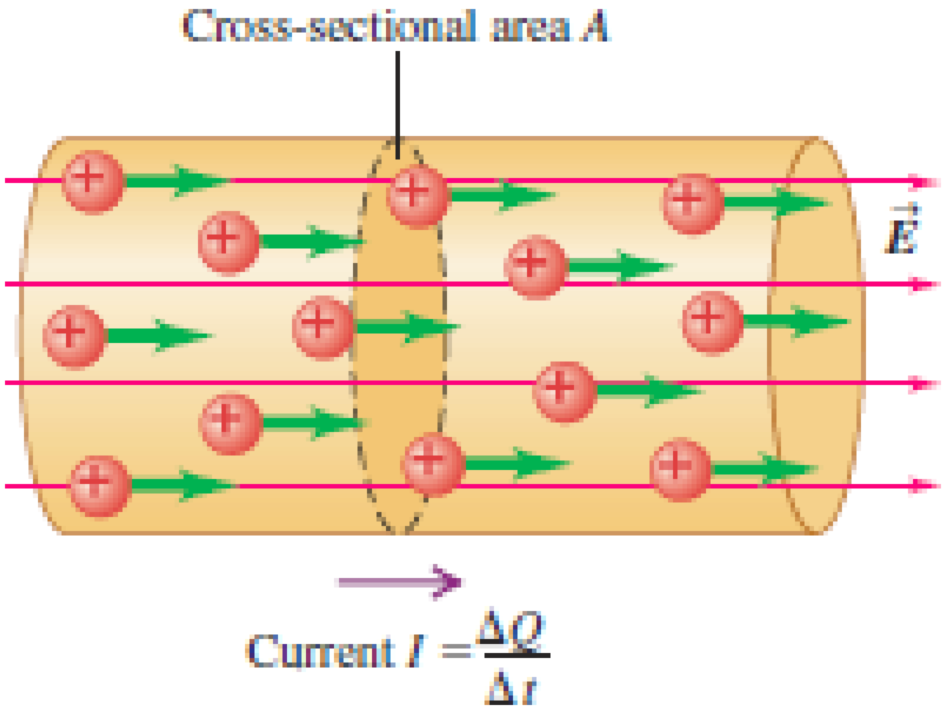
19 Current, Resistance, and Direct-Current Circuits

19.1 Current
Charges in motion

In this chapter, we shift our emphasis to situations in which non-zero electric fields exist inside conductors, causing motion of the mobile charges within the conductors. A current (also called *electric current*) is any motion of charge from one region of a conductor to another.



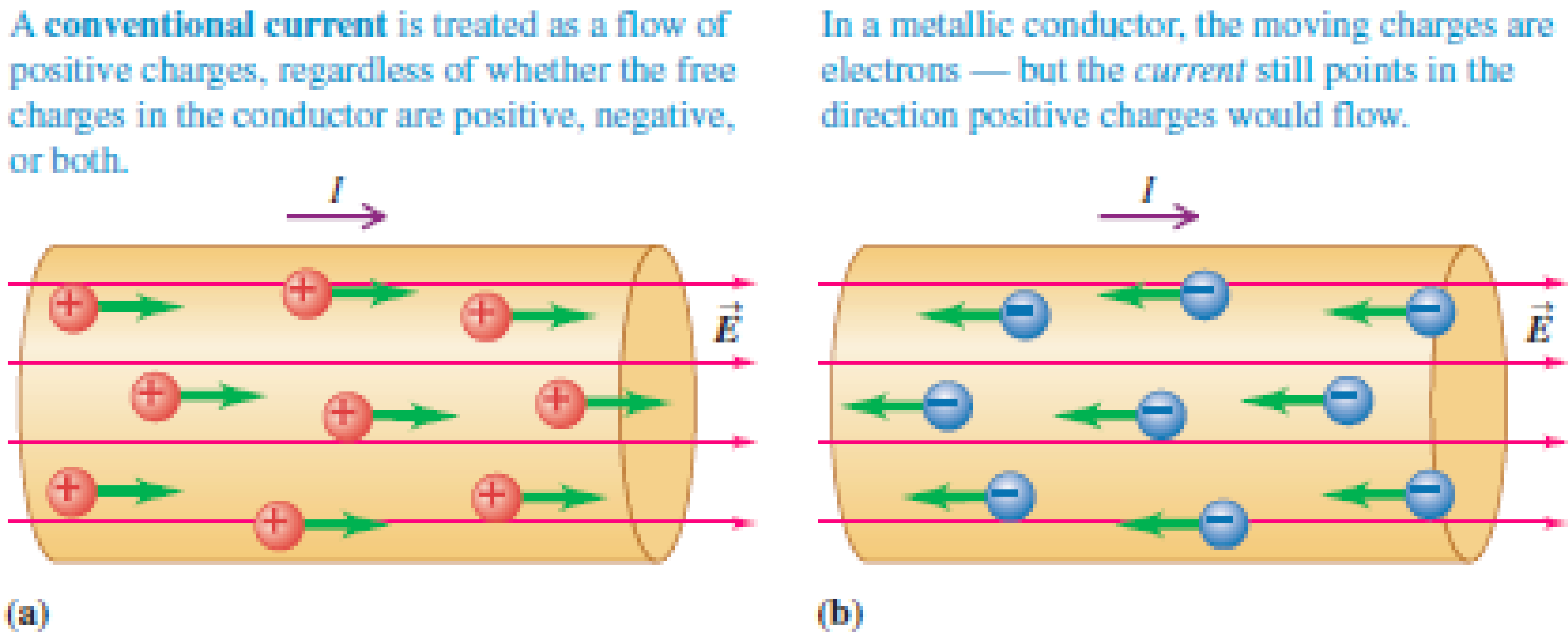
Definition of current

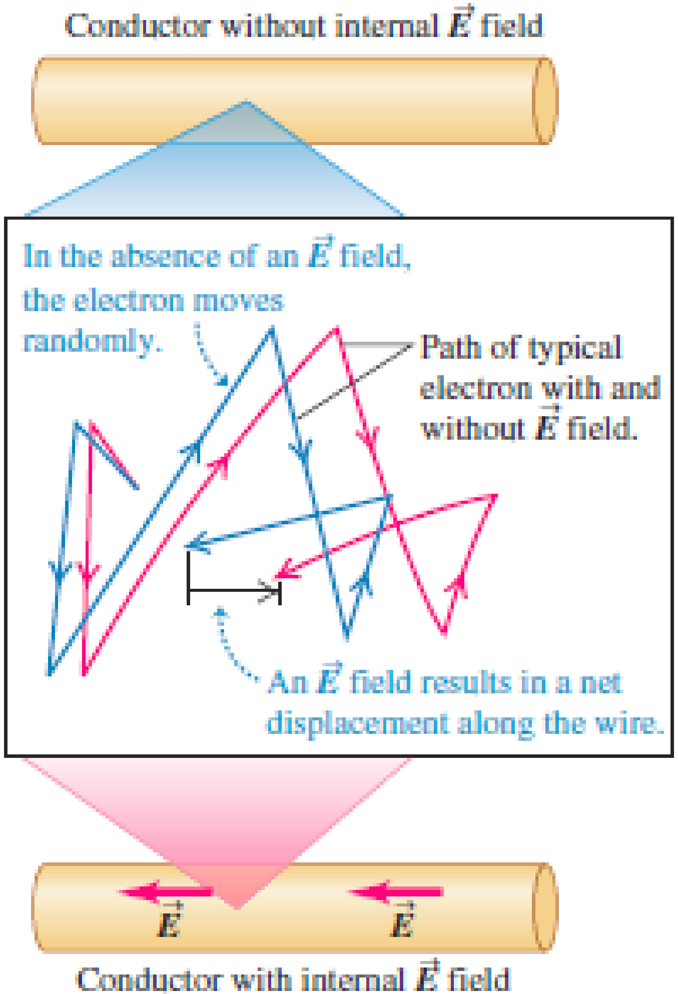
When a net charge ΔQ passes through a cross section of conductor during time Δt, the current is

$$I = \frac{\Delta Q}{\Delta t}. \tag{19.1}$$

Unit: 1 coulomb/second = 1 C/s = 1 ampere = 1 A.

Current is a *scalar* quantity. The SI unit of current is the **ampere**


A **conventional current** is treated as a flow of positive charges, regardless of whether the free charges in the conductor are positive, negative, or both.
I
$\vec{E}$
(a)
In a metallic conductor, the moving charges are electrons — but the *current* still points in the direction positive charges would flow.
I
$\vec{E}$
(b)



▲ **FIGURE 19.3** The presence of an electric field imposes a small drift (greatly exaggerated here) on an electron's random motion.

The current at any instant is the same at all cross sections.

When you turn on a light switch, the light comes on almost instantaneously because the electric fields in the conductors travel with a speed approaching the speed of light. You don't have to wait for individual electrons to travel from the switch to the bulb!

EXAMPLE 19.1 How many electrons?

One of the circuits in a small portable CD player operates on a current of 2.5 mA. How many electrons enter and leave this part of the player in 1.0 s?

SET UP Conservation of charge tells us that when a steady current flows, the same amount of current enters and leaves the player per unit time.

SOLVE We use the current to find the total charge that flows in 1.0 s. We have

$$I = \frac{\Delta Q}{\Delta t}, \quad \text{so}$$

$$\Delta Q = I\,\Delta t = (2.5 \times 10^{-3}\ \text{A})(1.0\ \text{s}) = 2.5 \times 10^{-3}\ \text{C}.$$

Each electron has charge of magnitude $e = 1.60 \times 10^{-19}$ C. The number N of electrons is the total charge ΔQ, divided by the magnitude of the charge e of one electron:

$$N = \frac{\Delta Q}{e} = \frac{2.5 \times 10^{-3}\ \text{C}}{1.60 \times 10^{-19}\ \text{C}} = 1.6 \times 10^{16}.$$

19.2 Resistance and Ohm's Law

Definition of resistance

When the potential difference V between the ends of a conductor is proportional to the current I in the conductor, the ratio V/I is called the resistance of the conductor:

$$R = \frac{V}{I}. \tag{19.2}$$

Unit: The SI unit of resistance is the **ohm,** equal to 1 volt per ampere. The ohm is abbreviated with a capital Greek omega, Ω. Thus, $1\ \Omega = 1\ \mathrm{V/A}$. The *kilohm* $(1\ \mathrm{k}\Omega = 10^3\ \Omega)$ and the *megohm* $(1\ \mathrm{M}\Omega = 10^6\ \Omega)$ are also in common use.

