20

Electrodynamics

DC Circuits

DOMINION SCIENCE PROBLEM

Transcontinental Telephone

It was 1907, and America's main telephone company, AT&T, formed by Alexander Graham Bell, was battling intense competition as his telephone patents began to expire. The company decided to introduce a new service to overshadow competing companies—transcontinental telephone. But there was a problem. Telephone signals would have to be significantly amplified to travel such great distances. How could engineers find a way to reliably and efficiently amplify telephone signals?

20-1 An early twentieth-century telephone sold by AT&T

20A CURRENT, VOLTAGE, AND RESISTANCE

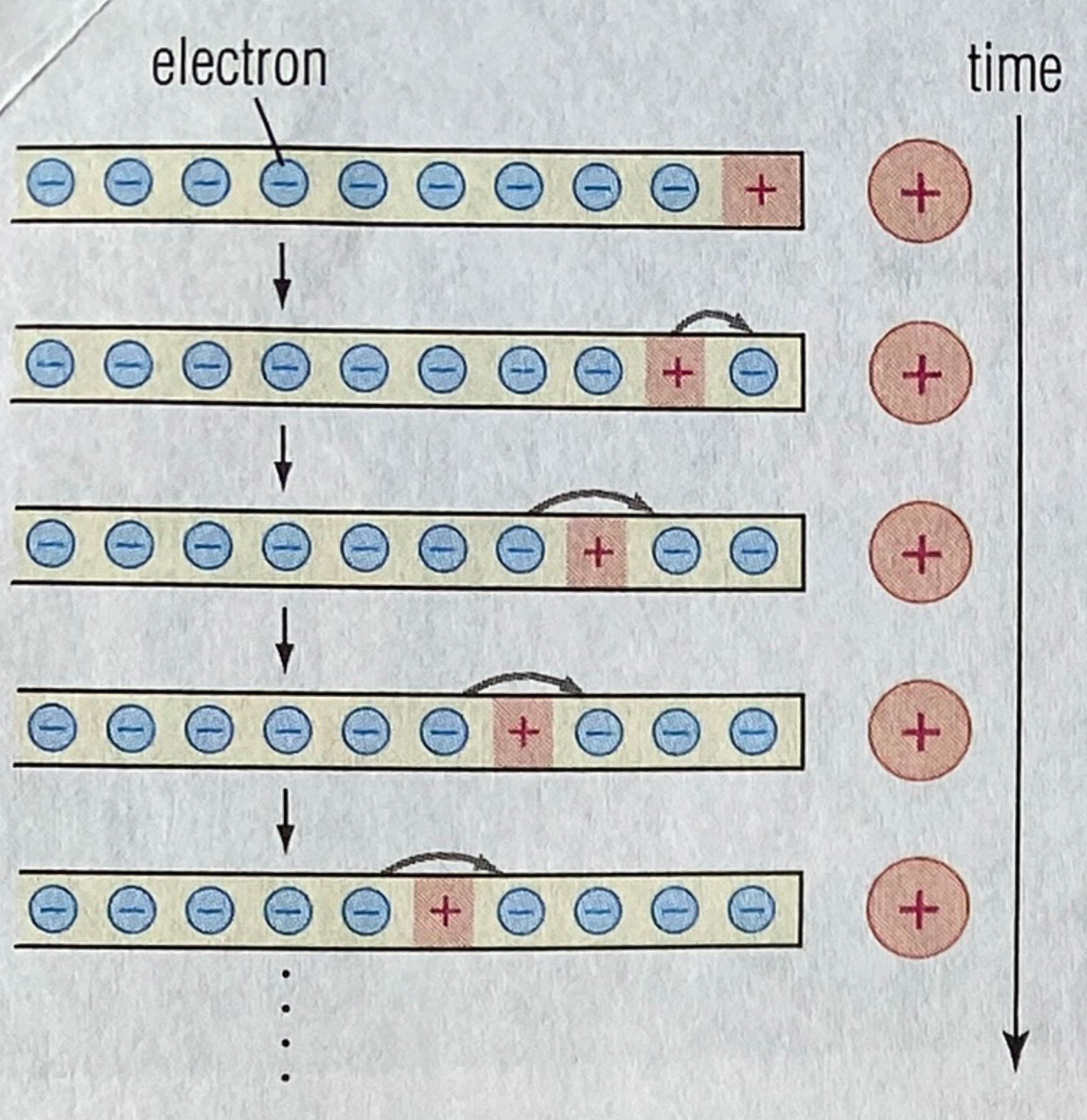
20.1 Current

The last two chapters dealt with stationary charged objects (electrostatics). However, charges do move when they are attracted or repelled by other charges. They may set up a **current** (***I***), which is defined as a continuous flow of charge. The study of the causes and effects of current electricity is called **electrodynamics**.

The motion of electrons creates a current in metals. This electrical conduction is similar to thermal conduction, which is the transmission of kinetic energy by collisions of free electrons. Electrical conduction is the transmission of electrical potential energy by repulsions and attractions of free electrons. Free electrons, remember, are electrons that are loosely held by the metal atoms' nuclei.

Electrical conduction in metals begins with a potential difference in the metal. For instance, if a positively charged object approaches one end of a wire, that end of the wire has a higher electrical potential than the other end. The wire's free electrons move toward the positively charged object. When the electrons move, they leave a space with a net positive charge. Therefore, new free electrons are attracted to the region that the other free electrons vacated.

Free electrons do not move far from their original positions, yet an impulse of motion spreads throughout the metal. To illustrate how this occurs, consider a line



20-2 Electrons moving in a metal-like solid

of dominoes with many dominoes standing on end less than one domino-length apart. If you push the first domino over, the last one will eventually fall. The dominoes have not moved far from their original positions, but the impulse of falling down has spread through all the dominoes.

The velocity of the electrons, called the *drift velocity*, is slow—on the order of millimeters per second. The free electrons in a conductor tend to move in random directions, even when an electrical potential is applied, but more electrons move toward the higher potential than in any other direction. This net movement with time is the drift velocity. Each electron needs to move only far enough to repel another electron. As soon as the electron moves even a small distance, the free electrons nearest it are affected. The impulse moves much faster than the electrons do—it can approach the speed of light.

In solid conductors, electrons usually carry the current. In *electrolytic* (conducting) solutions, though, electrons are not the sole current-carriers. *Electrolytes* are materials that are able to conduct electricity when they are dissolved. They separate into positive ions, or *cations* (atoms or molecules that have a deficiency of electrons), and negative ions, or *anions* (atoms or molecules that have an excess of electrons). In a solution, the current consists of anions and cations traveling in opposite directions.

Since current is the flow of charge, it is natural to define the unit of current, the **ampere (A)**, as 1 coulomb of charge per second:

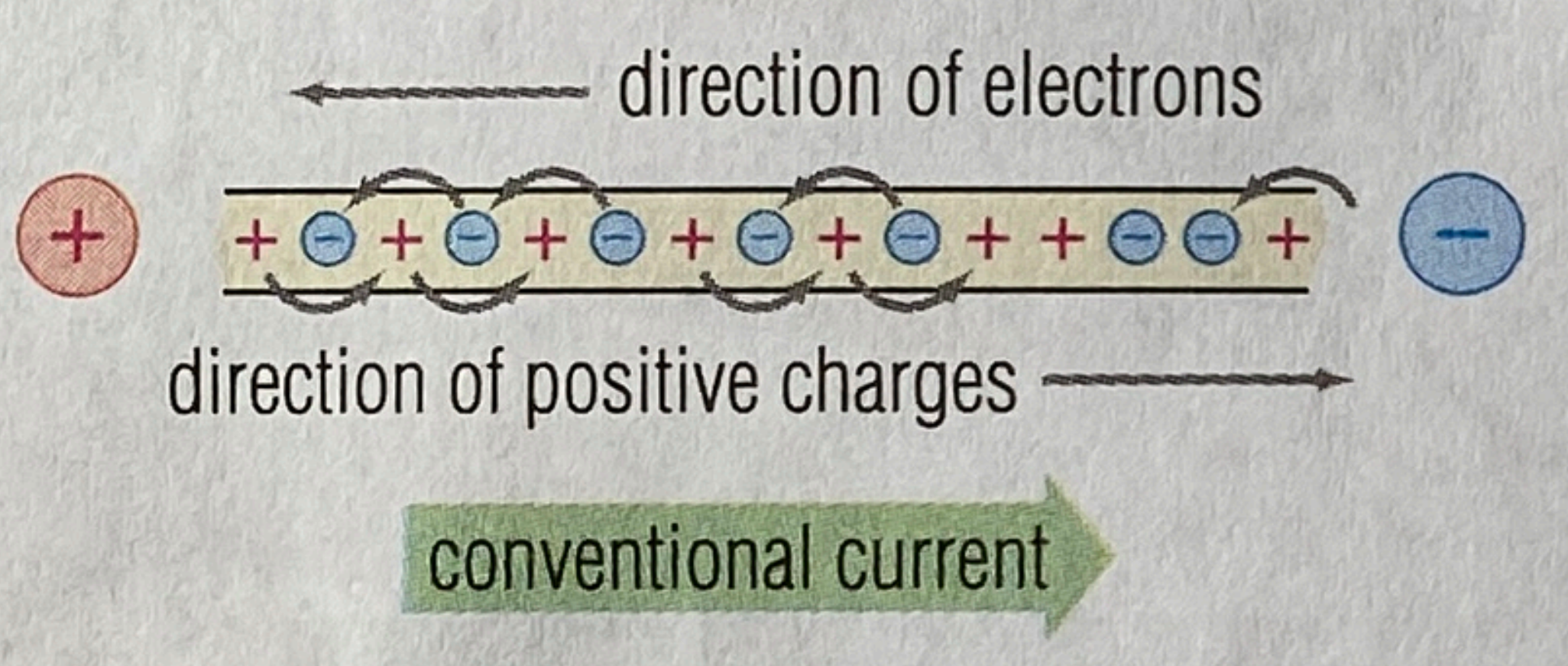
$$1\ \text{A} \equiv \frac{1\ \text{C}}{1\ \text{s}}$$

This equation is the classical empirical definition of the ampere. The present-day SI definition is given in Appendix A.

20.2 Current Direction

These facts raise a question: What is the current direction? The choice of current direction is arbitrary. The first scientists to study electricity assumed that current was the flow of positive charge (after Ben Franklin's naming convention). Therefore, they decided that current flows from a higher potential (positive charge) to a lower potential (negative charge). This text will follow this convention. When considering current in a solid, such as a wire, you need to be careful to avoid confusion. Although both positive and negative charges move through solutions, in solids only the electrons move.

Since the *conventional current* direction is the direction that positive charges would move, this direction is opposite the direction of the actual electron flow. It makes little difference, since the flow of positive charge in one direction is equivalent to the flow of negative charge in the opposite direction. In either case, the charges move to cancel the potential difference. The motion of charges to cancel a *constant-direction* potential difference is called **direct current**, or **DC**.



20-3 The direction of conventional current flow

The flow of current is in the direction that tends to cancel the potential difference causing the current. This textbook adopts the convention that current is the flow of positive charges from higher (positive) potentials to lower potentials.

