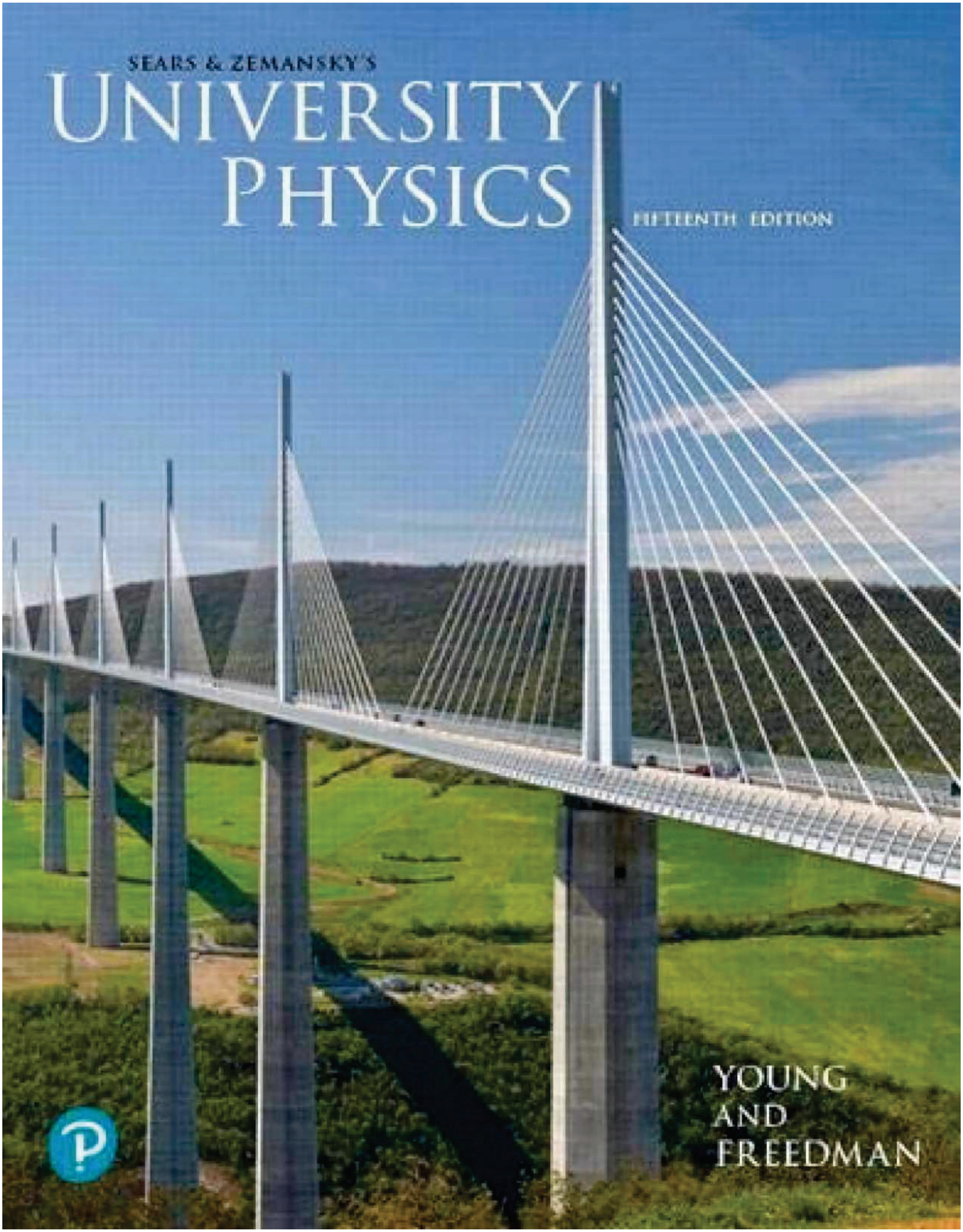


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? In flash photography, the energy used to make the flash is stored in a capacitor, which consists of two closely spaced conductors that carry opposite charges. If the amount of charge on the conductors is doubled, by what factor does the stored energy increase? (i) $\sqrt{2}$; (ii) 2; (iii) $2\sqrt{2}$; (iv) 4; (v) 8.