Ohm's law

The potential difference V between the ends of a conductor is proportional to the current I through the conductor; the proportionality factor is the resistance R.

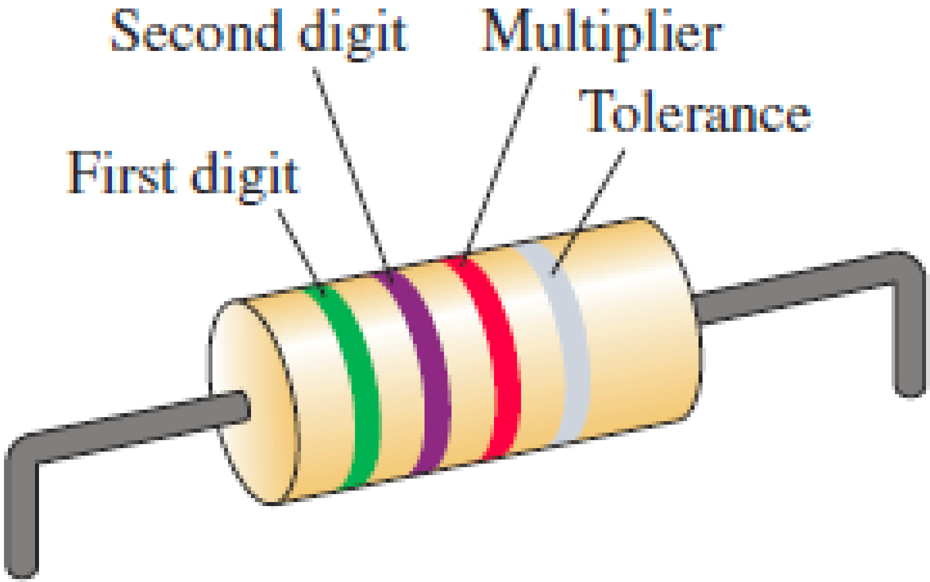
Ohm's Law

For many conductors of electricity, the electric current which will flow through them is directly proportional to the voltage applied to them. When a microscopic view of Ohm's law is taken, it is found to depend upon the fact that the drift velocity of charges through the material is proportional to the electric field in the conductor. The ratio of voltage to current is called the resistance, and if the ratio is constant over a wide range of voltages, the material is said to be an "ohmic" material. If the material can be characterized by such a resistance, then the current can be predicted from the relationship:

Ohm's Law

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

Electric current = Voltage / Resistance



▲ **FIGURE 19.4** Commercial resistors use a code consisting of colored bands to indicate their resistance.

Definition of resistivity

The resistance R is proportional to the length L and inversely proportional to the cross-sectional area A, with a proportionality factor ρ called the **resistivity** of the material. That is,

$$R = \rho \frac{L}{A}, \tag{19.3}$$

where ρ, in general different for different materials, characterizes the conduction properties of a material.

Unit: The SI unit of resistivity is 1 ohm · meter $= 1\ \Omega \cdot \text{m}$.

Resistivity Calculation

The electrical resistance of a wire would be expected to be greater for a longer wire, less for a wire of larger cross sectional area, and would be expected to depend upon the material out of which the wire is made (resistivity). Experimentally, the dependence upon these properties is a straightforward one for a wide range of conditions, and the resistance of a wire can be expressed as

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

TABLE 19.1 Resistivities at room temperature

Substance	ρ ($\Omega \cdot$m)	Substance	ρ ($\Omega \cdot$m)
Conductors:		Mercury	95×10^{-8}
Silver	1.47×10^{-8}	Nichrome alloy	100×10^{-8}
Copper	1.72×10^{-8}	Insulators:	
Gold	2.44×10^{-8}	Glass	$10^{10} - 10^{14}$
Aluminum	2.63×10^{-8}	Lucite	$> 10^{13}$
Tungsten	5.51×10^{-8}	Quartz (fused)	75×10^{16}
Steel	20×10^{-8}	Teflon®	$> 10^{13}$
Lead	22×10^{-8}	Wood	$10^{8} - 10^{11}$

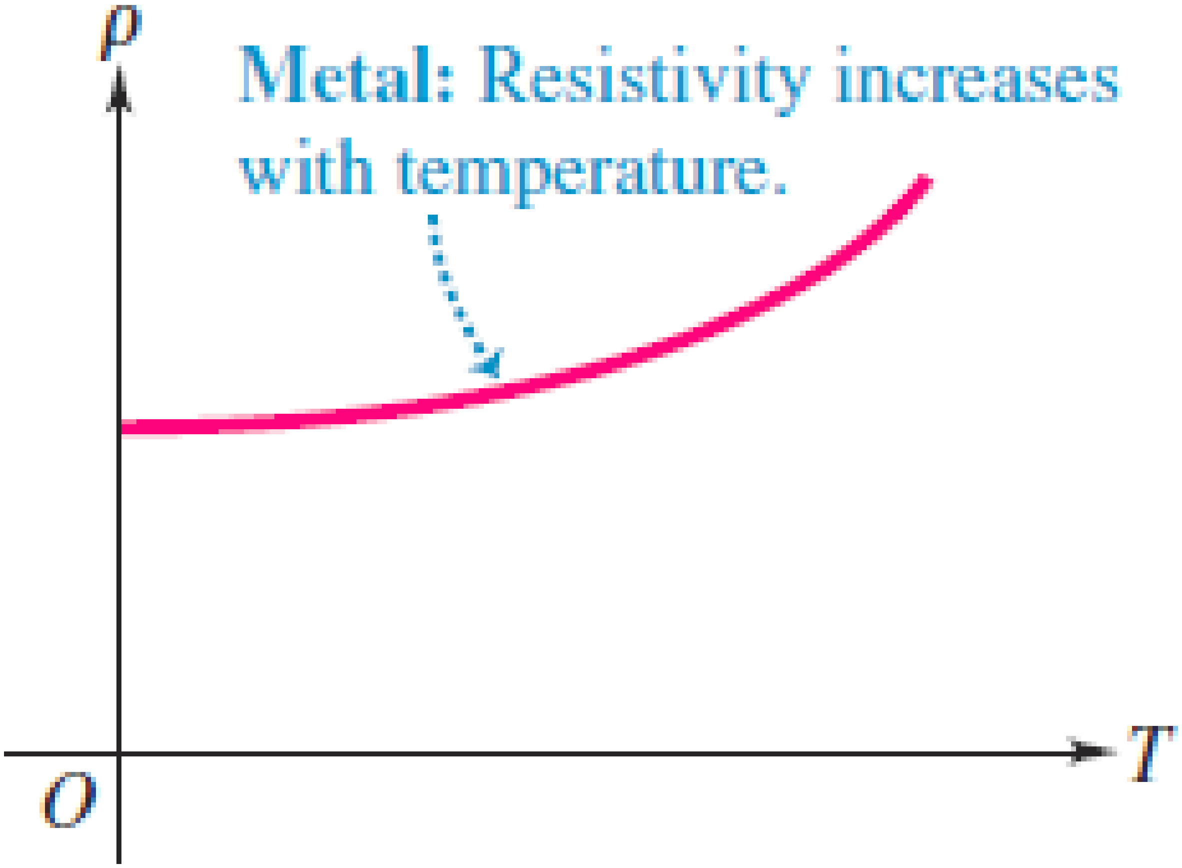
$$R = \rho \frac{L}{A}$$

Temperature Dependence of Resistance

The resistance of every conductor varies somewhat with temperature. The resistivity of a *metallic* conductor nearly always increases with increasing temperature (Figure 19.5a). Over a small temperature range (up to 100 C° or so), the change in resistivity of a metal is approximately proportional to the temperature change. If R_0 is the resistance at a reference temperature T_0 (often taken as 0°C or 20°C) and R_T is the resistance at temperature T, then the variation of R with temperature is described approximately by the equation

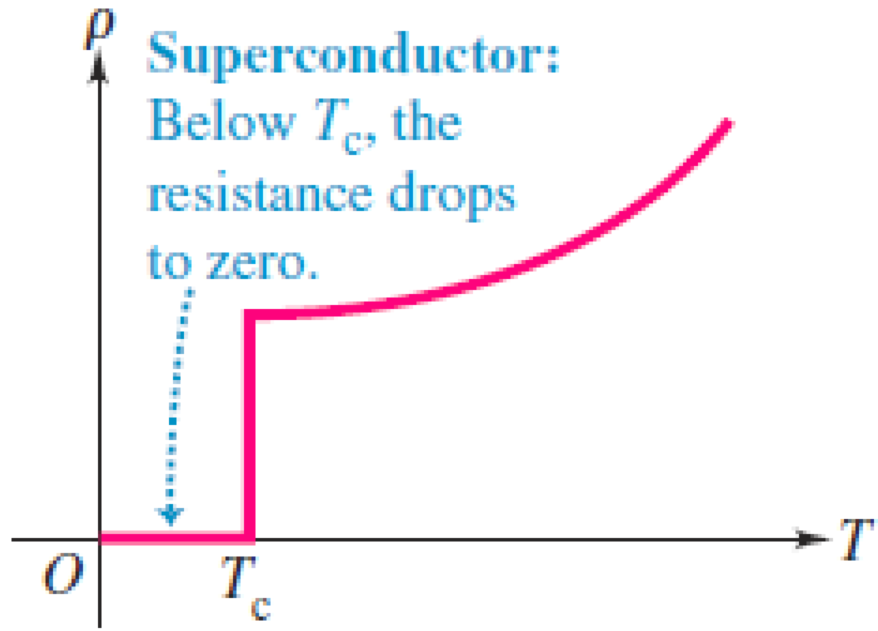
$$R_T = R_0[1 + \alpha(T - T_0)]. \tag{19.4}$$

The factor α is called the **temperature coefficient of resistivity.** For common metals, α typically has a value of 0.003 to 0.005 $(\text{C}°)^{-1}$. That is, an increase in temperature of 1 C° increases the resistance by 0.3% to 0.5%.