20.3 Potential Difference and Voltage

Potential difference is a difference in electrical potential between two positions. The potential difference between point *A* and point *B* is $V_A - V_B$, while the potential difference between point *B* and point *A* is $V_B - V_A$. The second number is always assumed to be the reference potential. Obviously, one value will be the negative of the other:

$$V_A - V_B = -(V_B - V_A)$$

Consequently, it is important to identify how potential difference is measured. Potential difference can be positive, negative, or zero. In order to identify the location of higher and lower potentials on a source of potential difference, **polarity markings** are used—positive (+) for the higher potential and negative (−) for the lower. These points do not necessarily have to be at positive or negative potentials,

The potential difference between a point at 10 V and a point at 5 V is 10 V − 5 V = +5 V. The potential difference between a point at 5 V and a point at 10 V is 5 V − 10 V = −5 V. The second number is always taken as the reference potential.

Polarity markings (+ and −) are used on sources of potential difference (as well as devices connected to these sources) in order to identify the location of higher and lower electrical potential.

respectively. It just means that the point with the + is at a higher (more positive) potential than the point with the −.

Any device that creates a difference in potential between two points is a source of potential difference. If the potential difference is created by a self-contained device, especially by a chemical reaction such as in a battery, it is sometimes called *electromotive force (emf)*. Emf is a term scientists gave to potential difference before they realized that it is not a force. Even though emf is not a force as we normally use the word in physics, it is sometimes useful to resort to this term for brevity's sake.

Differences in electrical potential can be produced in several ways. Most processes involve a change from another form of energy to electrical potential energy. A *battery* changes chemical energy to electrical potential; a *photovoltaic cell* changes light energy to electrical potential; a *Van de Graaff generator* (static electricity generator) and *piezoelectric crystals* convert mechanical energy to electrical potential; and a *thermocouple* converts thermal energy to electrical potential.

Potential difference is measured in volts (V), or joules of energy per coulomb of charge:

$$1\ \text{V} \equiv \frac{1\ \text{J}}{1\ \text{C}}$$

One coulomb (C) is defined as the total charge of a specific number of fundamental charges:

$$\boxed{1\ \text{C} = 6.24 \times 10^{18}\ e,}$$

where *e* is the absolute value of the charge of an electron. Since a specific number of a large quantity of fundamental charges is impossible to measure with present technology, scientists resort to the classical definition of the ampere and define the coulomb in SI units as an ampere-second:

$$1\ \text{C} \equiv 1\ \text{A·s}$$

20.4 The Voltaic Cell

Probably the most convenient source of steady potential difference for laboratory use is one based on the **voltaic cell**, an electrochemical device that spontaneously changes chemical energy to electrical energy. The conversion of chemical energy to electrical energy was first observed by Luigi Galvani as he was studying the anatomy of a frog. He discovered that if he touched a nerve in a frog's leg with a metal scalpel while the frog was on a metal tray, the touch established an electric current, which contracted the frog's leg muscles. Galvani touched the nerve with different metals and discovered that some metals caused a stronger contraction than others. He thought that the frog's tissues were the source of the current.

Considering Galvani's observations, Alessandro Volta correctly concluded that the source of the current is the contact of two different metals (the tray and the scalpel) in a conducting medium (the frog's body fluids). The difference in chemical activities of the two metals causes electrons and positive ions to flow between the metals if both metals contact an electrolytic solution. Volta made a cell from pieces of copper and zinc separated by seawater-soaked cardboard. This cell is called a *voltaic pile*, after Volta.

The metal conductors in voltaic cells are called **electrodes**. One electrode (the *cathode*) is made of a metal that has a more electronegative stronger attraction for electrons (on the *external* circuit) than the other electrode (the *anode*). The cathode pulls electrons from the anode through the wire. The accumulation of electrons on the cathode attracts positive ions (cations) from the electrolytic solution that accept the electrons to form a neutral plating on the cathode. The anode, which lost electrons to

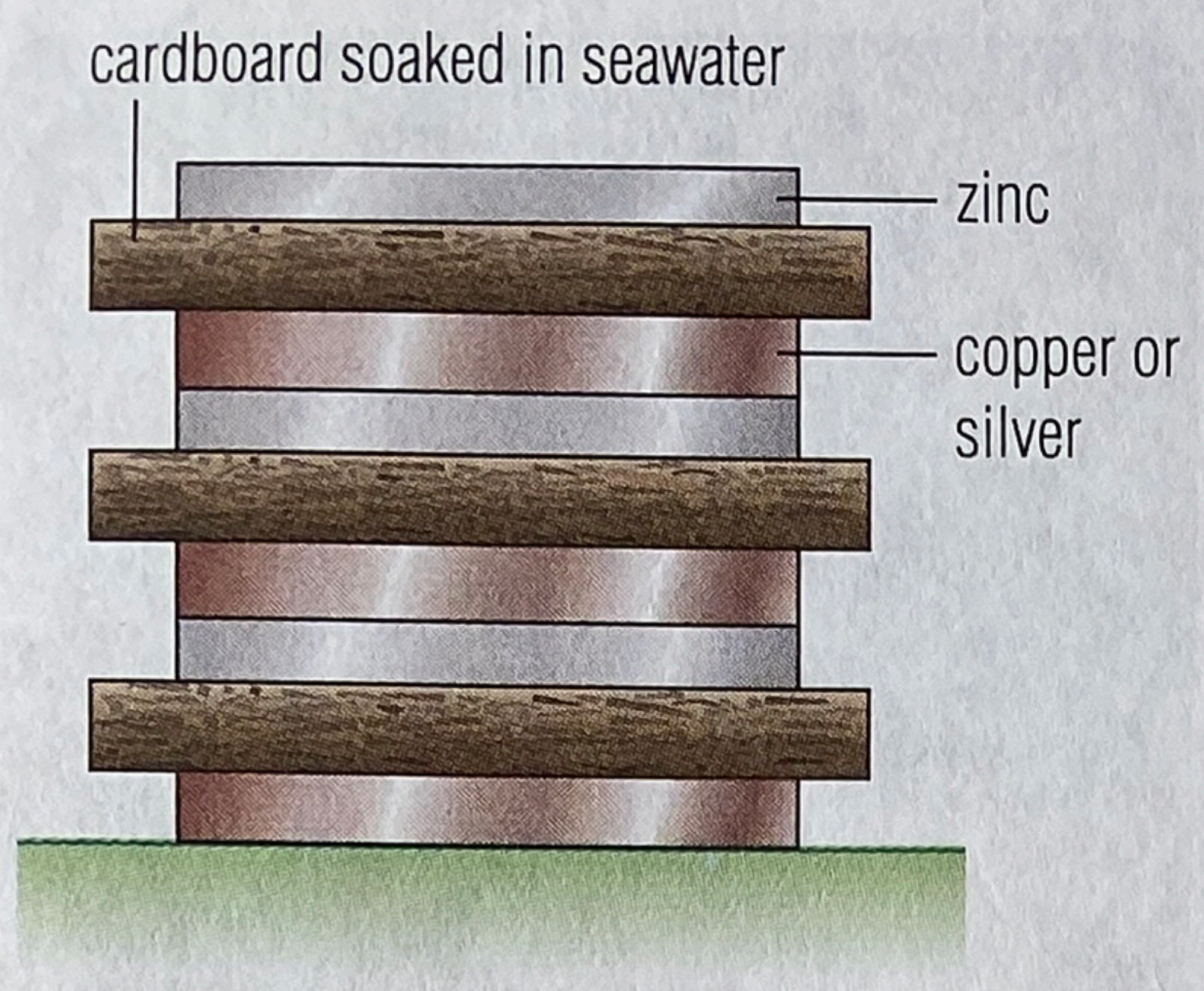
20-4 A Van de Graaff generator can safely produce large static electrical potentials. A static charge can be the beginning of a bad-hair day!

Robert Jemison Van de Graaff (1901–67) was an American physicist who conducted research in high-energy physics. He invented the static electrical generator that bears his name.

Luigi Galvani (1737–98) was an Italian physiologist and anatomist.

Voltaic cells are also called **galvanic cells** after Galvani. Both names refer to a device that uses spontaneous electrochemical reactions to produce a potential difference between the anode and cathode of the cell.

Count Alessandro Volta (1745–1827) was an Italian physicist known for his pioneering work in electricity. He invented the voltaic pile, which was the first electric battery.



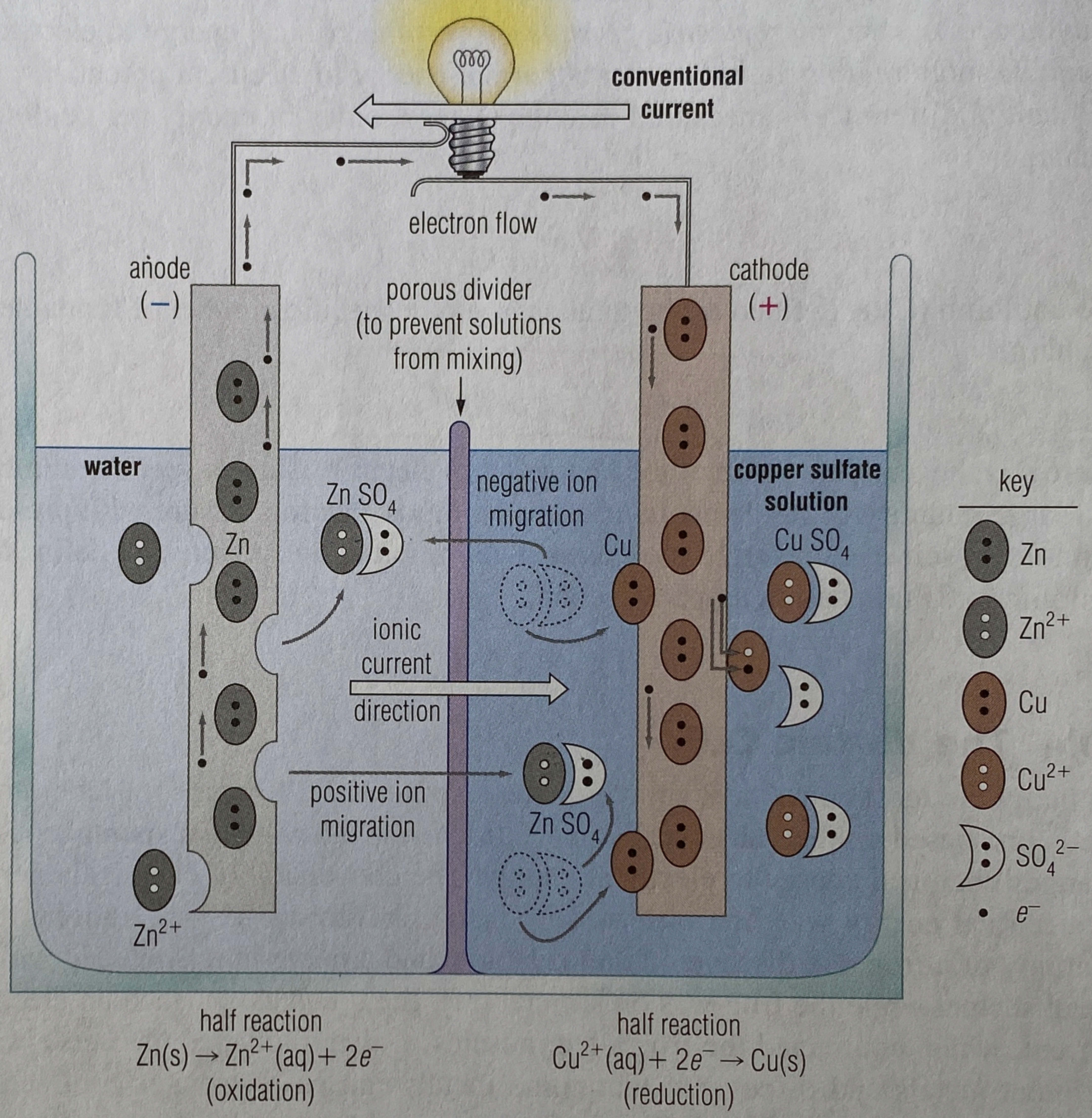
20-5 A voltaic pile

the cathode via the wire, is a site of positive charges from the solution. It attracts electrons from the negative ions (anions) in the solution. This process continues as long as electrolytic ions remain in the solution and the metal electrodes remain in contact with the solution.