# 24 Capacitance and Dielectrics

When you stretch the rubber band of a slingshot or pull back the string of an archer's bow, you are storing mechanical energy as elastic potential energy. A capacitor is a device that stores *electric* potential energy and electric charge. To make a capacitor, just insulate two conductors from each other. To store energy in this device, transfer charge from one conductor to the other so that one has a negative charge and the other has an equal amount of positive charge. Work must be done to move the charges through the resulting potential difference between the conductors, and the work done is stored as electric potential energy.

Capacitors have a tremendous number of practical applications in devices such as electronic flash units for photography, mobile phones, airbag sensors for cars, and radio and television receivers. We'll encounter many of these applications in later chapters (particularly Chapter 31, in which we'll see the crucial role played by capacitors in the alternating-current circuits that pervade our technological society). In this chapter, however, our emphasis is on the fundamental properties of capacitors. For a particular capacitor, the ratio of the charge on each conductor to the potential difference between the conductors is a constant, called the *capacitance*. The capacitance depends on the sizes and shapes of the conductors and on the insulating material (if any) between them. Compared to the case in which there is only vacuum between the conductors, the capacitance increases when an insulating material (a *dielectric*) is present. This happens because a redistribution of charge, called *polarization,* takes place within the insulating material. Studying polarization will give us added insight into the electrical properties of matter.

Capacitors also give us a new way to think about electric potential energy. The energy stored in a charged capacitor is related to the electric field in the space between the conductors. We'll see that electric potential energy can be regarded as being stored *in the field itself.* The idea that the electric field is itself a storehouse of energy is at the heart of the theory of electromagnetic waves and our modern understanding of the nature of light, to be discussed in Chapter 32.

## LEARNING OUTCOMES

***In this chapter, you'll learn...***

**24.1** The nature of capacitors, and how to calculate a quantity that measures their ability to store charge.
**24.2** How to analyze capacitors connected in a network.
**24.3** How to calculate the amount of energy stored in a capacitor.
**24.4** What dielectrics are, and how they make capacitors more effective.
**24.5** How a dielectric inside a charged capacitor becomes polarized.
**24.6** How to use Gauss's laws when dielectrics are present.

***You'll need to review...***

**21.2, 21.5, 21.7** Polarization; field of charged conductors; electric dipoles.
**22.3–22.5** Gauss's law.
**23.3, 23.4** Potential for charged conductors; potential due to a cylindrical charge distribution.



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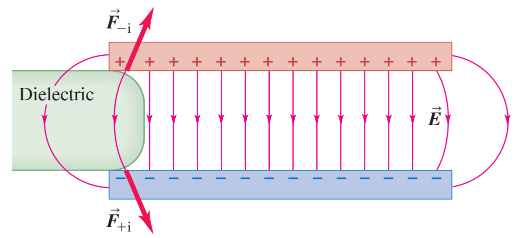
**EVALUATE** We can check our answer for $u_0$ by noting that the volume between the plates is $V_{between} = (0.200\ m^2)(0.0100\ m) = 0.00200\ m^3$. Since the electric field between the plates is uniform, $u_0$ is uniform as well and the energy density is just the stored energy divided by the volume:

$$u_0 = \frac{U_0}{V_{between}} = \frac{7.97 \times 10^{-4}\ J}{0.00200\ m^3} = 0.398\ J/m^3$$

This agrees with our earlier answer. You can use the same approach to check our result for $u$.