$$R_T = R_0[1 + \alpha(T - T_0)].$$

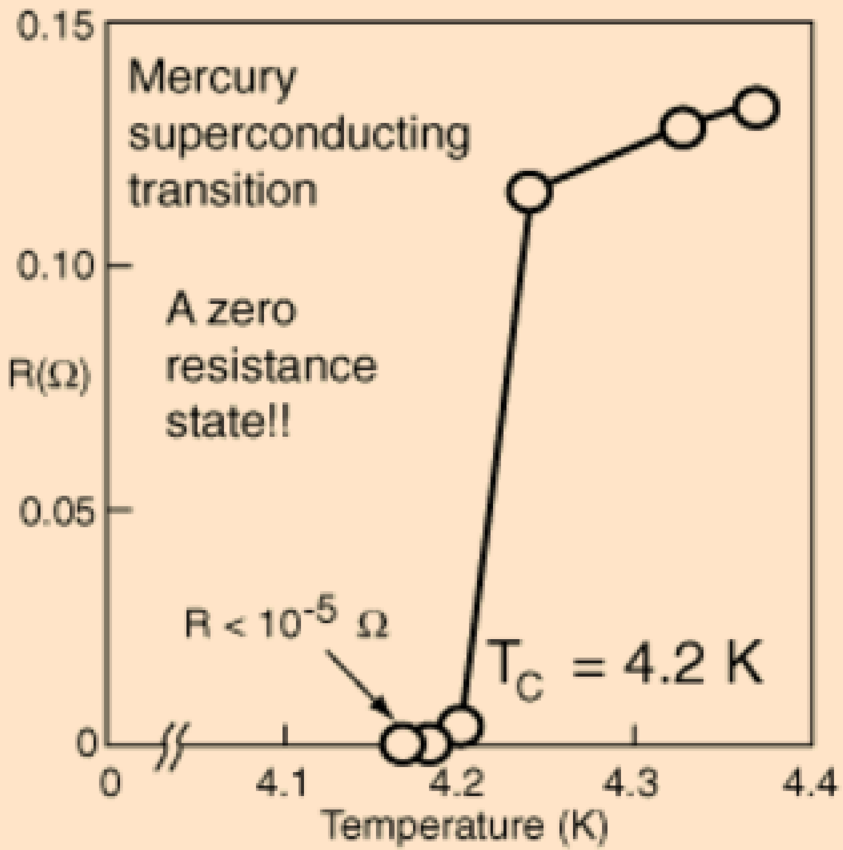
Superconductivity



(b)

▲ **FIGURE 19.6** A maglev train in Shanghai. Maglev ("magnetic-levitation") trains use superconducting electromagnets to create magnetic fields strong enough to levitate a train off the tracks.

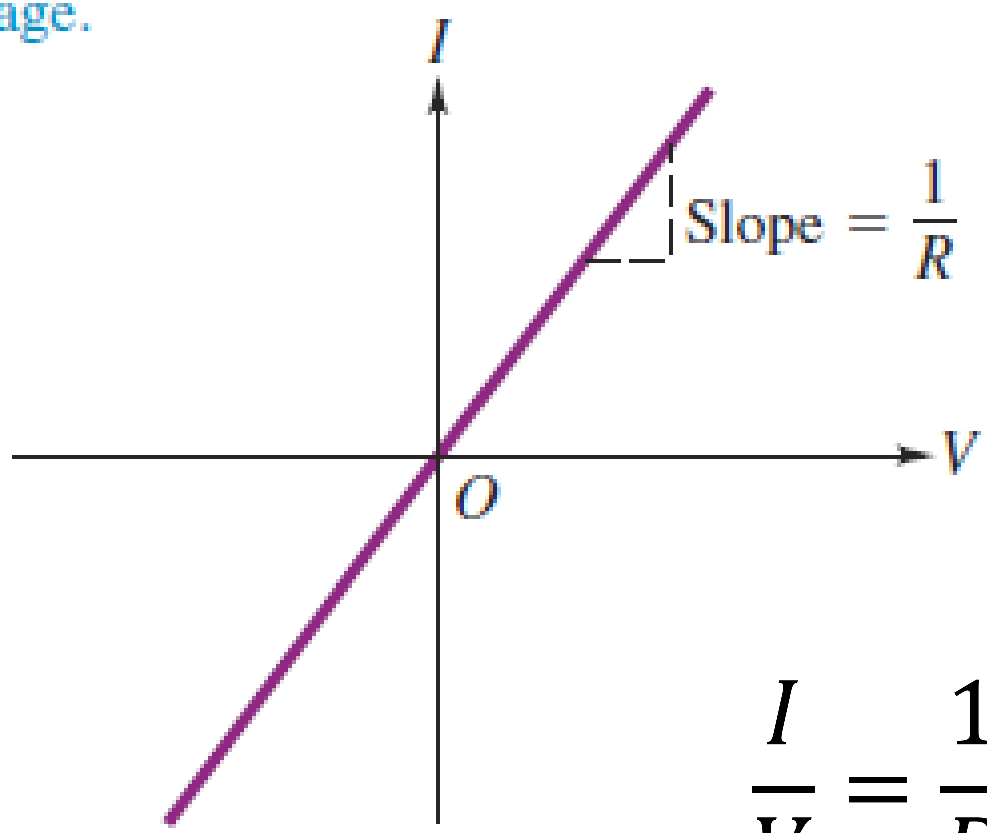
The Discovery of Superconductivity



H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

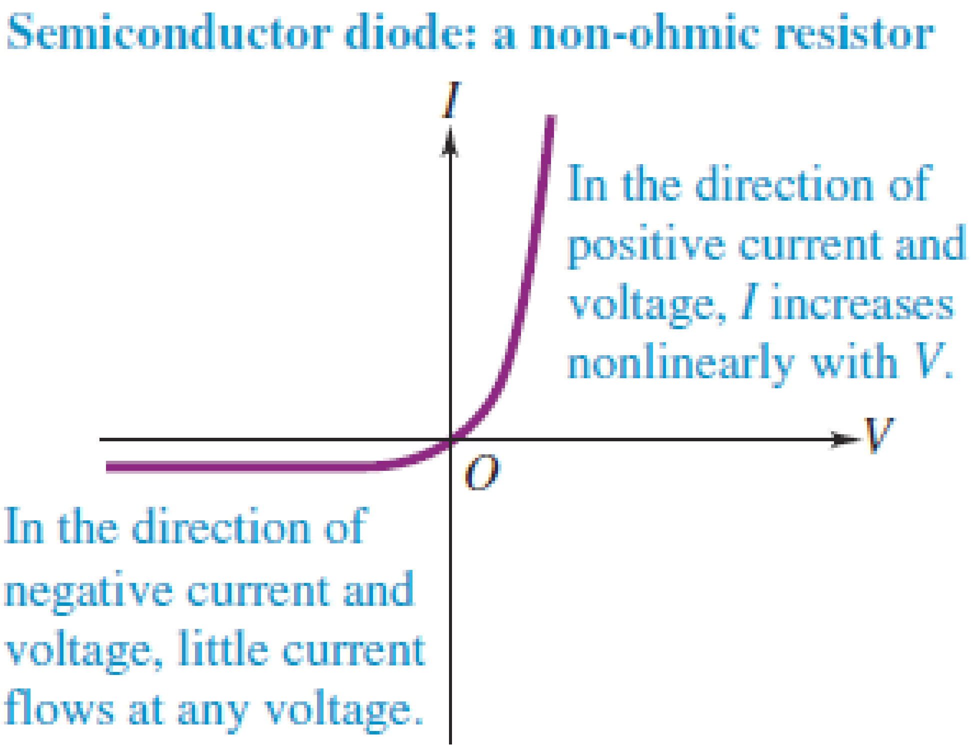
H. Kamerlingh Onnes found that the resistivity of mercury suddenly dropped to zero at 4.2K, a phase transition to a zero resistance state. This phenomenon was called superconductivity, and the temperature at which it occurred is called its critical temperature.

Ohmic resistor (e.g., typical metal wire): At a given temperature, current is proportional to voltage.



$$\frac{I}{V} = \frac{1}{R}$$

Non-ohmic conductors



This is a graph for a semiconductor diode, a device that is decidedly *non*-ohmic. Notice that the resistance of a diode depends on the *direction* of the current. Diodes act like one-way valves for current; they are used to perform a wide variety of logic functions in computer circuitry.

EXAMPLE 19.2 **Resistance in your stereo system**

Suppose you're hooking up a pair of stereo speakers. (a) You happen to have on hand some 20-m-long pieces of 16 gauge copper wire (diameter 1.3 mm); you use them to connect the speakers to the amplifier. These wires are longer than needed, but you just coil up the excess length instead of cutting them. What is the resistance of one of these wires? (b) To improve the performance of the system, you purchase 3.0-m-long speaker cables that are made with 8 gauge copper wire (diameter 3.3 mm). What is the resistance of one of these cables?

SOLUTION

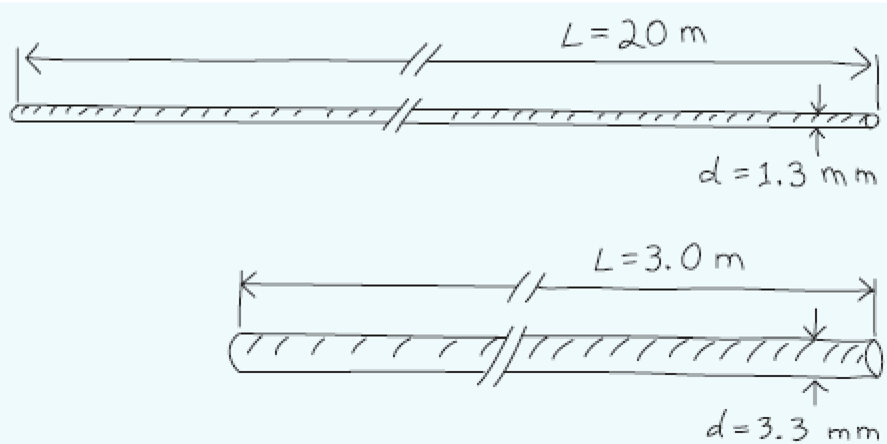
SET UP Figure 19.8 shows our sketch. The resistivity of copper at room temperature is $\rho = 1.72 \times 10^{-8}\ \Omega \cdot \mathrm{m}$ (Table 19.1). The cross-sectional area A of a wire is related to its radius by $A = \pi r^2$.

SOLVE To find the resistances, we use Equation 19.3, $R = \rho L/A$.

Part (a): $$R = \frac{(1.72 \times 10^{-8}\ \Omega \cdot \mathrm{m})(20\ \mathrm{m})}{\pi(6.5 \times 10^{-4}\ \mathrm{m})^2} = 0.26\ \Omega.$$

Part (b): $$R = \frac{(1.72 \times 10^{-8}\ \Omega \cdot \mathrm{m})(3.0\ \mathrm{m})}{\pi(1.65 \times 10^{-3}\ \mathrm{m})^2} = 6.0 \times 10^{-3}\ \Omega.$$

REFLECT The shorter, fatter wires offer over forty times less resistance than the longer, skinnier ones.