Although the electrons flow from the anode to the cathode, their charge is negative, so the external *conventional current* from a voltaic cell is, by our convention, directed from the cathode to the anode. With the wire in place, the current has a complete path: positive ions go from the anode to the cathode in the *solution*, and positive charges flow back to the anode through the *wire*. The closed path of electrical current thus described is called a **circuit**.

Problem-Solving Strategy 20.1

It is not normally necessary to keep track of which direction the moving charges are going. Just remember that current flows from the highest potential to the lowest potential in the external circuit.



20-6 A voltaic or electrochemical cell

20.5 Types of Electrochemical Cells and Batteries

Modern voltaic cells function in a similar way to Volta's cell. There are several different types of cells. **Primary cells** simply convert chemical energy to electrical energy. A primary cell depends on irreversible (one-way) chemical reactions, so it cannot be recharged. The standard battery cells you use in a flashlight are primary cells.

Unlike primary cells, **storage cells** rely on reversible (two-way) chemical reactions. Therefore, storage cells can be recharged by the addition of electrical energy, which is converted back to chemical energy. Probably the most familiar storage cell is found in an automobile battery. These batteries usually consist of a group of connected storage cells. (Technically, a **battery** is a series of cells. Flashlight "batteries" are really single voltaic cells.) Rechargeable storage cells that use

An electrochemical cell consists of a single anode and cathode immersed in an electrolyte. A **battery** is two or more cells connected together.

lithium-ion or nickel-metal hydride technology are found in the batteries used in cellular phones, digital cameras, and laptop computers.

Another term you may hear applied to voltaic cells is "dry cell." A **dry cell** is a primary or storage cell that has an electrolytic paste instead of a liquid solution. Since there is no chance of spilling the solution, a dry cell is easier and safer to use than a "wet" cell. The common D-cell is a dry primary cell, whereas a car battery consists of wet cells.

20.6 Resistance

Every material tends to impede the flow of charge. In wires, the free electrons collide with the electric fields of the inner atoms when these atoms are in the electrons' path. Such collisions convert the kinetic energy of the free electrons to kinetic energy of the inner atoms. At higher temperatures, the inner atoms have more kinetic energy and collide more forcefully with the conducting electrons. Therefore, both the material and the temperature of an object affect how well it conducts electricity.

The tendency to impede current is represented by **resistivity (ρ)**. Resistivity (a different quantity from resistance) is a property of a material that varies with temperature but is not dependent on its size and shape. Good conductors such as copper have lower resistivities than poor conductors such as glass. Only **superconductors**—certain materials at low temperatures (<138 K) — have zero resistivity.

Resistivity is a temperature-dependent property of a material and is the measure of the way it impedes current flow. The symbol for resistivity is the Greek letter rho (ρ). The unit of resistivity is the ohm-meter ($\Omega \cdot m$).

Any circuit component that is designed to convert electrical potential energy to thermal energy (and produce a potential difference in the process) is called a **resistor**. Electrons in a long, thin wire suffer more collisions than those in a short, thick wire, since they are forced into a very narrow space and they must travel past more inner atoms. Thus a long, thin wire is a better resistor than a short, heavy wire. The geometry of a circuit component affects how well it conducts or resists.

Resistance (*R*) is a quantity that takes into account both the resistivity of the material and the geometry of the resistor. Objects with long current paths resist more than short objects of the same material, and thin objects resist more than wide objects of the same material. The following equation represents this relationship:

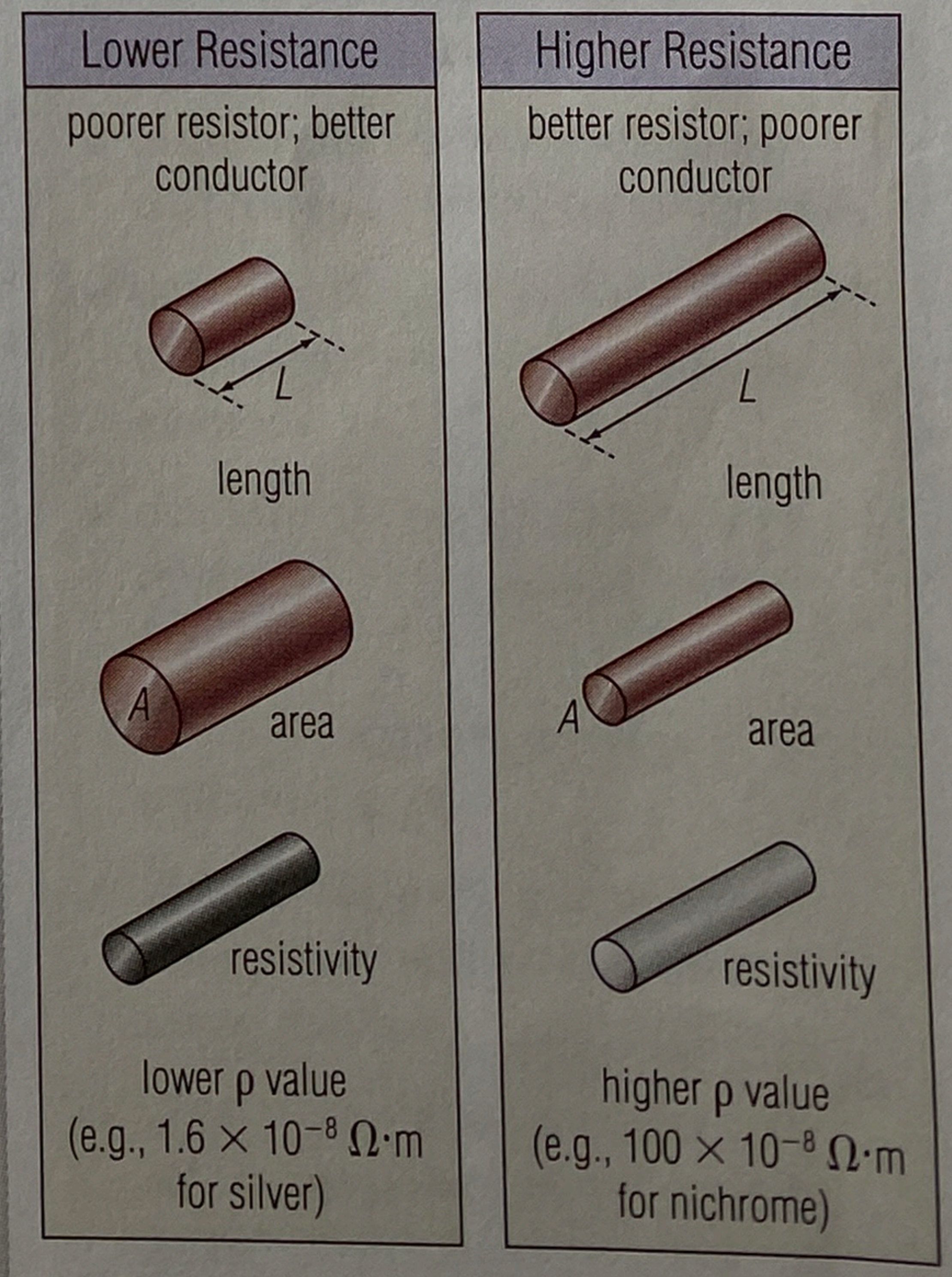
TABLE 20-1

Resistivities at Room Temperature

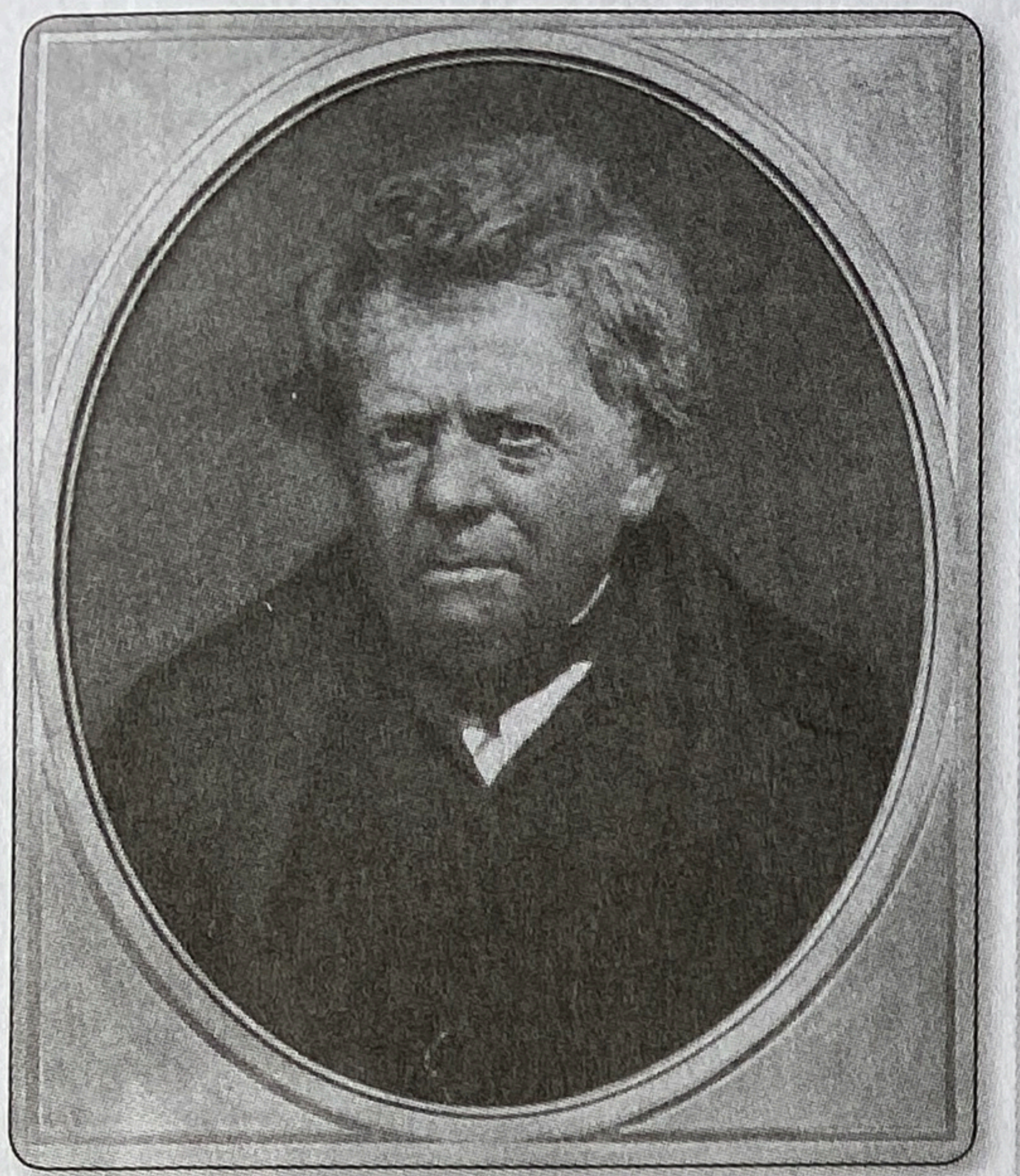
Material	ρ ($\Omega \cdot m$)
Conductors	
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Aluminum	2.6×10^{-8}
Tungsten	5.5×10^{-8}
Nickel	7.8×10^{-8}
Lead	21×10^{-8}
Nichrome	100×10^{-8}
Semiconductors	
Carbon	3.5×10^{-5}
Germanium	0.5
Silicon	2.3×10^{3}
Insulators	
Glass	$10^{10} - 10^{14}$
Hard Rubber	10^{16}
Quartz	7.5×10^{17}

$$R = \rho \frac{L}{A}, \qquad (20.1)$$

where *L* is the length of the object's current path and *A* is the cross-sectional area of the current path. A good conductor has a low resistance, and a poor conductor has a high resistance. The symbol -ww- represents a resistor in a circuit diagram. The unit for resistance is the ohm (Ω), which is further defined below.



