy commonly used in heating elements.) When the potential difference across the coil is 12 V and the current through the coil is 5.2 A , the liquid evaporates at the steady rate of $21 \mathrm{mg} / \mathrm{s}$. Calculate the heat of vaporization of the liquid (see Section 18-8).
74 © The current density in a wire is uniform and has magnitude $2.0 \times 10^{6} \mathrm{~A} / \mathrm{m}^{2}$, the wire's length is 5.0 m , and the density of conduction electrons is $8.49 \times 10^{28} \mathrm{~m}^{-3}$. How long does an electron take (on the average) to travel the length of the wire?

75 A certain x-ray tube operates at a current of 7.00 mA and a potential difference of 80.0 kV . What is its power in watts?
76 A current is established in a gas discharge tube when a sufficiently high potential difference is applied across the two electrodes in the tube. The gas ionizes; electrons move toward the positive terminal and singly charged positive ions toward the negative terminal. (a) What is the current in a hydrogen discharge tube in which $3.1 \times 10^{18}$ electrons and $1.1 \times 10^{18}$ protons move past a cross-sectional area of the tube each second? (b) Is the direction of the current density $\vec{J}$ toward or away from the negative terminal?