▲ **FIGURE 19.8** Our sketch for this problem.

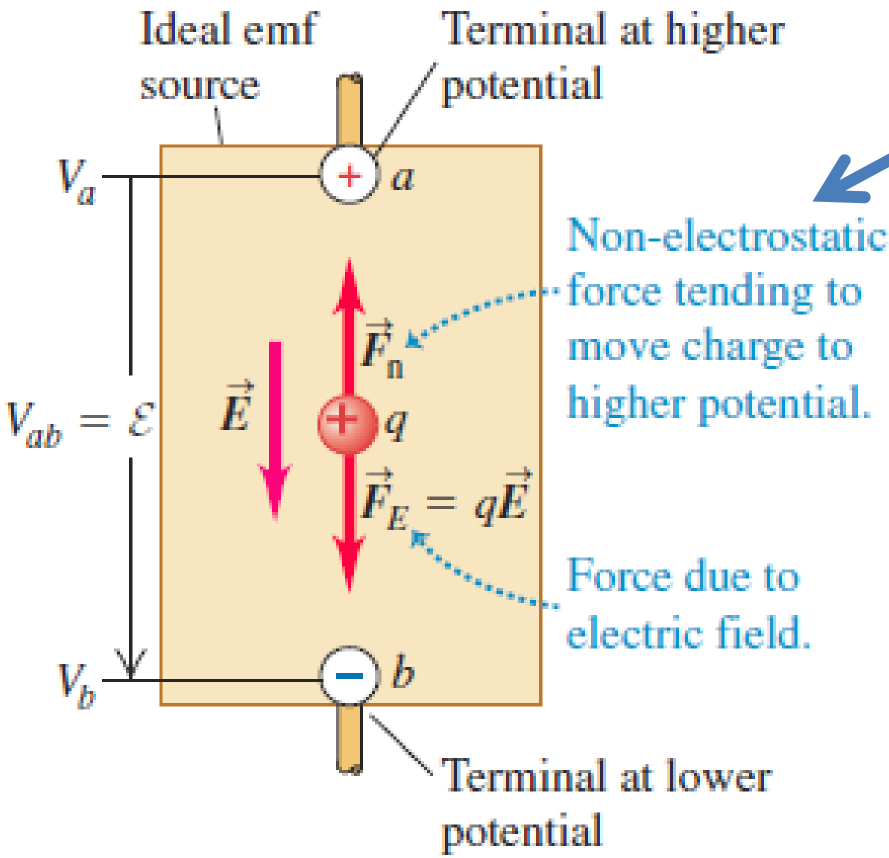
Practice Problem: 14 gauge copper wire has a diameter of 1.6 mm. What length of this wire has a resistance of 1.0 Ω? *Answer:* 120 m.

19.3 Electromotive Force and Circuits

The influence that moves charge from lower to higher potential (despite the electric-field forces in the opposite direction) is called electromotive force (abbreviated emf and pronounced “ee-em-eff”).

A battery with an emf of 1.5 V does 1.5 J of
work on every coulomb of charge that passes through it.

We’ll use the symbol $\mathcal{E}$ for emf.



When the emf source is not part of a closed circuit, $F_n = F_E$ and there is no net motion of charge between the terminals.

The nature of this additional influence depends on the source. In a battery, it is due to chemical processes; in an electric generator, it results from magnetic forces.

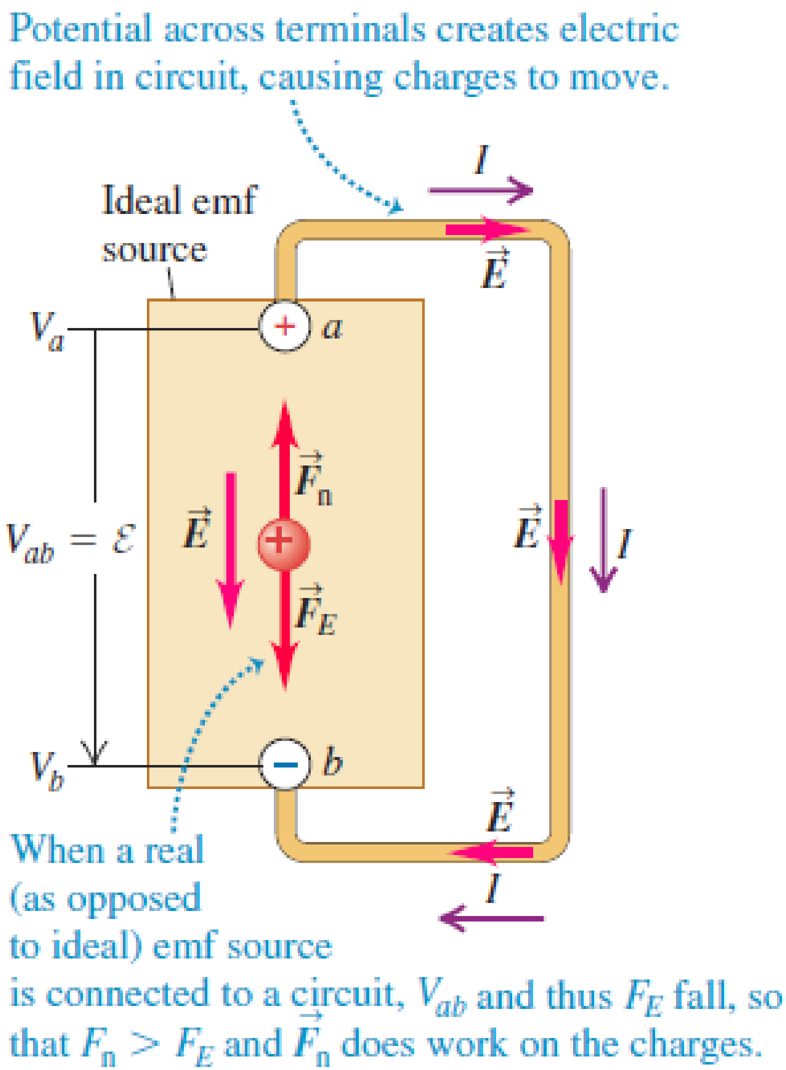


FIGURE 19.11 Schematic diagram of an ideal emf source in a complete circuit.

No complete circuit

$$V_{ab} = \varepsilon$$

Ideal source

$$V_{ab} = \varepsilon = \mathrm{IR}$$

Real source with internal resistance

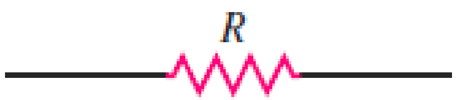
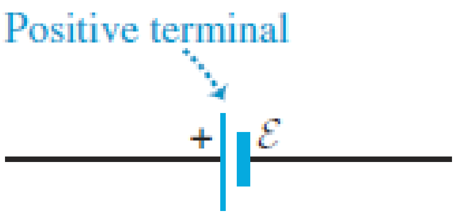
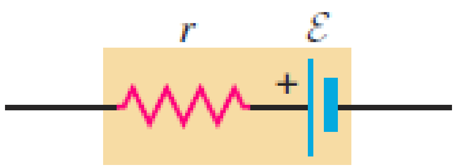
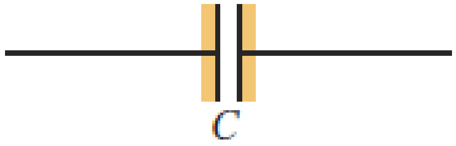
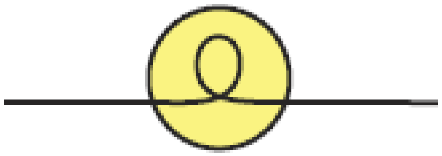
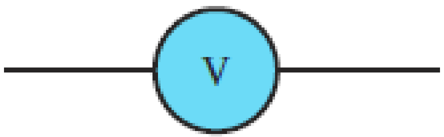
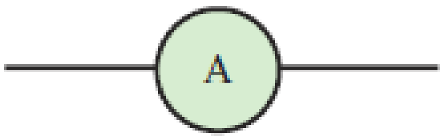
$$V_{ab} = \varepsilon - \mathrm{Ir}$$

Internal Resistance in a Source of emf

Real sources of emf don't behave exactly like the ideal sources we've described because charge that moves through the material of any real source encounters *resistance*. We call this the **internal resistance** of the source, denoted by r. If this resistance behaves according to Ohm's law, r is constant. The current through r has an associated drop in potential equal to Ir. The terminal potential difference V_{ab} is then

$$V_{ab} = \mathcal{E} - Ir. \qquad \text{(source with internal resistance)} \qquad (19.7)$$

TABLE 19.2 Circuit symbols used in this chapter

	Wire with negligible resistance
	Resistor
	emf source
	emf source with internal resistance
	Capacitor
	Switch (open)
	Switch (closed)
	Bulb
	Voltmeter (measures potential difference between its terminals)
	Ammeter (measures current)
	Ground

EXAMPLE 19.5 A dim flashlight

As a flashlight battery ages, its emf stays approximately constant, but its internal resistance increases. A fresh battery has an emf of 1.5 V and negligible internal resistance. When the battery needs replacement, its emf is still 1.5 V, but its internal resistance has increased to 1000 Ω. If this old battery is supplying 1.0 mA to a lightbulb, what is its terminal voltage?