20-7 Factors influencing magnitude of resistance



20-8 Georg Simon Ohm (1789–1854) was a German physicist.

20.7 Ohm's Law

Every electrical component converts some electrical potential energy to thermal energy; each circuit component causes a decrease of potential in the direction of current flow. How much potential energy is lost? In 1827, Georg Ohm found the answer to this question. He began experimenting by measuring the current in a circuit made from uniform wire while he changed the potential difference, and he found that current is directly proportional to the potential difference. Then, keeping the potential difference the same, Ohm measured the current while he changed the length of the current path by adding or removing identical wires. He found that current is inversely proportional to the length of wire (the resistance). Ohm expressed his findings in an equation known as **Ohm's law**, which says that the change of potential across any circuit component is

$$V = IR, \tag{20.2}$$

where V is the potential difference across the component, I is the current through the component, and R is the resistance of the component.

The unit of resistance, the **ohm** (Ω), is defined according to Ohm's law: one volt of potential difference across one ohm of resistance produces one ampere of current through the resistance:

$$1\ \Omega \equiv \frac{1\ \text{V}}{1\ \text{A}}$$

Problem-Solving Strategy 20.2

Ohm's law is true for a single circuit component, a segment of a circuit, or an entire circuit.

20.8 Electrical Work and Power

The purpose of most electrical components is to convert electrical energy to some other form of energy. That is, electrical components are intended to do work. Since potential difference is measured in volts, or joules per coulomb, and work is expressed in joules,

$$\text{potential difference} = \frac{\text{work}}{\text{charge}}.$$

From this equation you can see that

$$\text{work} = \text{potential difference} \times \text{charge, or}$$

$$W = V \times Q. \tag{20.3}$$

Equation 20.3 is true for a circuit as well as for individual components in the circuit. The rate at which work is done (work per unit time) is the definition of power:

$$P = \frac{W}{\Delta t}$$

The electrical power consumed by a circuit is

$$P = \frac{VQ}{\Delta t} = V\frac{Q}{\Delta t}.$$

But $Q/\Delta t$ is the flow of charges per unit time, or the current, I. Therefore, the electrical power used is

$$P = VI. \tag{20.4}$$

The electrical power used in the component is the product of the potential difference and the current.

Each resistor absorbs a specific amount of electric power when it changes the electrical energy of the free electrons going through it to thermal energy. Joule discovered that the thermal energy produced by a resistor each second (thermal power) is related to electrical power by the expression

$$P = I^2R. \tag{20.5}$$

Equation 20.5, known as **Joule's law**, looks different from the first equation for power. But is it? Ohm's law says that

$$V = IR.$$

Joule's law, expanded a bit, is

$$P = IR \times I.$$

So Joule's law can be written

$$P = VI,$$

which is Equation 20.4.

The electrical power used in a circuit or a circuit component can be expressed in three ways:

$$\boxed{\begin{aligned} P &= VI \\ P &= I^2R \\ P &= \frac{V^2}{R} \end{aligned}} \qquad (20.6)$$

You can prove that Equation 20.6 is equivalent to the other two using Ohm's law.

Since power is energy or work per unit time, it is expressed in joules per second, or watts (W). The kilowatt (kW) is 1000 W. The **kilowatt-hour (kWh)**, a unit of energy, is equal to

$$1 \text{ kWh} = 1000 \text{ W} \times 3600 \text{ s, or}$$

$$1 \text{ kWh} = 3\,600\,000 \text{ J}.$$

Table 20-2 sums up the relationships between the various electrical variables and their units.

20A Section Review

1. Describe how electrical conduction occurs in a conductor.
2. Discuss the main difference between conduction in a solid conductor and in an electrolytic solution.
3. How can you tell which electrical connection on a device is supposed to be at the higher potential?
4. List at least three sources of electrical potential.
5. Which wire would impede the flow of current less, copper or aluminum? Explain your answer.
6. What is the resistance of a silver wire 10.0 m long and 0.050 cm in diameter?
7. How much power is used in a coil of copper wire 100. m long with a wire diameter 0.010 cm if there is 1.00 A of current flowing through it?
8. **a.** How many kilowatt-hours do you waste if you forget to turn off your 100. W bedroom lamp in the morning before school and it remains on for 9.0 hours?

   b. How many joules of energy does this quantity represent?
9. How many grams of water could you heat from 0.0 °C to 100.0 °C with the thermal equivalent of the energy used in Question 8?

Electrical "power" companies sell electrical *energy*, not power. They care for only how much energy you use, not how fast you use it.

TABLE 20-2

Some Basic Electrical Dimensions

Dimension	Unit Symbol	Definition	Formula Symbol
current	ampere (A)	1 C/s	I
potential	volt (V)	1 J/C	V
resistance	ohm (Ω)	1 V/A	R
charge	coulomb (C)	1 A·s	q or Q
power	watt (W)	1 J/s	P

Problem-Solving Strategy 20.3

Remember that the unit symbol indicates the kind of dimension of a property, while the variable (formula) symbol represents its numerical value.

20A Objectives

After completing this section, I can

- ✓ describe electric current and identify the charge carriers in various conductors.
- ✓ differentiate between electron current and conventional current.
- ✓ describe the conventions for identifying potential difference in electrical circuits.
- ✓ describe the structure and general operation of voltaic cells and batteries.
- ✓ differentiate between resistivity and resistance.
- ✓ discuss the principle behind Ohm's law and work problems using the law.
- ✓ derive the three formulas for electrical power in a circuit by using Ohm's law.