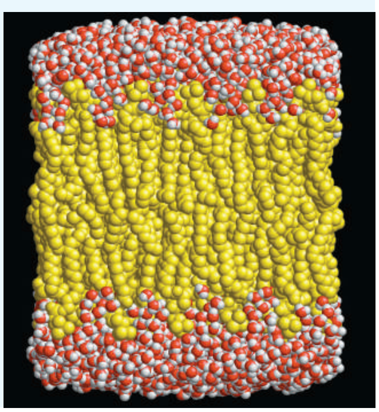
In general, when a dielectric is inserted into a capacitor while the charge on each plate remains the same, the permittivity $\epsilon$ increases by a factor of $K$ (the dielectric constant), and the electric field $E$ and the energy density $u = \frac{1}{2}\epsilon E^2$ decrease by a factor of $1/K$. Where does the energy go? The answer lies in the fringing field at the edges of a real parallel-plate capacitor. As **Fig. 24.16** shows, that field tends to pull the dielectric into the space between the plates, doing work on it as it does so. We could attach a spring to the left end of the dielectric in Fig. 24.16 and use this force to stretch the spring. Because work is done by the field, the field energy density decreases.

Figure 24.16 The fringing field at the edges of the capacitor exerts forces $\vec{F}_{-i}$ and $\vec{F}_{+i}$ on the negative and positive induced surface charges of a dielectric, pulling the dielectric into the capacitor.




**KEYCONCEPT** Adding a dielectric (with dielectric constant $K$) that fills the space between the plates of a capacitor reduces the electric field, the electric energy density, and the total stored energy, all by a factor of $1/K$.

**BIO APPLICATION Dielectric Cell Membrane** The membrane of a living cell behaves like a dielectric between the plates of a capacitor. The membrane is made of two sheets of lipid molecules, with their water-insoluble ends in the middle and their water-soluble ends (shown in red) on the outer surfaces. Conductive fluids on either side of the membrane (water with negative ions inside the cell, water with positive ions outside) act as charged capacitor plates, and the nonconducting membrane acts as a dielectric with $K$ of about 10. The potential difference $V$ across the membrane is about 0.07 V and the membrane thickness $d$ is about $7 \times 10^{-9}$ m, so the electric field $E = V/d$ in the membrane is about $10^7$ V/m—close to the dielectric strength of the membrane. If the membrane were made of air, $V$ and $E$ would be larger by a factor of $K \approx 10$ and dielectric breakdown would occur.



## Dielectric Breakdown

We mentioned earlier that when a dielectric is subjected to a sufficiently strong electric field, *dielectric breakdown* takes place and the dielectric becomes a conductor. This occurs when the electric field is so strong that electrons are ripped loose from their molecules and crash into other molecules, liberating even more electrons. This avalanche of moving charge forms a spark or arc discharge. Lightning is a dramatic example of dielectric breakdown in air.

Because of dielectric breakdown, capacitors always have maximum voltage ratings. When a capacitor is subjected to excessive voltage, an arc may form through a layer of dielectric, burning or melting a hole in it. This arc creates a conducting path (a short circuit) between the conductors. If a conducting path remains after the arc is extinguished, the device is rendered permanently useless as a capacitor.

The maximum electric-field magnitude that a material can withstand without the occurrence of breakdown is called its **dielectric strength.** This quantity is affected significantly by temperature, trace impurities, small irregularities in the metal electrodes, and other factors that are difficult to control. For this reason we can give only approximate figures for dielectric strengths. The dielectric strength of dry air is about $3 \times 10^6$ V/m. **Table 24.2** lists the dielectric strengths of a few common insulating materials. All of the values are substantially greater than the value for air. For example, a layer of polycarbonate 0.01 mm thick (about the smallest practical thickness) has 10 times the dielectric strength of air and can withstand a maximum voltage of about $(3 \times 10^7\ V/m)(1 \times 10^{-5}\ m) = 300$ V.

**TABLE 24.2** Dielectric Constant and Dielectric Strength of Some Insulating Materials

| Material | Dielectric Constant, $K$ | Dielectric Strength, $E_m$ (V/m) |
|---|---|---|
| Polycarbonate | 2.8 | $3 \times 10^7$ |
| Polyester | 3.3 | $6 \times 10^7$ |
| Polypropylene | 2.2 | $7 \times 10^7$ |
| Polystyrene | 2.6 | $2 \times 10^7$ |
| Pyrex® glass | 4.7 | $1 \times 10^7$ |

? In a flashlight, how does the amount of current that flows out of the bulb compare to the amount that flows into the bulb? (i) Current out is less than current in; (ii) current out is greater than current in; (iii) current out equals current in; (iv) the answer depends on the brightness of the bulb.