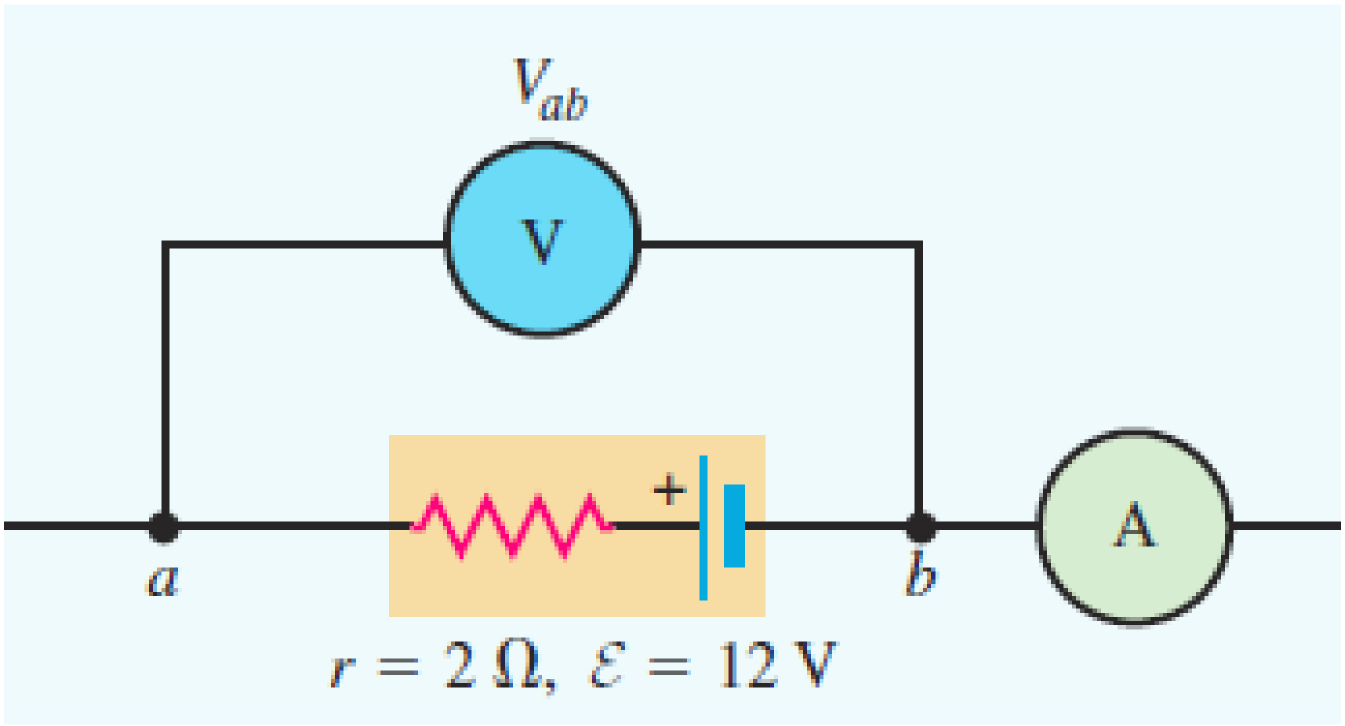
SET UP AND SOLVE The terminal voltage of a new battery is 1.5 V. The terminal voltage of the old, worn-out battery is given by $V_{ab} = \mathcal{E} - Ir$, so

$$V_{ab} = 1.5\ \text{V} - (1.0 \times 10^{-3}\ \text{A})(1000\ \Omega) = 0.5\ \text{V}.$$

It’s important to understand how the meters in the circuit work.

The symbol V in a circle represents an ideal voltmeter. It measures the potential difference between the two points in the circuit where it is connected, but *no current flows through the volt-meter.*
The symbol A in a circle represents an ideal ammeter. It measures the current that flows through it, but *there is no potential difference between its terminals.*

Thus, the behavior of a circuit doesn’t change when an ideal ammeter or voltmeter is connected to it.

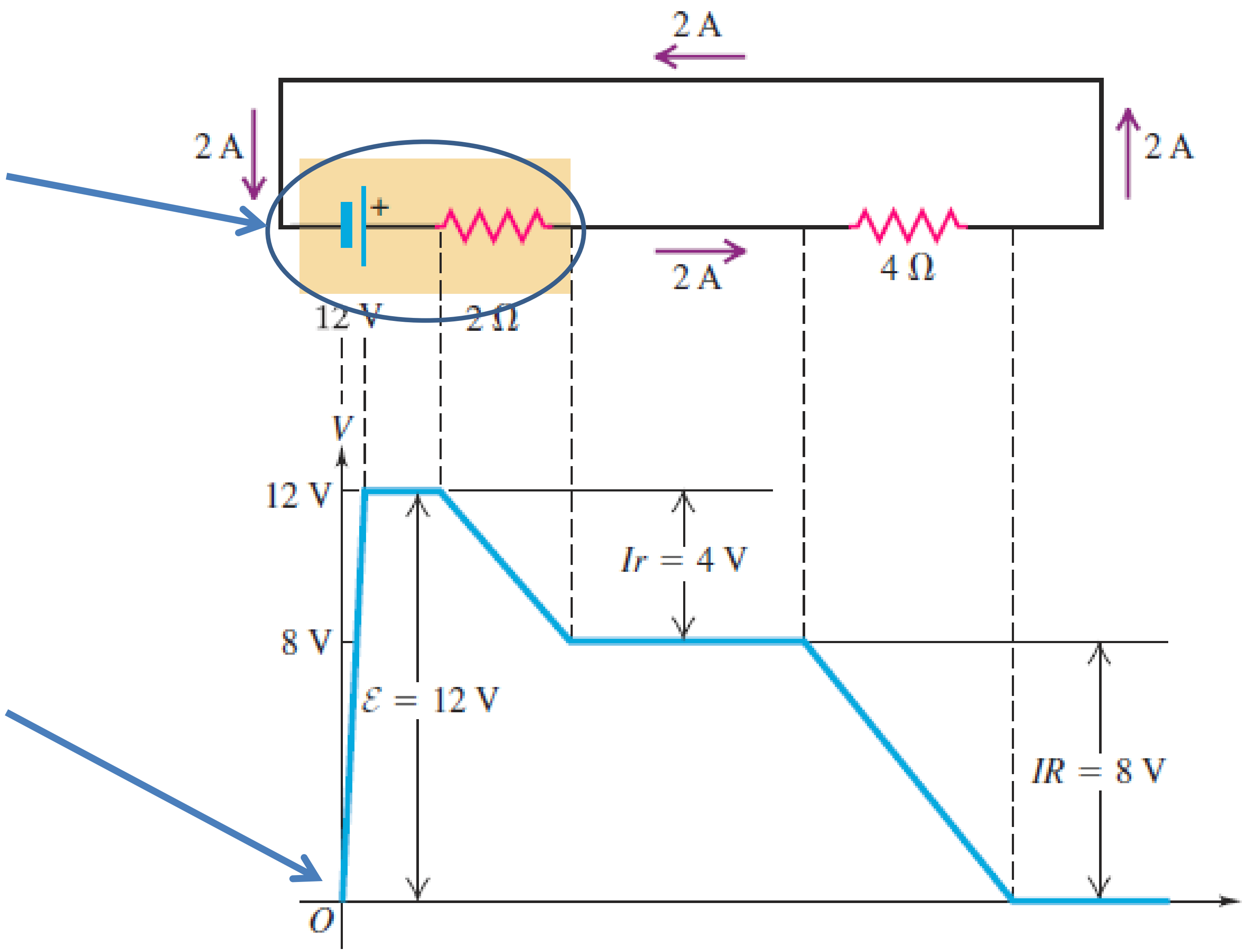


V_{ab}
V
+
A
a
b
$r = 2\ \Omega,\ \mathcal{E} = 12\ \text{V}$

How the potential changes in a circuit.

Battery or cell

Take the potential to be zero at the negative terminal of the battery.



▲ **FIGURE 19.16** Potential rises and drops in the circuit.

19.4 Energy and Power in Electric Circuits

$$Since\ I = \frac{\Delta Q}{\Delta t}\ \ and\ V = \frac{\Delta W}{\Delta Q}$$

Then

$$\Delta W = V\Delta Q = VI\Delta t$$

This work represents electrical energy transferred *into* the circuit element. The time rate of energy transfer is *power,* denoted by P. Dividing the preceding equation by Δt, we obtain the *time rate* at which the rest of the circuit delivers electrical energy to the circuit element:

$$\frac{\Delta W}{\Delta t} = P = V_{ab} I. \tag{19.9}$$

$$P = V_{ab} I = I^2 R = \frac{V_{ab}^{\ 2}}{R}. \qquad (19.10)$$

What becomes of this energy? The moving charges collide with atoms in the resistor and transfer some of their energy to these atoms, increasing the internal energy of the material. Either the temperature of the resistor increases, or there is a flow of heat out of it, or both. We say that energy is *dissipated* in the resistor at a rate I^2R. Too high a temperature can change the resistance unpredictably; the resistor may melt or even explode. Of course, some devices, such as electric heaters, are designed to get hot and transfer heat to their surroundings. But every resistor has a *power rating:* the maximum power that the device can dissipate without becoming overheated and damaged. In practical applications, the power rating of a resistor is often just as important a characteristic as its resistance.

▲ Application **Cheap light** If you've had incandescent flashlights or bicycle lights and changed to lights that use light-emitting diodes (LEDs), you know the large difference in energy consumption. A halogen bicycle headlight might go through a set of batteries in 3 hours, but an even brighter LED headlight will last 30 hours. Why the difference? The answer is that any incandescent bulb (including a halogen bulb) works by using the dissipation of electrical energy to heat a filament white hot. Some of the energy is converted to visible light, but most is lost as heat. In an LED, electrical energy is used to move semiconductor electrons to a region where they emit light. Most of the electrical energy, then, emerges as light; little is lost as heat.

Power Output of a Source

Using $V = \varepsilon - Ir$

$$P = VI = \varepsilon I - I^2 r$$

Quantitative Analysis 19.4

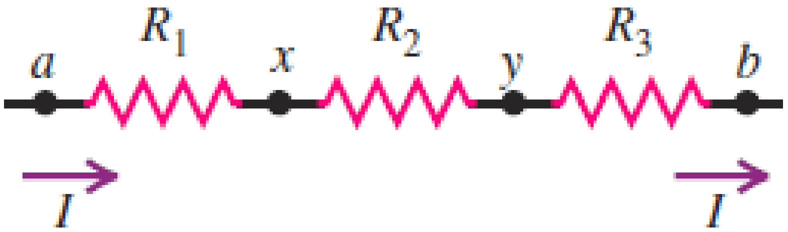
Power and current

A 1200 W floor heater, a 360 W television, and a hand iron operating at 900 W are all plugged into the same 120 volt circuit in a house (that is, the same pair of wires that come from the basement fuse box). What is the total current flowing through this circuit?

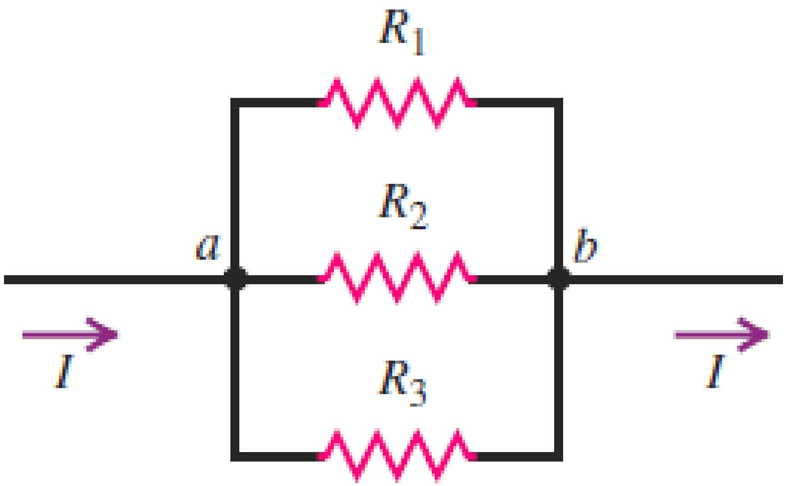
A. 20.5 A.
B. 17.5 A.
C. 15 A.
D. 12.5 A.