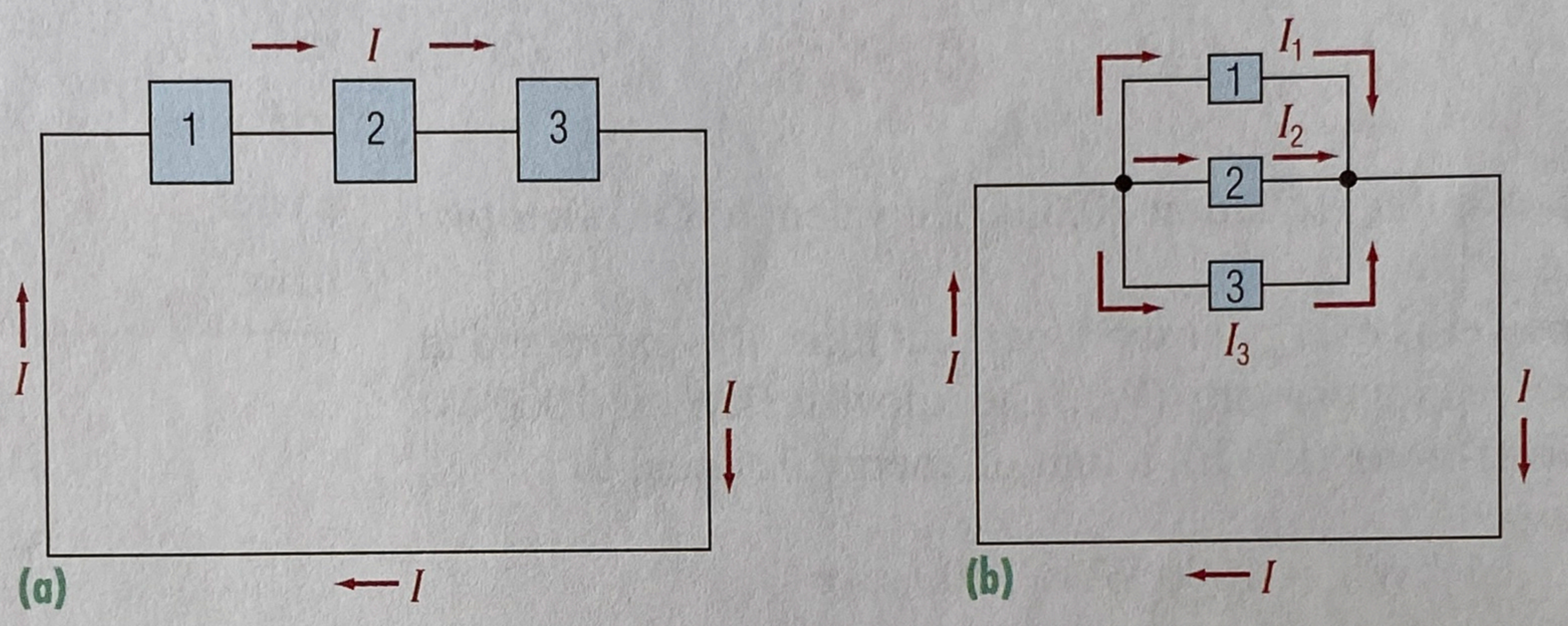
20B ELECTRICAL CIRCUITS

20.9 Terminology and Symbols

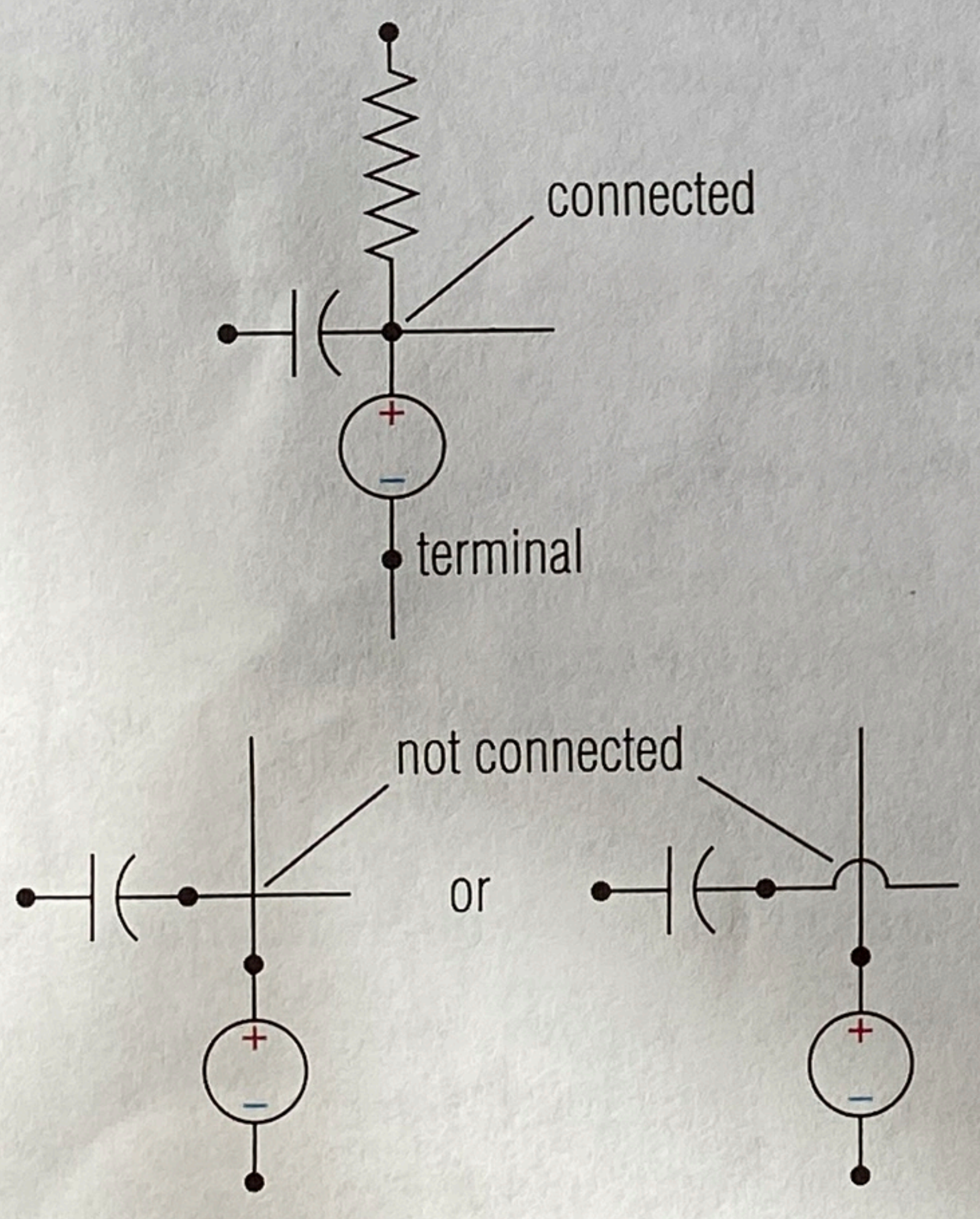
Recall from Chapter 19 that there are two ways of connecting multiple electrical components together—series and parallel. A **series** circuit has a single path for current. The components are linked together like a train or chain. The current, denoted I, passes through each circuit component in turn. A **parallel** circuit has more than one path for current. The current therefore divides up, and only a portion of the current goes through each path. The direction of current in a circuit diagram is represented by an arrow, and a value may be written by the arrow if it is known. A source of potential difference (V) is represented by a generic voltage source symbol •–⊕–• or by a symbol of one or more voltaic cells ⊣|⊢. A curved arrow points from the lower potential to the higher potential alongside the symbol.

Problem-Solving Strategy 20.4

The symbol for a potential difference source has parallel lines of different lengths. The shorter line is conventionally the negative end of the source. Think of it as a minus sign.



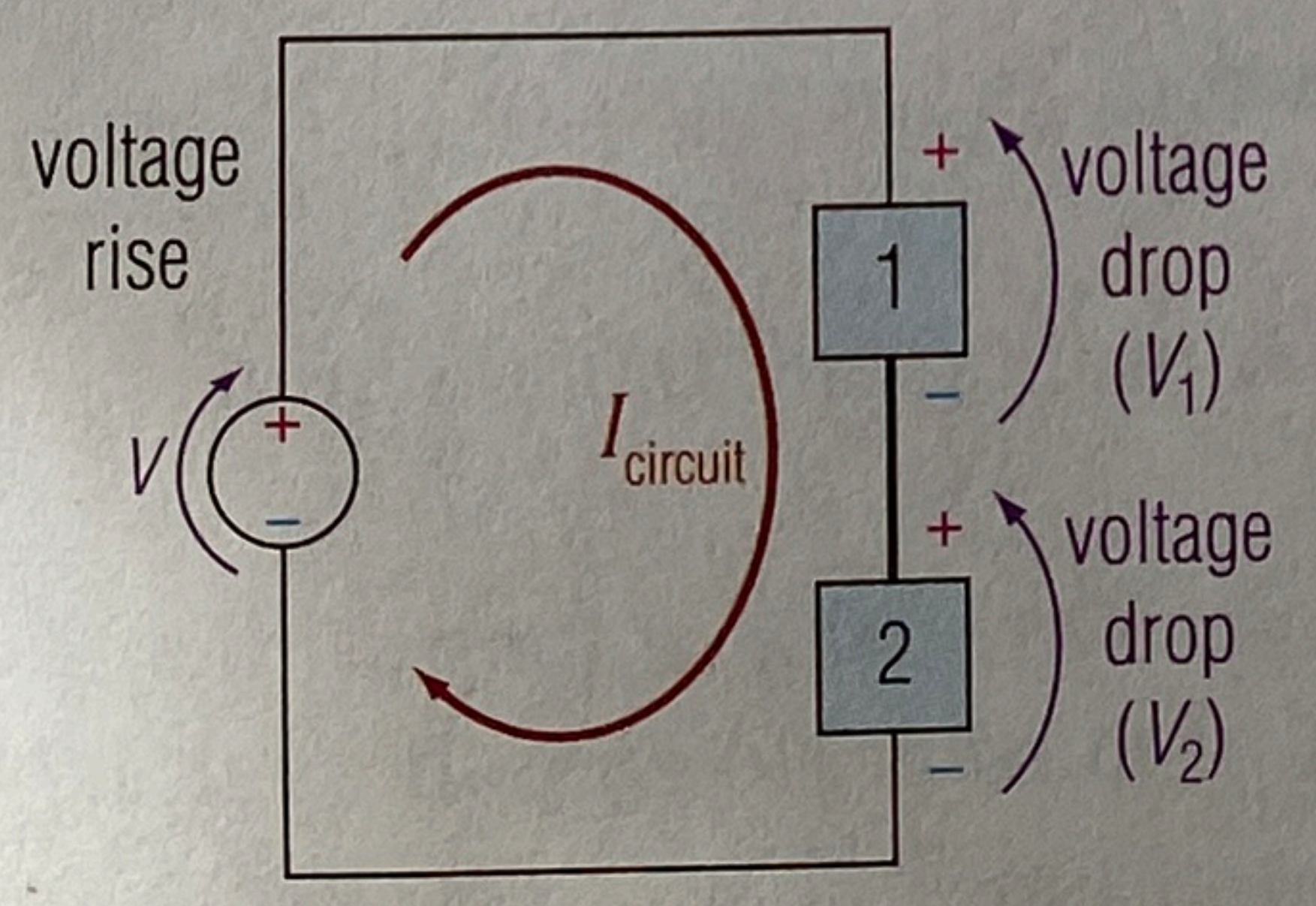
20-9 (a) A series circuit; (b) A parallel circuit



20-10 The points where components are joined to other components or to conductors are indicated on an electrical circuit schematic as a black dot. If lines on a schematic cross without connecting, this fact is indicated by the lack of a dot or an arch in the crossing line.

Electrical components must be connected to each other in order to create a circuit. Their conductors are either permanently connected by soldering (using a type of low-melting-point metal), or they are clamped together using bolts, screws, spring clamps, or some other method.

In a series circuit, the current flows through the circuit components sequentially. Since the circuit does not produce or consume electrons, the current must remain constant throughout the circuit. (That is, electrical current does not speed up or slow down in different parts of a series circuit.) The potential difference changes throughout a series circuit because each circuit component converts some electrical potential energy to kinetic energy of the conductor atoms (thermal energy). Therefore, the electrical potential is higher just before the component than just after the component. This decrease in potential is known as a **voltage drop**. Calling a potential difference "voltage" is similar to talking about the "acreage" of a piece of land, meaning its area. The magnitude of the potential difference across the voltage source is equal to the magnitude of the sum of the voltage drops in the circuit:



20-11 Voltage drops in a series circuit

$$|V_{\text{circuit}}| = |V_1 + V_2 + \ldots + V_n|$$

This is similar to gravitational potential energy. Imagine a forklift that raises a box to a platform 2 m high. The box must fall down two steps in order to return to floor level, where the forklift can raise it again. The sum of the drops through

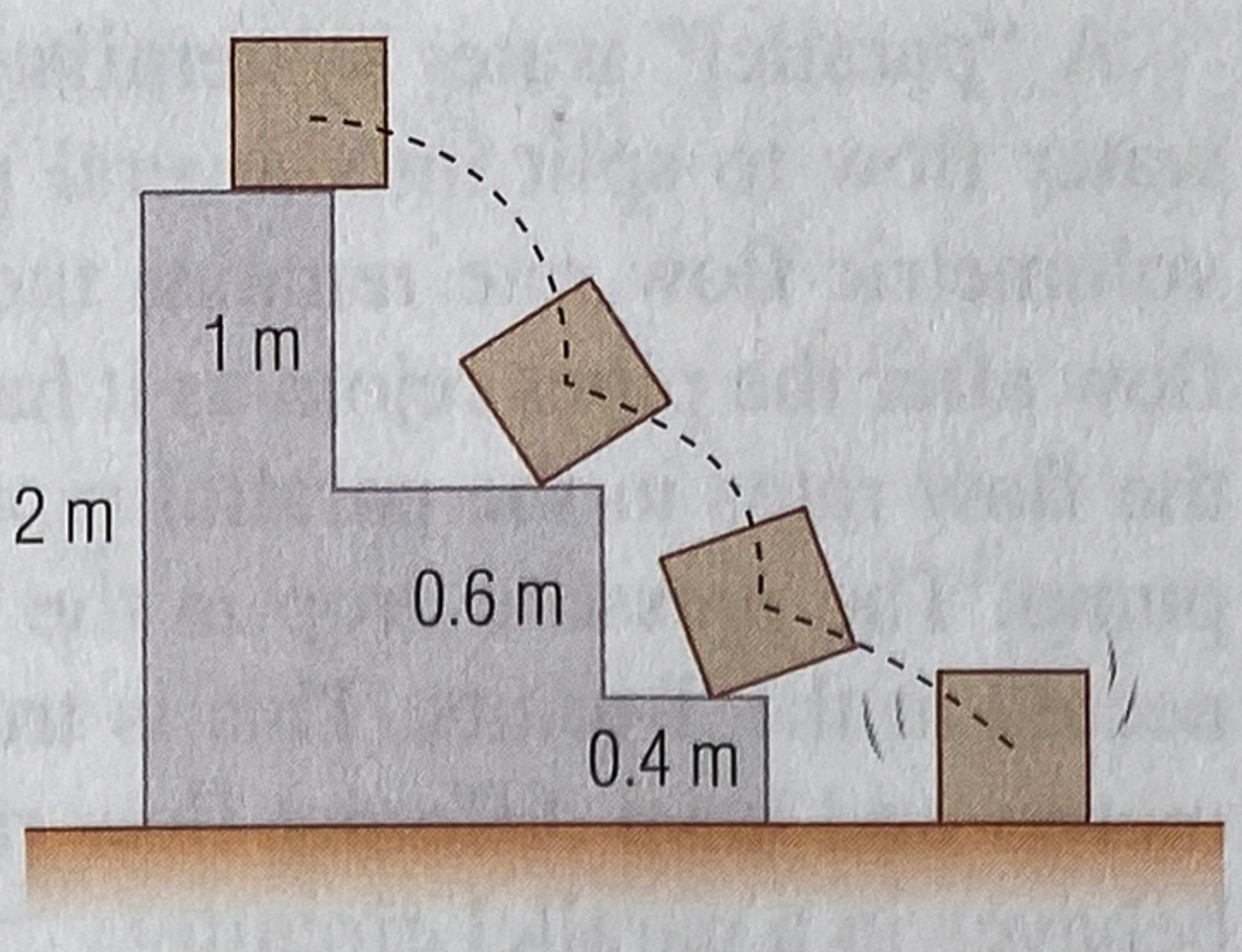
Voltage rises in the direction of current flow through a voltage *source*. Voltage drops as current flows through components connected in a circuit.

which the box falls is equal to the height at which the box was originally. Similarly, the sum of the voltage drops in a series circuit is equal to the potential difference of the voltage source.