# 25 Current, Resistance, and Electromotive Force

## LEARNING OUTCOMES

***In this chapter, you'll learn...***

**25.1** The meaning of electric current, and how charges move in a conductor.
**25.2** What is meant by the resistivity and conductivity of a substance.
**25.3** How to calculate the resistance of a conductor from its dimensions and its resistivity.
**25.4** How an electromotive force (emf) makes it possible for current to flow in a circuit.
**25.5** How to do calculations involving energy and power in circuits.
**25.6** How to use a simple model to understand the flow of current in metals.

***You'll need to review...***

**17.7** Thermal conductivity.
**23.2** Voltmeters, electric field, and electric potential.
**24.4** Dielectric breakdown in insulators.

In the past four chapters we studied the interactions of electric charges *at rest;* now we're ready to study charges *in motion*. An *electric current* consists of charges in motion from one region to another. If the charges follow a conducting path that forms a closed loop, the path is called an *electric circuit*.

Fundamentally, electric circuits are a means for conveying *energy* from one place to another. As charged particles move within a circuit, electric potential energy is transferred from a source (such as a battery or generator) to a device in which that energy is either stored or converted to another form: into sound in a stereo system or into heat and light in a toaster or light bulb. Electric circuits are useful because they allow energy to be transported without any moving parts (other than the moving charged particles themselves). They are at the heart of computers, television transmitters and receivers, and household and industrial power distribution systems. Your nervous system is a specialized electric circuit that carries vital signals from one part of your body to another.

In Chapter 26 we'll see how to analyze electric circuits and examine some practical applications of circuits. To prepare you for that, in this chapter we'll examine the basic properties of electric currents. We'll begin by describing the nature of electric conductors and considering how they are affected by temperature. We'll learn why a short, fat, cold copper wire is a better conductor than a long, skinny, hot steel wire. We'll study the properties of batteries and see how they cause current and energy transfer in a circuit. In this analysis we'll use the concepts of current, potential difference (or voltage), resistance, and electromotive force. Finally, we'll look at electric current in a material from a microscopic viewpoint.



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In many simple circuits, such as flashlights or cordless electric drills, the direction of the current is always the same; this is called *direct current*. But home appliances such as toasters, refrigerators, and televisions use *alternating current,* in which the current continuously changes direction. In this chapter we'll consider direct current only. Alternating current has many special features worthy of detailed study, which we'll examine in Chapter 31.

### EXAMPLE 25.1 Current density and drift velocity in a wire

An 18 gauge copper wire (the size usually used for lamp cords), with a diameter of 1.02 mm, carries a constant current of 1.67 A to a 200 W lamp. The free-electron density in the wire is $8.5 \times 10^{28}$ per cubic meter. Find (a) the current density and (b) the drift speed.

**IDENTIFY and SET UP** This problem uses the relationships among current $I$, current density $J$, and drift speed $v_d$. We are given $I$ and the wire diameter $d$, so we use Eq. (25.3) to find $J$. We use Eq. (25.3) again to find $v_d$ from $J$ and the known electron density $n$.

**EXECUTE** (a) The cross-sectional area is

$$A = \frac{\pi d^2}{4} = \frac{\pi(1.02 \times 10^{-3}\ \text{m})^2}{4} = 8.17 \times 10^{-7}\ \text{m}^2$$

The magnitude of the current density is then

$$J = \frac{I}{A} = \frac{1.67\ \text{A}}{8.17 \times 10^{-7}\ \text{m}^2} = 2.04 \times 10^6\ \text{A/m}^2$$

(b) From Eq. (25.3) for the drift velocity magnitude $v_d$, we find

$$v_d = \frac{J}{n|q|} = \frac{2.04 \times 10^6\ \text{A/m}^2}{(8.5 \times 10^{28}\ \text{m}^{-3})|-1.60 \times 10^{-19}\ \text{C}|}$$
$$= 1.5 \times 10^{-4}\ \text{m/s} = 0.15\ \text{mm/s}$$

**EVALUATE** At this speed an electron would require 6700 s (almost 2 h) to travel 1 m along this wire. The speeds of random motion of the electrons are roughly $10^6$ m/s, around $10^{10}$ times the drift speed. Picture the electrons as bouncing around frantically, with a very slow drift!