SOLUTION The electric power input to an appliance is given by $P = VI$. Each device is attached to the same 120 volt source. That is, the devices are in parallel, and their currents add to give the total current in the pair of wires coming from the fuse box. The current I through each device is given by $I = P/120$ V. The currents through each, in the order listed, are 10 A, 3 A, and 7.5 A. The sum of these currents is 20.5 A. This would likely trip the circuit breaker for that circuit.

19.5 Resistors in Series and in Parallel

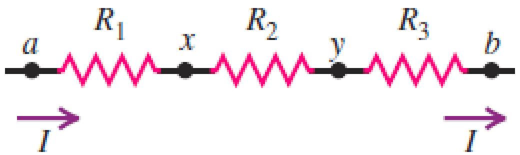


(a) Resistors in series



(b) Resistors in parallel

Resistors in Series



(a) Resistors in series

The potential difference V_{ab} is the sum of these three quantities:

$$V_{ab} = V_{ax} + V_{xy} + V_{yb} = I(R_1 + R_2 + R_3),$$

or

$$\frac{V_{ab}}{I} = R_1 + R_2 + R_3.$$

But V_{ab}/I is, by definition, the equivalent resistance R_{eq}. Therefore,

$$R_{eq} = R_1 + R_2 + R_3.$$

It is easy to generalize this relationship to any number of resistors:

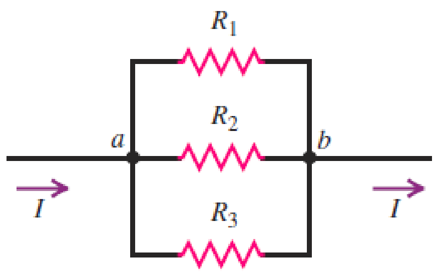
Equivalent resistance for resistors in series

The equivalent resistance of *any number* of resistors in series equals the sum of their individual resistances:

$$R_{eq} = R_1 + R_2 + R_3 + \cdots. \qquad (19.12)$$

The equivalent resistance is always *greater than* any individual resistance.

Resistors in Parallel



(b) Resistors in parallel

Charge is neither accumulating at, nor draining out of, point *a*; all charge that enters point *a* also leaves that point. Thus, the total current *I* must equal the sum of the three currents in the resistors:

$$I = I_1 + I_2 + I_3 = V_{ab}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right),$$

or

$$\frac{I}{V_{ab}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

But by the definition of the equivalent resistance R_{eq}, $I/V_{ab} = 1/R_{eq}$, so

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

Again, it is easy to generalize this relationship to *any number* of resistors in parallel:

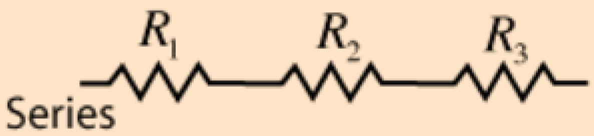
Equivalent resistance for resistors in parallel

For *any number* of resistors in parallel, the *reciprocal* of the equivalent resistance equals the *sum of the reciprocals* of their individual resistances:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots. \tag{19.13}$$

The equivalent resistance is always *less than* any individual resistance.

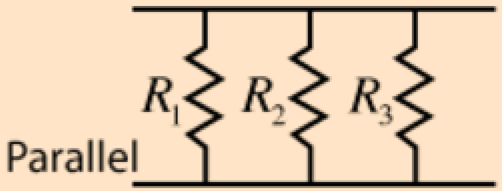
The combination rules for any number of resistors in series or parallel can be derived with the use of Ohm's Law, the voltage law, and the current law.



$$R_{equivalent} = R_1 + R_2 + R_3 + \ldots$$

$$R_{equivalent} = \frac{V}{I} = \frac{V_1 + V_2 + V_3 + \ldots}{I} = \frac{V_1}{I_1} + \frac{V_2}{I_2} + \frac{V_3}{I_3} + \ldots = R_1 + R_2 + R_3 + \ldots$$

Series key idea: The current is the same in each resistor by the current law.



$$\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

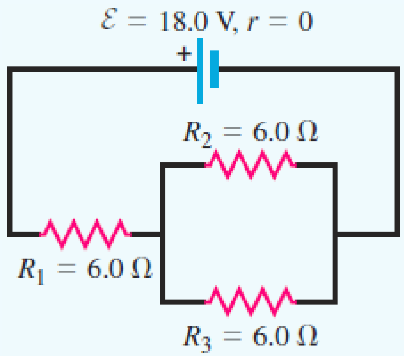
Parallel: $$\frac{V}{R_{equivalent}} = I = I_1 + I_2 + I_2 + \ldots = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \ldots$$

$$\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

Parallel key idea: The voltage is the same across each resistor by the voltage law.

EXAMPLE 19.9 **A resistor network**

Three identical resistors with resistances of 6.0 Ω are connected as shown in Figure 19.20 to a battery with an emf of 18.0 V and zero internal resistance. (**a**) Find the equivalent resistance of the resistor network. (**b**) Find the current in each resistor.



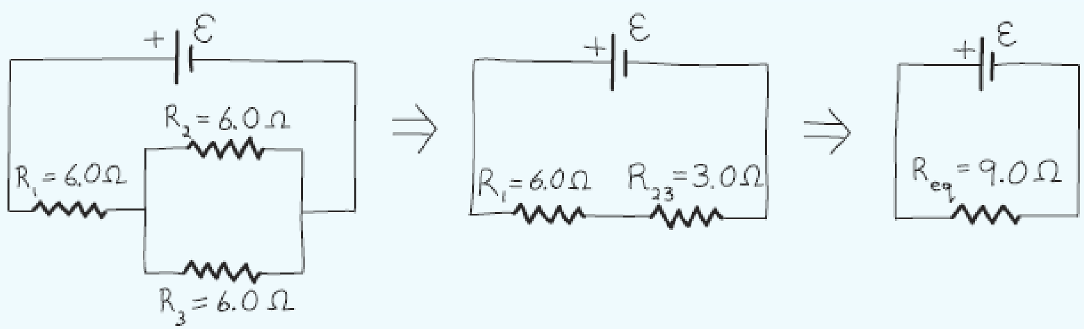
▶ **FIGURE 19.20**

SOLUTION

SET UP AND SOLVE **Part (a):** To find the equivalent resistance, we identify series or parallel combinations of resistors and replace them by their equivalent resistors, continuing this process until the circuit has just a single resistor that is the equivalent resistor for the network. Figure 19.21 shows the procedure.

In this network, R_2 and R_3 are in parallel, so their equivalent resistance R_{23} is given by

$$\frac{1}{R_{23}} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{6.0\ \Omega} + \frac{1}{6.0\ \Omega} = \frac{2}{6.0\ \Omega} = \frac{1}{3.0\ \Omega}.$$



▶ **FIGURE 19.21** Our procedure for finding the equivalent resistance.

(**a**) Original circuit (**b**) Parallel resistors combined (**c**) Equivalent resistor

Continued

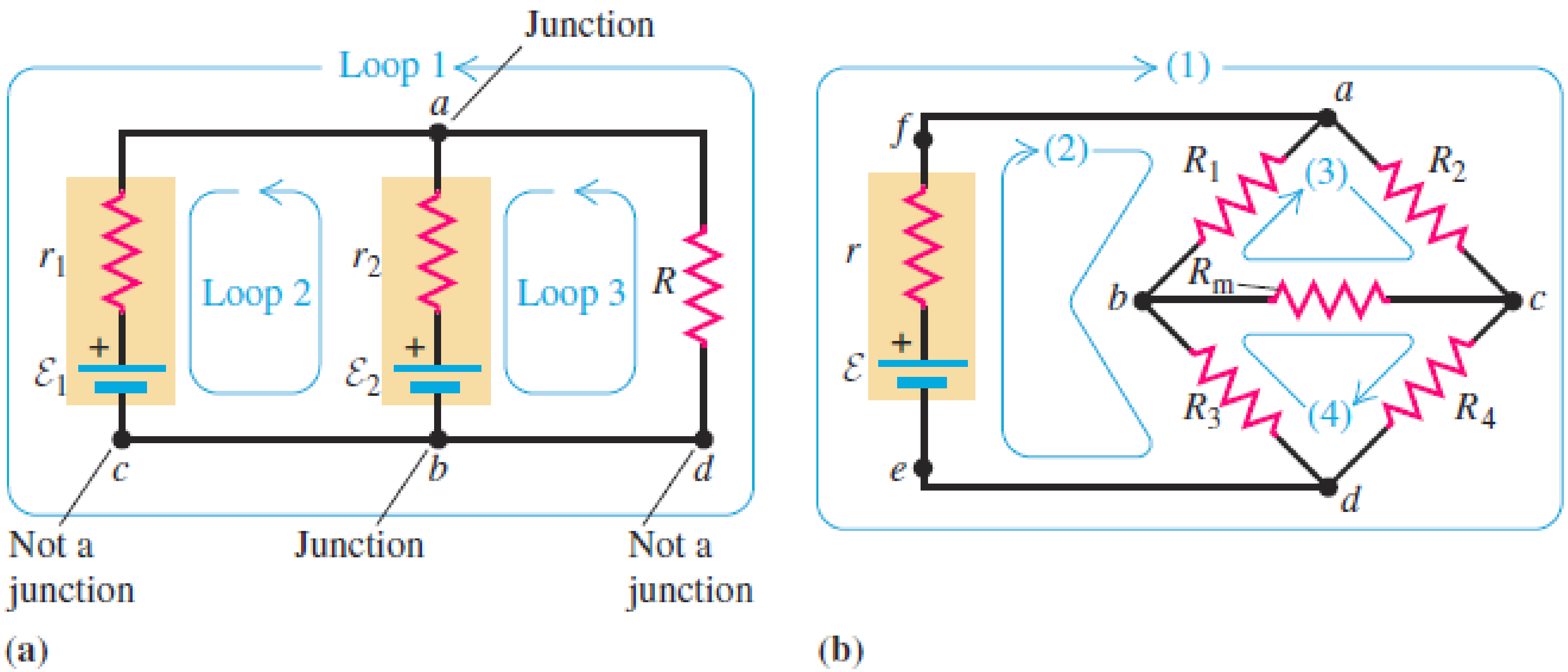
This gives $R_{23} = 3.0\ \Omega$. In Figure 19.21b, we've replaced the parallel combination of R_2 and R_3 with R_{23}. The circuit now has R_1 and R_{23} in series. Their equivalent resistance R_{eq} is given by

$$R_{eq} = R_1 + R_{23} = 6.0\ \Omega + 3.0\ \Omega = 9.0\ \Omega.$$

Thus, the equivalent resistance of the entire network is 9.0 Ω (Figure 19.21c).