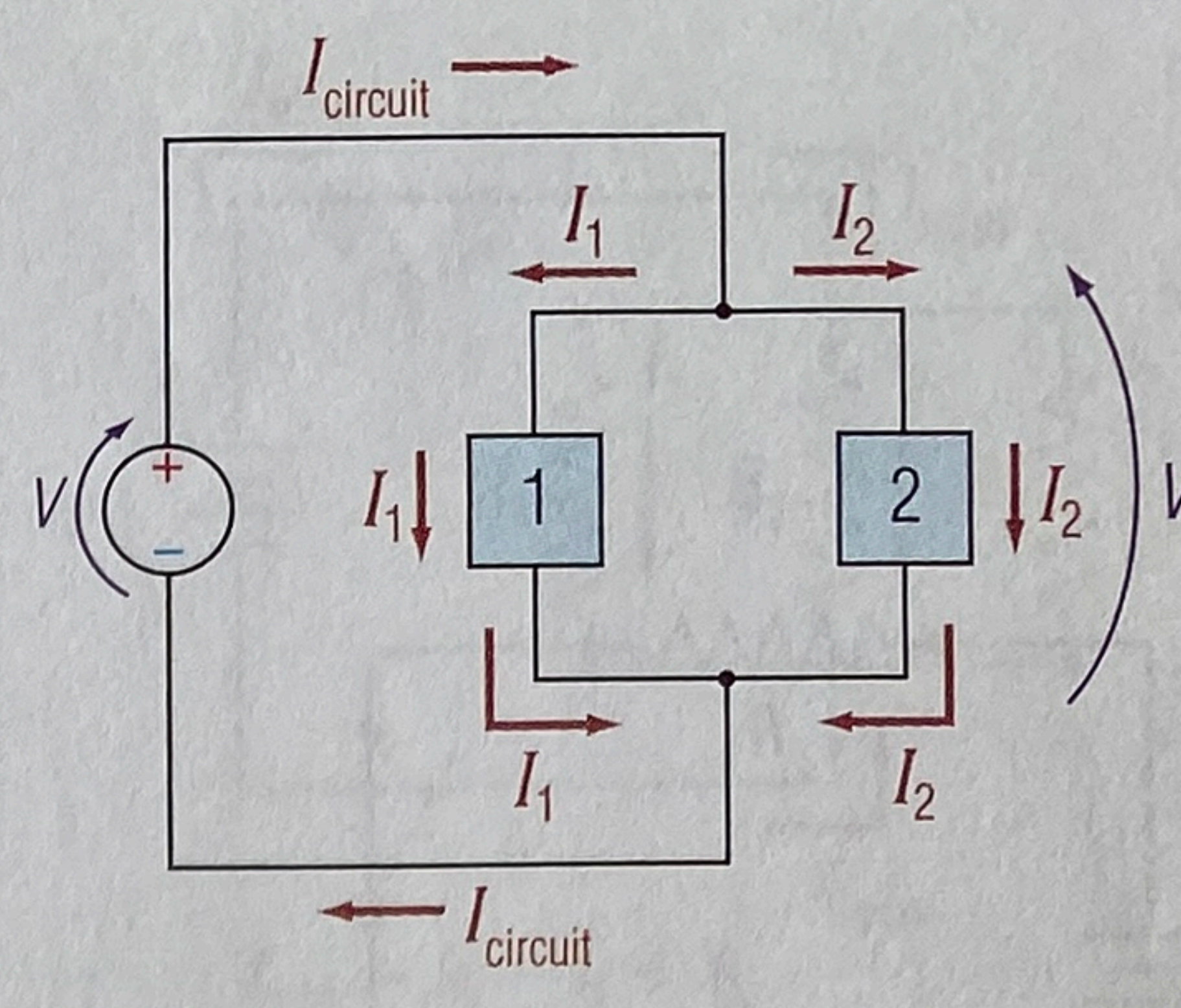
In a parallel circuit, there is more than one path for the current to follow. Since there are no sources or sinks to create or consume electrons, the sum of the currents of the parallel branches is equal to the current entering or leaving the parallel portion of the circuit. In Figure 20-13,

$$I_{\text{circuit}} = I_1 + I_2.$$

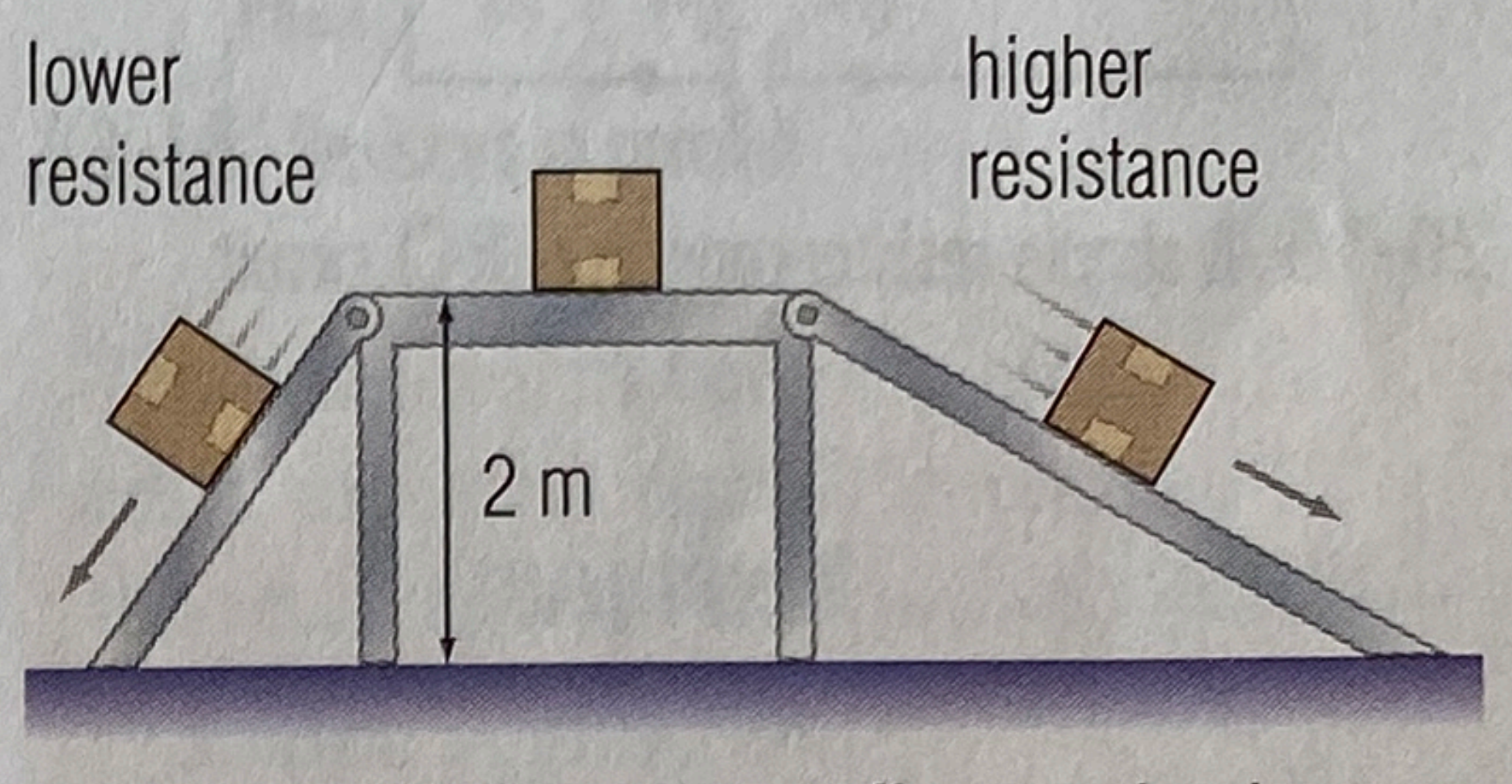
The potential difference is the same across all parallel paths. Returning to the forklift situation, imagine that the forklift raises several boxes 2 m to a platform. There are two ramps from the platform to the floor. Some boxes slide down the steep ramp, and the other boxes slide down the shallow ramp. Both ramps span a 2 m height between the platform and the floor. Therefore, the two ramps have the same gravitational potential. Similarly, all parallel circuit paths have the same potential difference at the points where they are connected together.



20-12 Stepwise drops in gravitational potential energy are analogous to voltage drops in a series circuit.



20-13 Current paths in a parallel circuit

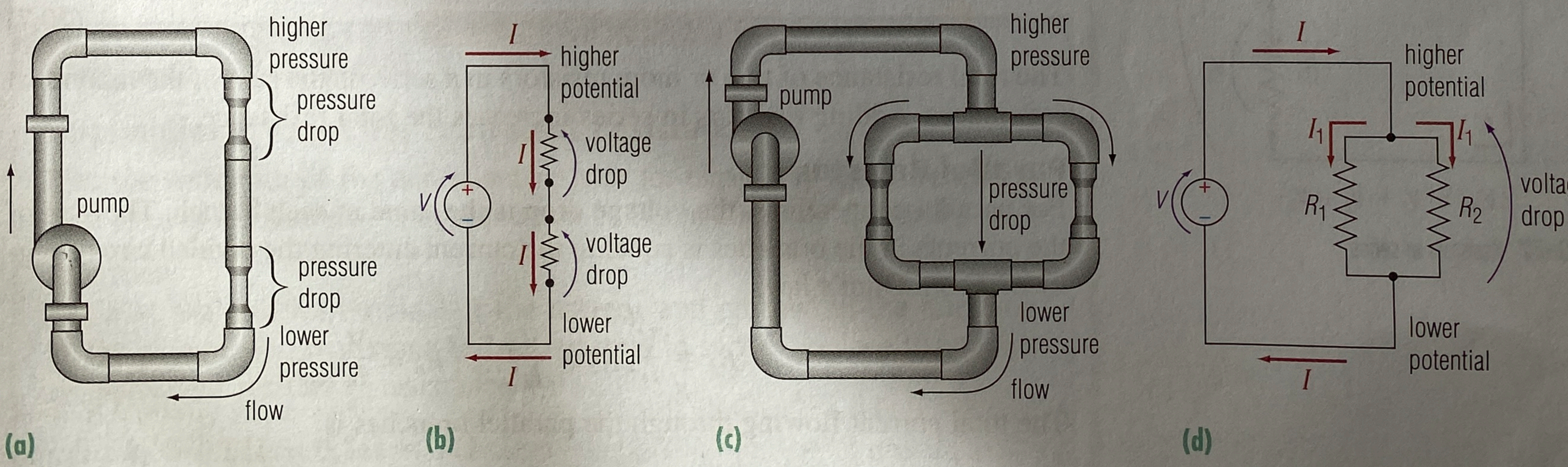


20-14 Boxes sliding down different inclined ramps from the same height are analogous to current falling through the same voltage drop via different paths.