**KEYCONCEPT** Current is the rate at which electric charge flows through an area, and current density is the current per unit area. Current density is proportional to the concentration of moving charged particles, the charge per particle, and the drift speed of the particles.

**TEST YOUR UNDERSTANDING OF SECTION 25.1** Suppose we replaced the wire in Example 25.1 with 12 gauge copper wire, which has twice the diameter of 18 gauge wire. If the current remains the same, what effect would this have on the drift speed $v_d$? (i) None—$v_d$ would be unchanged; (ii) $v_d$ would be twice as great; (iii) $v_d$ would be four times greater; (iv) $v_d$ would be half as great; (v) $v_d$ would be one-fourth as great.

**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 RESISTIVITY

The current density $\vec{J}$ in a conductor depends on the electric field $\vec{E}$ and on the properties of the material. In general, this dependence can be quite complex. But for some materials, especially metals, at a given temperature, $\vec{J}$ is nearly *directly proportional* to $\vec{E}$, and the ratio of the magnitudes of $E$ and $J$ is constant. This relationship, called Ohm's law, was discovered in 1826 by the German physicist Georg Simon Ohm (1787–1854). The word "law" should actually be in quotation marks, since **Ohm's law,** like the ideal-gas equation and Hooke's law, is an *idealized model* that describes the behavior of some materials quite well but is not a general description of *all* matter. In the following discussion we'll assume that Ohm's law is valid, even though there are many situations in which it is not.

We define the **resistivity** $\rho$ of a material as

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

Resistivity of a material ($\rho$); $E$: Magnitude of electric field in material; $J$: Magnitude of current density caused by electric field

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**TABLE 25.1** Resistivities at Room Temperature (20°C)

| | Substance | $\rho\ (\Omega \cdot m)$ | Substance | $\rho\ (\Omega \cdot m)$ |
|---|---|---|---|---|
| **Conductors** | | | **Semiconductors** | |
| Metals | Silver | $1.47 \times 10^{-8}$ | Pure carbon (graphite) | $3.5 \times 10^{-5}$ |
| | Copper | $1.72 \times 10^{-8}$ | Pure germanium | 0.60 |
| | Gold | $2.44 \times 10^{-8}$ | Pure silicon | 2300 |
| | Aluminum | $2.75 \times 10^{-8}$ | **Insulators** | |
| | Tungsten | $5.25 \times 10^{-8}$ | Amber | $5 \times 10^{14}$ |
| | Steel | $20 \times 10^{-8}$ | Glass | $10^{10}$–$10^{14}$ |
| | Lead | $22 \times 10^{-8}$ | Lucite | $>10^{13}$ |
| | Mercury | $95 \times 10^{-8}$ | Mica | $10^{11}$–$10^{15}$ |
| Alloys | Manganin (Cu 84%, Mn 12%, Ni 4%) | $44 \times 10^{-8}$ | Quartz (fused) | $75 \times 10^{16}$ |
| | Constantan (Cu 60%, Ni 40%) | $49 \times 10^{-8}$ | Sulfur | $10^{15}$ |
| | Nichrome | $100 \times 10^{-8}$ | Teflon | $>10^{13}$ |
| | | | Wood | $10^{8}$–$10^{11}$ |

The greater the resistivity, the greater the field needed to cause a given current density, or the smaller the current density caused by a given field. From Eq. (25.5) the units of $\rho$ are $(V/m)/(A/m^2) = V \cdot m/A$. As we'll discuss in Section 25.3, 1 V/A is called one *ohm* (1 $\Omega$; the Greek letter $\Omega$, omega, is alliterative with "ohm"). So the SI units for $\rho$ are $\Omega \cdot m$ (ohm-meters). **Table 25.1** lists some representative values of resistivity. A perfect conductor would have zero resistivity, and a perfect insulator would have an infinite resistivity. Metals and alloys have the smallest resistivities and are the best conductors. The resistivities of insulators are greater than those of the metals by an enormous factor, on the order of $10^{22}$.