19.6 Kirchhoff's Rules

These help us work out more complicated problems.



▲ **FIGURE 19.23** Two networks that cannot be reduced to simple series–parallel combinations of resistors.

Kirchhoff's junction (or point) rule:
The algebraic sum of the currents into any junction is zero; that is,

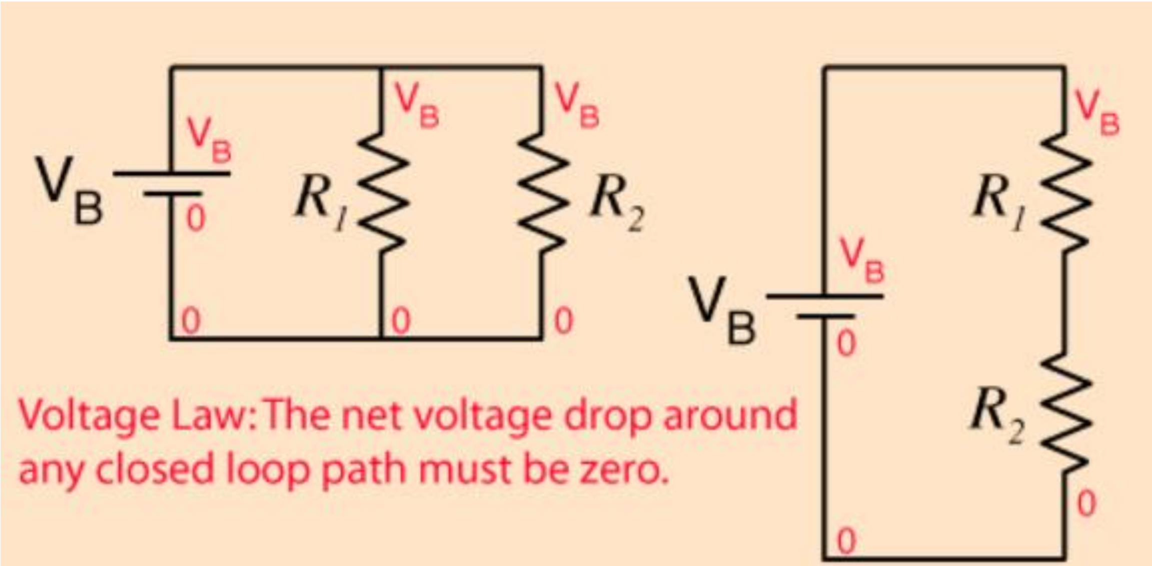
$$\sum I = 0. \tag{19.14}$$

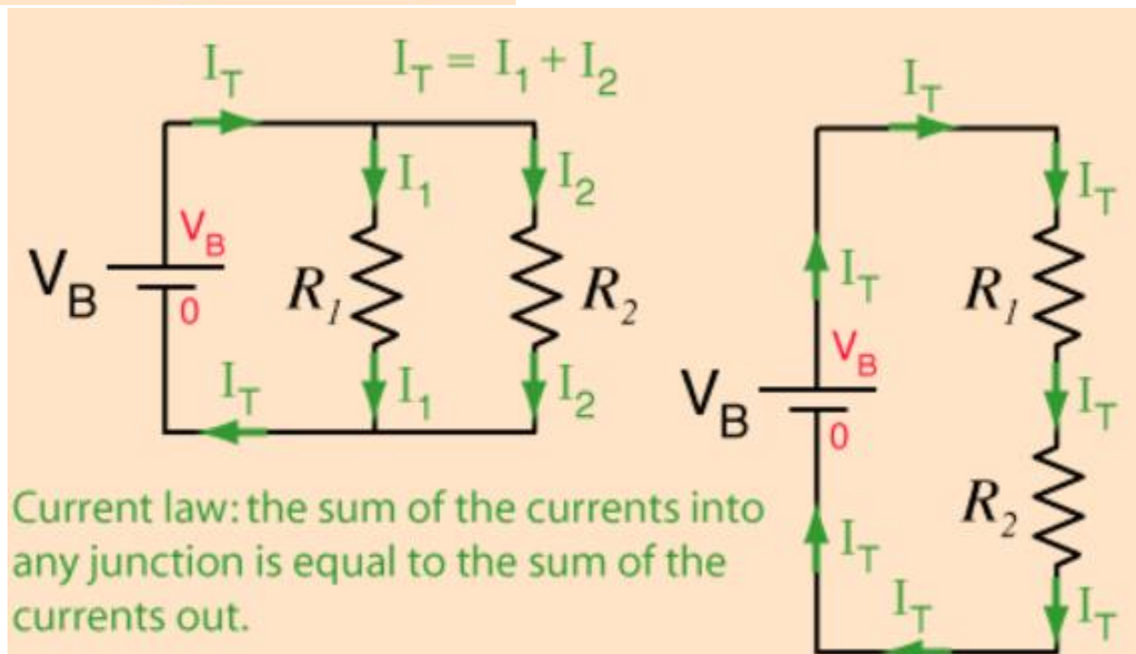
Currents *into* a junction are positive; currents *out of* a junction are negative.

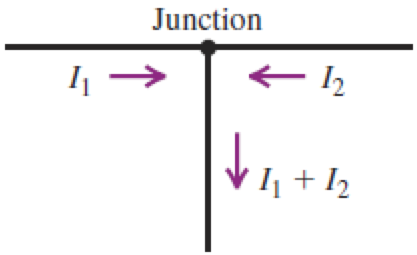
Kirchhoff's loop rule:
The algebraic sum of the potential differences in any loop, including those associated with emf's and those of resistive elements, **must equal zero**; that is,

$$\sum_{\text{around loop}} V = 0. \tag{19.15}$$

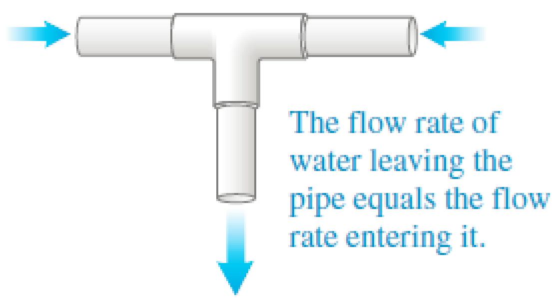
Kirchoff


V_B
R_1
R_2
0
Voltage Law: The net voltage drop around any closed loop path must be zero.


I_T = I_1 + I_2
I_T
I_1
I_2
V_B
R_1
R_2
0
Current law: the sum of the currents into any junction is equal to the sum of the currents out.



(a) Kirchhoff's junction rule



(b) Water-pipe analogy for Kirchhoff's junction rule

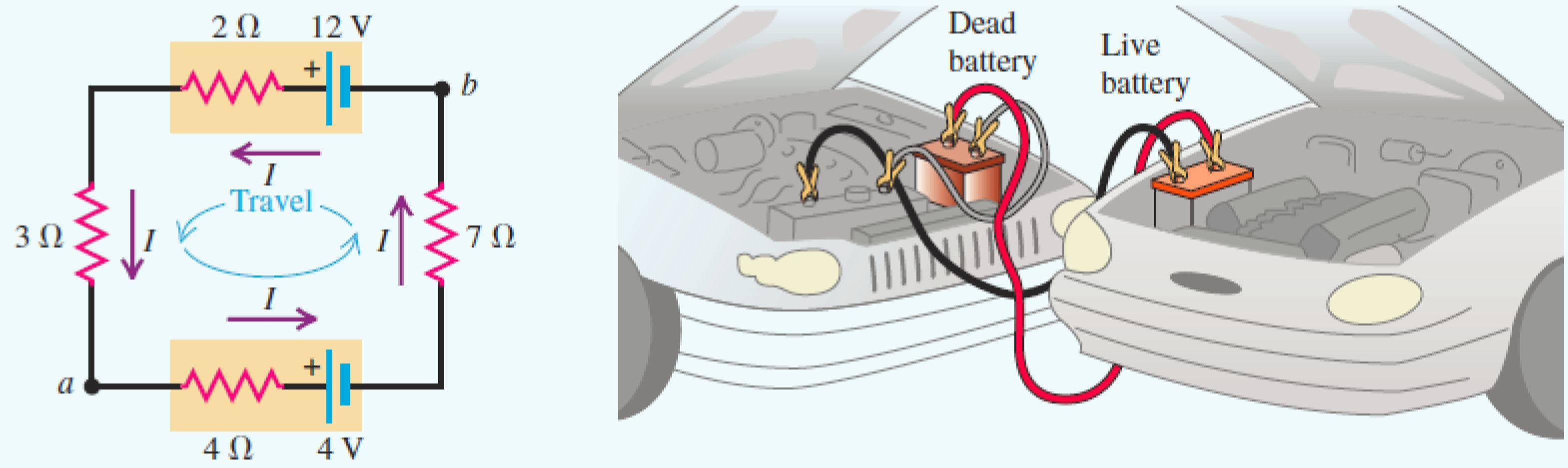
FIGURE 19.24 Kirchhoff's junction rule.

Kirchhoff's first rule for junctions is to do with **conservation of charge**. The same number of electrons out of a junction that went in.

Kirchhoff's second rule for loops is to do with **conservation of energy**. The amount of energy we put into a system must be the same as the amount we get out.

EXAMPLE 19.10 **Jump-start your car**

The circuit shown in Figure 19.28 is used to start a car that has a dead (i.e., discharged) battery. It includes two batteries, each with an emf and an internal resistance, and two resistors. Find the current in the circuit and the potential difference V_{ab}.