20.10 Plumbing Analogy

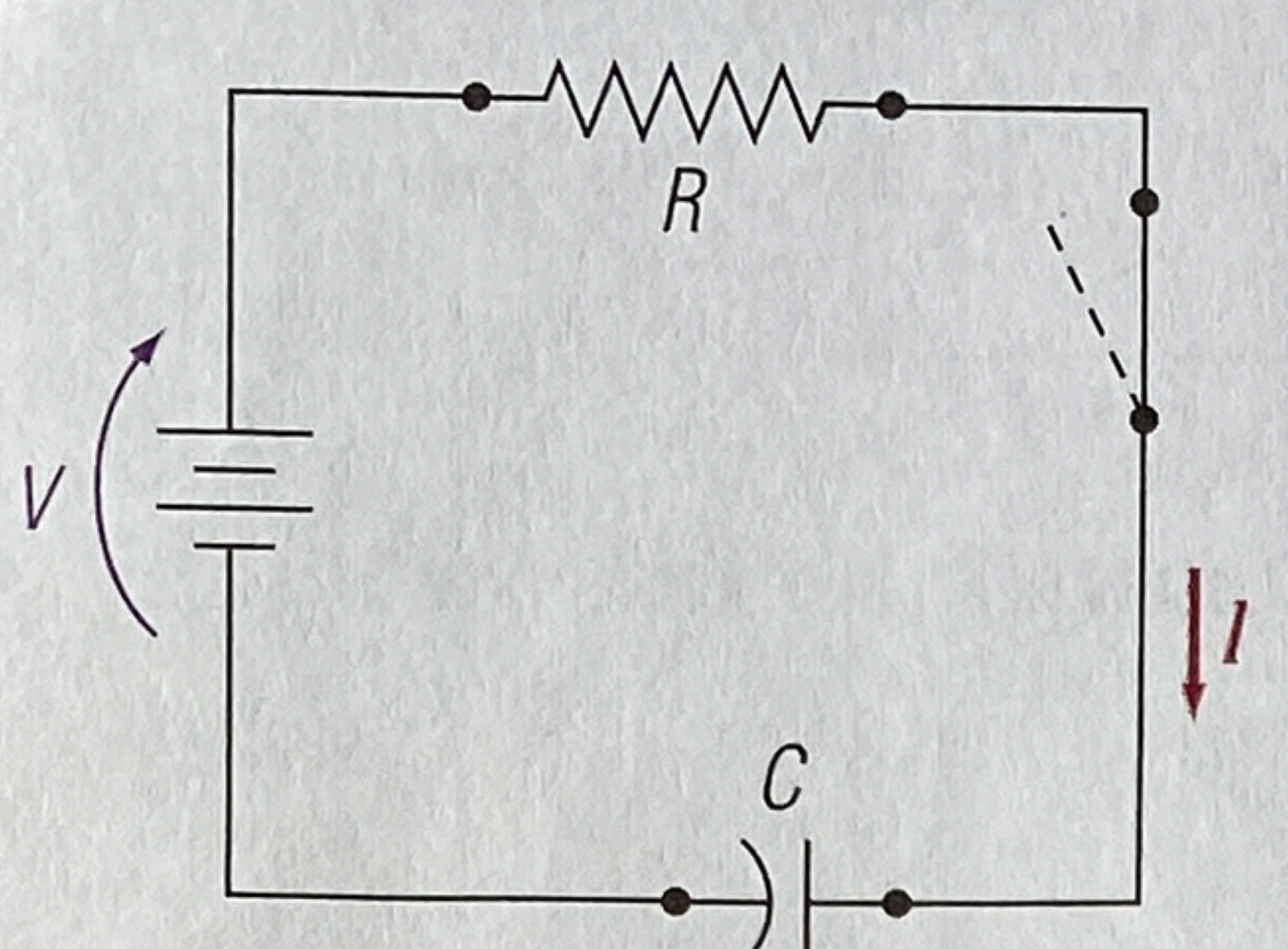
If the principles governing electrical circuits are unfamiliar, an analogy may make them clearer. Electrons flowing through a circuit behave somewhat like water flowing through connected pipes. (This analogy is not perfect, since electrons are not identical to water in pipes, but the similarities can clarify the new ideas.) Current, the flow of charges, is similar to the flow of water. A pump acts as a source of potential difference, and pressure is analogous to voltage. Pressure is highest at the outlet of the pump and lowest at its inlet. Resistance is like the fluid friction that occurs when a constriction is encountered in the pipe. Electrical switches are like valves in a pipe. They open and close the circuit to control current flow.

Consider a "series" water system. The pump raises the pressure of the water at the pump outlet pipe. As the water encounters constrictions, friction causes drops in pressure (see Chapter 17). Since no water is added or removed, all the water must be moving at the same volumetric rate (volume per unit time). The pressure drops are similar to voltage drops. The pipes decrease the water pressure by friction just as wires decrease potential difference by resistance.



20-15 Similarities between water circuits and electrical circuits. Figures (a) and (b) show series circuits; Figures (c) and (d) compare parallel circuits.

A "parallel" water system is also possible. In this system, T-joints allow the water flow to split into several paths. Some water flows in each pipe. The total volumetric flow rate remains the same, so the water must have the same rate of flow after the pipes rejoin as it had before the pipes divided. Therefore, the sum of the flow rates in the parallel pipes is equal to the rate of flow coming out of the pump. The pressure drop in the two arms is the same, since both pipes are connected at the T-joints. This is true even if the parallel pipes are of different diameters and have different flow rates. As was noted before, this is how electricity behaves in a parallel circuit.



20-16 A simple resistor-capacitor (R-C) circuit

Symbol	Meaning
—⊕— V	DC voltage source
—|||— V	battery
$\xrightarrow{I}$	current
—∿∿∿—	resistor
—)|—	capacitor
—⁄ —	switch

The total resistance of series-connected resistors is the simple sum of all individual resistances:
$R_{\text{total}} = R_1 + R_2 + \ldots + R_n$

20.11 Analyzing Circuits

Figure 20-16 is a diagram of a simple circuit. Each circuit component has a symbol that represents it on a diagram. Direct-current potential difference is —⊕— V or —|||— V; current is $\xrightarrow{I}$; resistance is —∿∿∿—; and capacitance is —)|—. A switch, —⁄ —, is used to start and stop current flow by opening and closing the circuit. Circuit schematic symbols can represent properties as well as discrete components. The values of components' properties are often shown adjacent to the components on the diagram.

20.12 Equivalent Resistance

Series Resistances

For series connections, current is uniform and the sum of the voltage drops across each component equals the total voltage drop across all of the series components. Resistance, from Ohm's law, is

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

For resistors in series, the total voltage drop is

$$V_{\text{total}} = V_1 + V_2 + \ldots + V_n.$$

The total resistance is therefore:

$$R_{\text{total}} = \frac{V_{\text{total}}}{I}$$

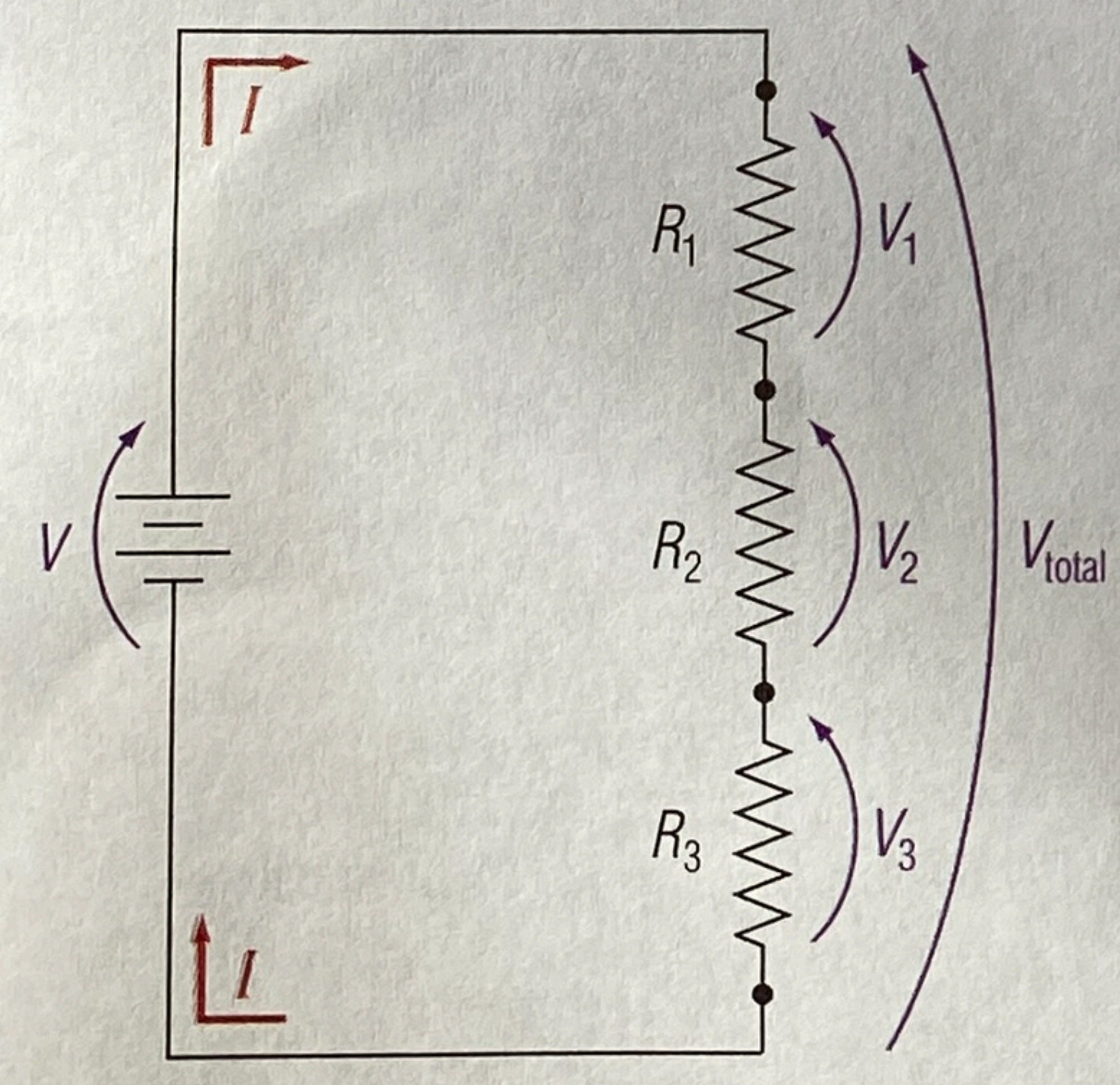
$$R_{\text{total}} = \frac{V_1 + V_2 + \ldots + V_n}{I}$$

$$R_{\text{total}} = \frac{V_1}{I} + \frac{V_2}{I} + \ldots + \frac{V_n}{I}$$

But V_1/I is R_1, V_2/I is R_2, and so forth, so

$$R_{\text{total}} = R_1 + R_2 + \ldots + R_n. \qquad (20.7)$$

The total resistance of two or more resistors in a series is the sum of the individual resistances. Adding resistors in series increases the total resistance.