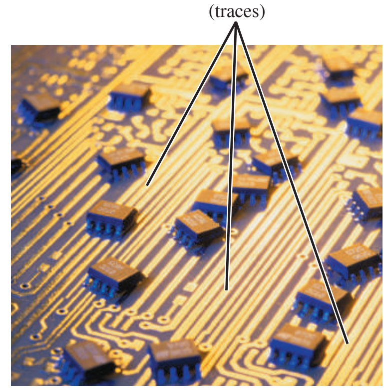
The reciprocal of resistivity is **conductivity.** Its units are $(\Omega \cdot m)^{-1}$. Good conductors of electricity have larger conductivity than insulators. Conductivity is the direct electrical analog of thermal conductivity. Comparing Table 25.1 with Table 17.5 (Thermal Conductivities), we note that good electrical conductors, such as metals, are usually also good conductors of heat. Poor electrical conductors, such as ceramic and plastic materials, are also poor thermal conductors. In a metal the free electrons that carry charge in electrical conduction also provide the principal mechanism for heat conduction, so we should expect a correlation between electrical and thermal conductivity. Because of the enormous difference in conductivity between electrical conductors and insulators, it is easy to confine electric currents to well-defined paths or circuits (**Fig. 25.5**). The variation in *thermal* conductivity is much less, only a factor of $10^3$ or so, and it is usually impossible to confine heat currents to that extent.

*Semiconductors* have resistivities intermediate between those of metals and those of insulators. These materials are important because of the way their resistivities are affected by temperature and by small amounts of impurities.

A material that obeys Ohm's law reasonably well is called an *ohmic* conductor or a *linear* conductor. For such materials, at a given temperature, $\rho$ is a *constant* that does not depend on the value of $E$. Many materials show substantial departures from Ohm's-law behavior; they are *nonohmic,* or *nonlinear.* In these materials, $J$ depends on $E$ in a more complicated manner.

Analogies with fluid flow can be a big help in developing intuition about electric current and circuits. For example, in the making of wine or maple syrup, the product is sometimes filtered to remove sediments. A pump forces the fluid through the filter under pressure; if the flow rate (analogous to $J$) is proportional to the pressure difference between the upstream and downstream sides (analogous to $E$), the behavior is analogous to Ohm's law.

Figure **25.5** The copper "wires," or traces, on this circuit board are printed directly onto the surface of the dark-colored insulating board. Even though the traces are very close to each other (only about a millimeter apart), the board has such a high resistivity (and low conductivity) that essentially no current can flow between the traces.




## Resistivity and Temperature

The resistivity of a *metallic* conductor nearly always increases with increasing temperature, as shown in **Fig. 25.6a** (next page). As temperature increases, the ions of the conductor vibrate with greater amplitude, making it more likely that a moving electron will

**TEST YOUR UNDERSTANDING OF SECTION 25.2** You maintain a constant electric field inside a piece of semiconductor while lowering the semiconductor's temperature. What happens to the current density in the semiconductor? (i) It increases; (ii) it decreases; (iii) it remains the same.