(a) (b)

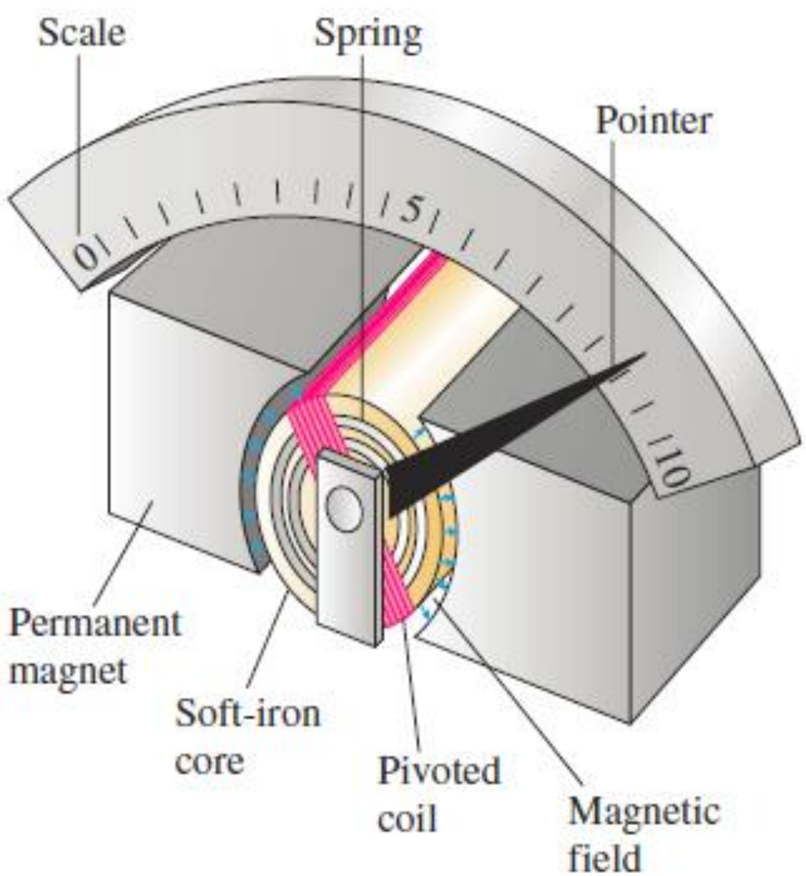
$$-I(4.0\ \Omega) - 4.0\ \text{V} - I(7.0\ \Omega) + 12\ \text{V} - I(2.0\ \Omega) - I(3.0\ \Omega) = 0.$$

$$8.0\ \text{V} = I(16\ \Omega) \quad \text{and} \quad I = 0.5\ \text{A}.$$

$$V_b + 12\ \text{V} - (0.50\ \text{A})(2.0\ \Omega) - (0.50\ \text{A})(3.0\ \Omega) = V_a,$$
$$V_{ab} = V_a - V_b = 12\ \text{V} - 1.0\ \text{V} - 1.5\ \text{V} = 9.5\ \text{V}.$$

$$V_b + (0.50\ \text{A})(7.0\ \Omega) + 4.0\ \text{V} + (0.50\ \text{A})(4.0\ \Omega) = V_a,$$
$$V_{ab} = V_a - V_b = 3.5\ \text{V} + 4.0\ \text{V} + 2.0\ \text{V} = 9.5\ \text{V}.$$

19.7 Electrical Measuring Instruments



▲ **FIGURE 19.30** One type of galvanometer.

When there is a current in the coil, the magnetic field exerts a torque on the coil that is proportional to the current.
Thus, the angular deflection of the coil and pointer is directly proportional to the coil current, and the device can be calibrated to measure current.

The ideal behavior for a meter would be for it to measure the circuit quantities of interest without disturbing or changing those quantities by its presence.

Ammeters

An instrument that measures current is usually called an ammeter. The essential concept is that *an ammeter always measures the current passing through it.* An *ideal* ammeter would have *zero* resistance.

Voltmeters

A voltmeter is a device that measures the potential difference (voltage) between two points. To make this measurement, a voltmeter must have its terminals connected to the two points in question. An ideal voltmeter would have *infinite* resistance, so that no current would flow through it.

DC Electric Power

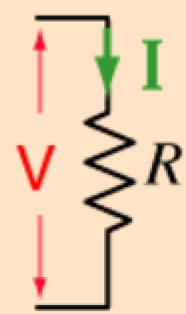
The electric power in watts associated with a complete electric circuit or a circuit component represents the rate at which energy is converted from the electrical energy of the moving charges to some other form, e.g., heat, mechanical energy, or energy stored in electric fields or magnetic fields. For a resistor in a D C Circuit the power is given by the product of applied voltage and the electric current:

$$P = VI$$

Power = Voltage x Current

Power Dissipated in Resistor

Convenient expressions for the power dissipated in a resistor can be obtained by the use of Ohm's Law.

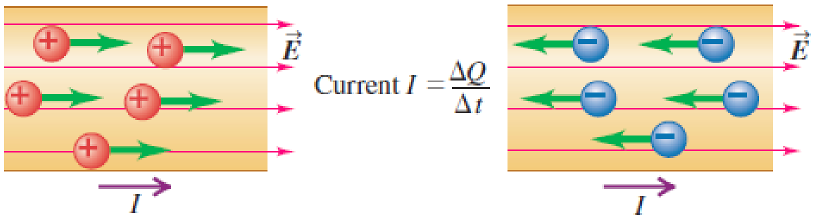


$$P = VI = \frac{V^2}{R} = I^2 R$$

SUMMARY

Current

(Section 19.1) Current is the amount of charge flowing through a conductor per unit time. The SI unit of current is the ampere, equal to 1 coulomb per second $(1\ \mathrm{A} = 1\ \mathrm{C/s})$. If a net charge ΔQ flows through a wire in time Δt, the current through the wire is $I = \Delta Q/\Delta t$ (Equation 19.1).

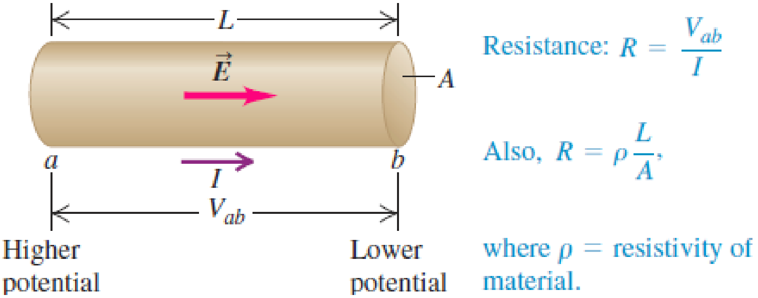


Resistance and Ohm's Law

(Section 19.2) In a conductor, the **resistance** R is the ratio of voltage to current: $R = V/I$ (Equation 19.2). The SI unit of resistance is the **ohm** (Ω), equal to 1 volt per ampere. In materials that obey **Ohm's law,** the potential difference V between the ends of a conductor is proportional to the current I through the conductor; the proportionality factor is the resistance R.

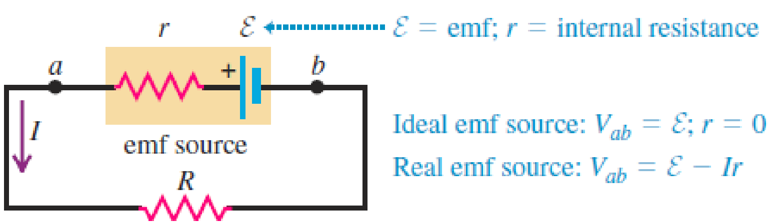
For a given conducting material, resistance R is proportional to length and inversely proportional to cross-sectional area. For a specific material, this relationship can be expressed as $R = \rho(L/A)$ (Equation 19.3), where ρ is the **resistivity** of that material.

Resistance and resistivity vary with temperature; for metals, they usually increase with increasing temperature.



Electromotive Force and Circuits

(Section 19.3) A **complete circuit** is a conductor in the form of a loop providing a continuous current-carrying path. A complete circuit carrying a steady current must contain a source of electromotive force (emf), symbolized by $\mathcal{E}$. An ideal source of emf maintains a constant potential difference $V_{ab} = \mathcal{E}$ (Equation 19.5), but every real source of emf has some internal resistance r. The terminal potential difference V_{ab} then depends on current: $V_{ab} = \mathcal{E} - Ir$ (Equation 19.7).



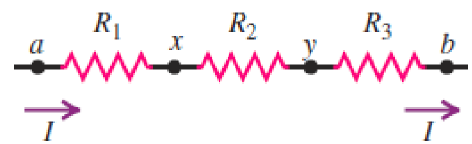
Energy and Power in Electric Circuits

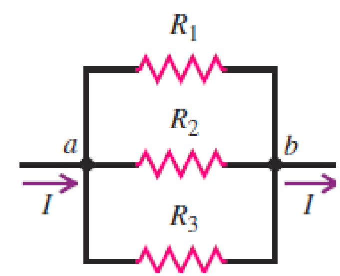
(Section 19.4) A circuit element with a potential difference V and a current I puts energy into a circuit if the current direction is from lower to higher potential in the device and takes energy out of the circuit if the current is opposite. The power P (rate of energy transfer) is $P = VI$ (Equation 19.9). A resistor R always takes energy out of a circuit, converting it to thermal energy at a rate given by $P = V_{ab}I = I^2R = V_{ab}^2/R$ (Equation 19.10).

Resistors in Series and in Parallel

(Section 19.5) When several resistors $R_1, R_2, R_3, \cdots$ are connected in series, the **equivalent resistance** R_{eq} is the sum of the individual resistances: $R_{eq} = R_1 + R_2 + R_3 + \cdots$. (Equation 19.12). When several resistors are connected in parallel, the equivalent resistance R_{eq} is given by

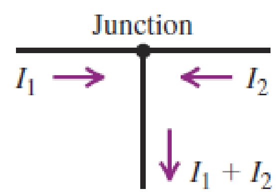
$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots. \qquad (19.13)$$



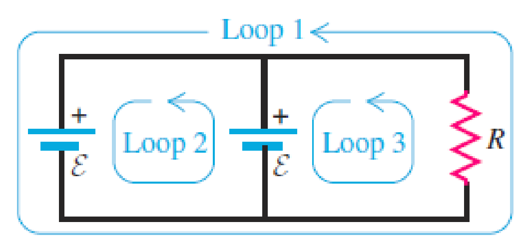


Kirchhoff's Rules

(Section 19.6) Kirchhoff's junction rule is based on conservation of charge. It states that the algebraic sum of the currents into any junction must be zero: $\sum I = 0$ (Equation 19.14). Kirchhoff's loop rule is based on conservation of energy and the conservative nature of electrostatic fields. It states that the algebraic sum of the potential differences around any loop must be zero: $\sum V = 0$ (Equation 19.15). Be especially careful with signs when using Kirchhoff's rules.



At any junction: $\Sigma I = 0$



Around any loop: $\Sigma V = 0$