**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 RESISTANCE

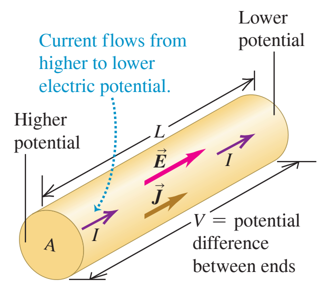
For a conductor with resistivity $\rho$, the current density $\vec{J}$ at a point where the electric field is $\vec{E}$ is given by Eq. (25.5), which we can write as

$$\vec{E} = \rho \vec{J} \tag{25.7}$$

When Ohm's law is obeyed, $\rho$ is constant and independent of the magnitude of the electric field, so $\vec{E}$ is directly proportional to $\vec{J}$. Often, however, we are more interested in the total current $I$ in a conductor than in $\vec{J}$ and more interested in the potential difference $V$ between the ends of the conductor than in $\vec{E}$. This is so largely because $I$ and $V$ are much easier to measure than are $\vec{J}$ and $\vec{E}$.

Suppose our conductor is a wire with uniform cross-sectional area $A$ and length $L$, as shown in **Fig. 25.7**. Let $V$ be the potential difference between the higher-potential and lower-potential ends of the conductor, so that $V$ is positive. (Another name for $V$ is the voltage across the conductor.) The *direction* of the current is always from the higher-potential end to the lower-potential end. That's because current in a conductor flows in the direction of $\vec{E}$, no matter what the sign of the moving charges (Fig. 25.2), and because $\vec{E}$ points in the direction of *decreasing* electric potential (see Section 23.2). As the current flows through the potential difference, electric potential energy is lost; this energy is transferred to the ions of the conducting material during collisions.

Figure **25.7** A conductor with uniform cross section. The current density is uniform over any cross section, and the electric field is constant along the length.




We can also relate the *value* of the current $I$ to the potential difference between the ends of the conductor. If the magnitudes of the current density $\vec{J}$ and the electric field $\vec{E}$ are uniform throughout the conductor, the total current $I$ is $I = JA$, and the potential difference $V$ between the ends is $V = EL$. We solve these equations for $J$ and $E$, respectively, and substitute the results into Eq. (25.7):

$$\frac{V}{L} = \frac{\rho I}{A} \quad \text{or} \quad V = \frac{\rho L}{A} I \tag{25.8}$$

This shows that when $\rho$ is constant, the total current $I$ is proportional to the potential difference $V$.

The ratio of $V$ to $I$ for a particular conductor is called its **resistance** $R$:

$$R = \frac{V}{I} \tag{25.9}$$

Comparing this definition of $R$ to Eq. (25.8), we see that

**Resistance of a conductor** $$R = \frac{\rho L}{A} \tag{25.10}$$
($\rho$: Resistivity of conductor material; $L$: Length of conductor; $A$: Cross-sectional area of conductor)

If $\rho$ is constant, as is the case for ohmic materials, then so is $R$.

The following equation is often called Ohm's law:

**Relationship among voltage, current, and resistance:** $$V = IR \tag{25.11}$$
($V$: Voltage between ends of conductor; $R$: Resistance of conductor; $I$: Current in conductor)

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However, it's important to understand that the real content of Ohm's law is the direct proportionality (for some materials) of $V$ to $I$ or of $J$ to $E$. Equation (25.9) or (25.11) *defines* resistance $R$ for *any* conductor, but only when $R$ is constant can we correctly call this relationship Ohm's law.

## Interpreting Resistance

Equation (25.10) shows that the resistance of a wire or other conductor of uniform cross section is directly proportional to its length and inversely proportional to its cross-sectional area. It is also proportional to the resistivity of the material of which the conductor is made.

The flowing-fluid analogy is again useful. In analogy to Eq. (25.10), a narrow water hose offers more resistance to flow than a fat one, and a long hose has more resistance than a short one (**Fig. 25.8**). We can increase the resistance to flow by stuffing the hose with cotton or sand; this corresponds to increasing the resistivity. The flow rate is approximately proportional to the pressure difference between the ends. Flow rate is analogous to current, and pressure difference is analogous to potential difference (voltage). Let's not stretch this analogy too far, though; the water flow rate in a pipe is usually *not* proportional to its cross-sectional area (see Section 14.6).

Figure **25.8** A long fire hose offers substantial resistance to water flow. To make water pass through the hose rapidly, the upstream end of the hose must be at much higher pressure than the end where the water emerges. In an analogous way, there must be a large potential difference between the ends of a long wire in order to cause a substantial electric current through the wire.

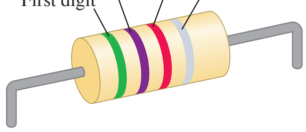
The SI unit of resistance is the **ohm,** equal to one volt per ampere $(1\ \Omega = 1\ \text{V/A})$. The *kilohm* $(1\ \text{k}\Omega = 10^3\ \Omega)$ and the *megohm* $(1\ \text{M}\Omega = 10^6\ \Omega)$ are also in common use. A 100 m length of 12 gauge copper wire, the size usually used in household wiring, has a resistance at room temperature of about 0.5 $\Omega$. A 100 W, 120 V incandescent light bulb has a resistance (at operating temperature) of 140 $\Omega$. If the same current $I$ flows in both the copper wire and the light bulb, the potential difference $V = IR$ is much greater across the light bulb, and much more potential energy is lost per charge in the light bulb. This lost energy is converted by the light bulb filament into light and heat. You don't want your household wiring to glow white-hot, so its resistance is kept low by using wire of low resistivity and large cross-sectional area.

Because the resistivity of a material varies with temperature, the resistance of a specific conductor also varies with temperature. For temperature ranges that are not too great, this variation is approximately linear, analogous to Eq. (25.6):

$$R(T) = R_0[1 + \alpha(T - T_0)] \tag{25.12}$$

In this equation, $R(T)$ is the resistance at temperature $T$ and $R_0$ is the resistance at temperature $T_0$, often taken to be 0°C or 20°C. The *temperature coefficient of resistance* $\alpha$ is the same constant that appears in Eq. (25.6) if the dimensions $L$ and $A$ in Eq. (25.10) do not change appreciably with temperature; this is indeed the case for most conducting materials. Within the limits of validity of Eq. (25.12), the *change* in resistance resulting from a temperature change $T - T_0$ is given by $R_0\alpha(T - T_0)$.

Figure **25.9** This resistor has a resistance of 5.7 k$\Omega$ with an accuracy (tolerance) of $\pm 10\%$.




A circuit device made to have a specific value of resistance between its ends is called a **resistor.** Resistors in the range 0.01 to $10^7\ \Omega$ can be bought off the shelf. Individual resistors used in electronic circuitry are often cylindrical, a few millimeters in diameter and length, with wires coming out of the ends. The resistance may be marked with a standard code that uses three or four color bands near one end (**Fig. 25.9**), according to the scheme in **Table 25.3**. The first two bands (starting with the band nearest an end) are digits, and the third is a power-of-10 multiplier. For example, green–violet–red means $57 \times 10^2\ \Omega$, or 5.7 k$\Omega$. The fourth band, if present, indicates the accuracy (tolerance) of the value; no band means $\pm 20\%$, a silver band $\pm 10\%$, and a gold band $\pm 5\%$. Another important characteristic of a resistor is the maximum *power* it can dissipate without damage. We'll return to this point in Section 25.5.

**TABLE 25.3** Color Codes for Resistors

| Color | Value as Digit | Value as Multiplier |
|---|---|---|
| Black | 0 | 1 |
| Brown | 1 | 10 |
| Red | 2 | $10^2$ |
| Orange | 3 | $10^3$ |
| Yellow | 4 | $10^4$ |
| Green | 5 | $10^5$ |
| Blue | 6 | $10^6$ |
| Violet | 7 | $10^7$ |
| Gray | 8 | $10^8$ |
| White | 9 | $10^9$ |

For a resistor that obeys Ohm's law, a graph of current as a function of potential difference (voltage) is a straight line (**Fig. 25.10a**). The slope of the line is $1/R$. If the sign of the potential difference changes, so does the sign of the current produced; in Fig. 25.7 this corresponds to interchanging the higher- and lower-potential ends of the conductor, so the electric field, current density, and current all reverse direction.

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