$V_{\text{total}} = V_1 + V_2 + V_3$

20-17 Resistors in series

Parallel Resistances

For parallel connections, the voltage drop is the same in each branch. The sum of the currents in the branches is equal to the current entering the divided circuit segment. From Ohm's law,

$$R_1 = \frac{V}{I_1};\ R_2 = \frac{V}{I_2};\ \ldots;\ R_n = \frac{V}{I_n}.$$

The total current flowing through the parallel branches is

$$I_{\text{total}} = I_1 + I_2 + \ldots + I_n.$$

Therefore, the combined resistance of the resistors is

$$R_{\text{total}} = \frac{V}{I_{\text{total}}}, \text{ or}$$

$$R_{\text{total}} = \frac{V}{I_1 + I_2 + \ldots + I_n}.$$

Taking the reciprocal of each side gives

$$\frac{1}{R_{\text{total}}} = \frac{I_1 + I_2 + \ldots + I_n}{V}, \text{ or}$$

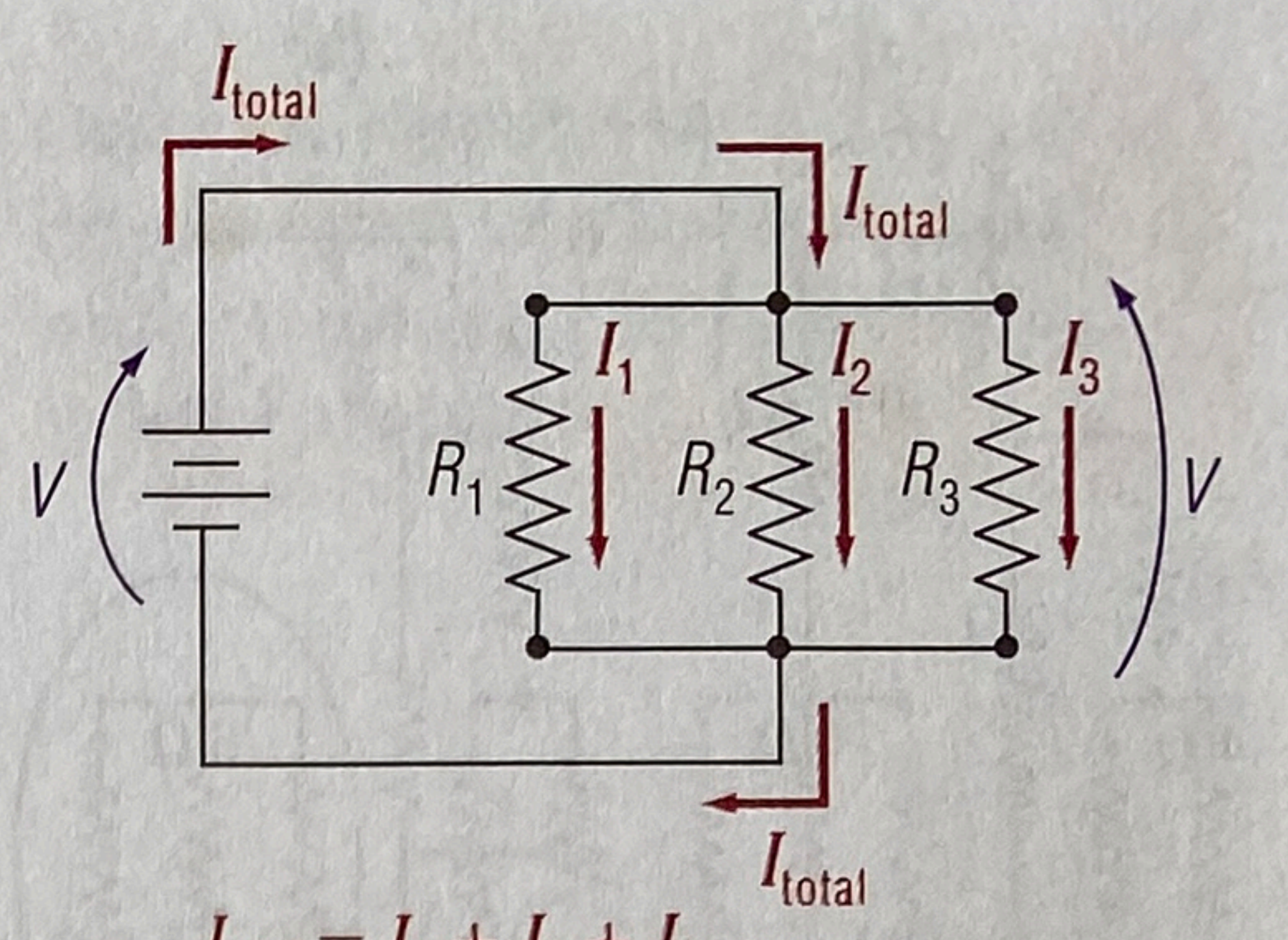
$$\frac{1}{R_{\text{total}}} = \frac{I_1}{V} + \frac{I_2}{V} + \ldots + \frac{I_n}{V}.$$

The terms I_1/V, I_2/V, and I_n/V are the reciprocals of R_1, R_2, and R_n, respectively:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n} \qquad (20.8)$$

The total resistance of two or more resistors in parallel is the reciprocal of the sum of the reciprocals of the individual resistances. Resistors connected in parallel have less total resistance than any of the individual resistors. Adding more resistors in parallel decreases the total resistance.

A technique used to simplify circuits for analysis is that of replacing several resistors with an equivalent resistor (R_{eq}). For example, circuit (a) in Figure 20-19 looks complicated, but it can theoretically be replaced by circuit (h), which has only one equivalent resistor. The replacement must be done in steps. It uses only the two resistance rules just discussed.



$$I_{\text{total}} = I_1 + I_2 + I_3$$
$$V_{\text{total}} = V_1 = V_2 = V_3$$
$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

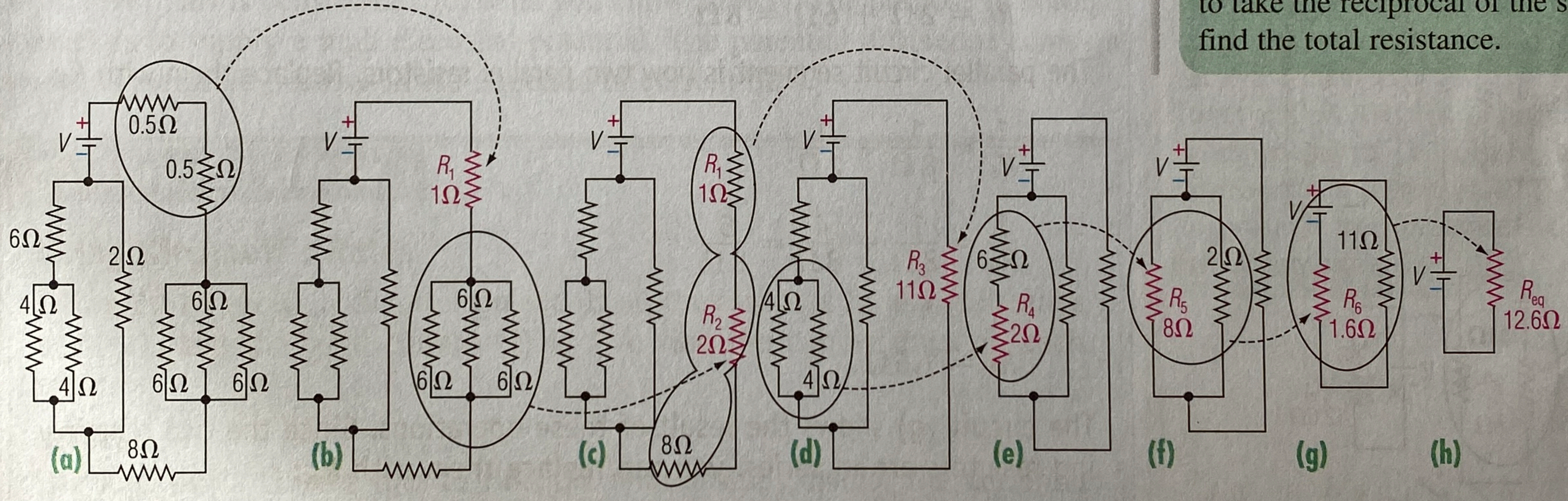
20-18 Resistors in parallel

The total resistance of a group of resistances connected in parallel is the reciprocal of the sum of the reciprocals of the individual resistances:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

Problem-Solving Strategy 20.5

After summing the reciprocals of the parallel resistances, remember to take the reciprocal of the sum to find the total resistance.



20-19 Simplifying a resistance circuit

EXAMPLE 20-1

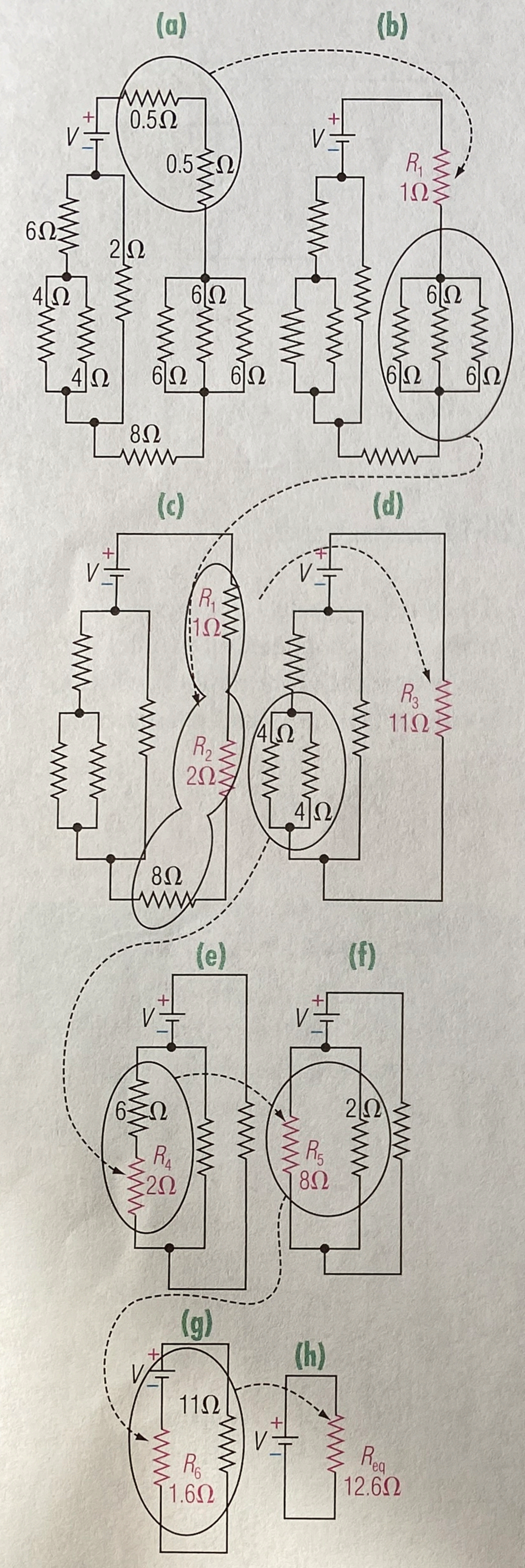
Uncomplicate Your Life: Equivalent Resistance

Find the resistance of the equivalent resistor for circuit (a) in Figure 20-19. (The circuits in Figure 20-19 appear again as Figure 20-20 on the next page.)

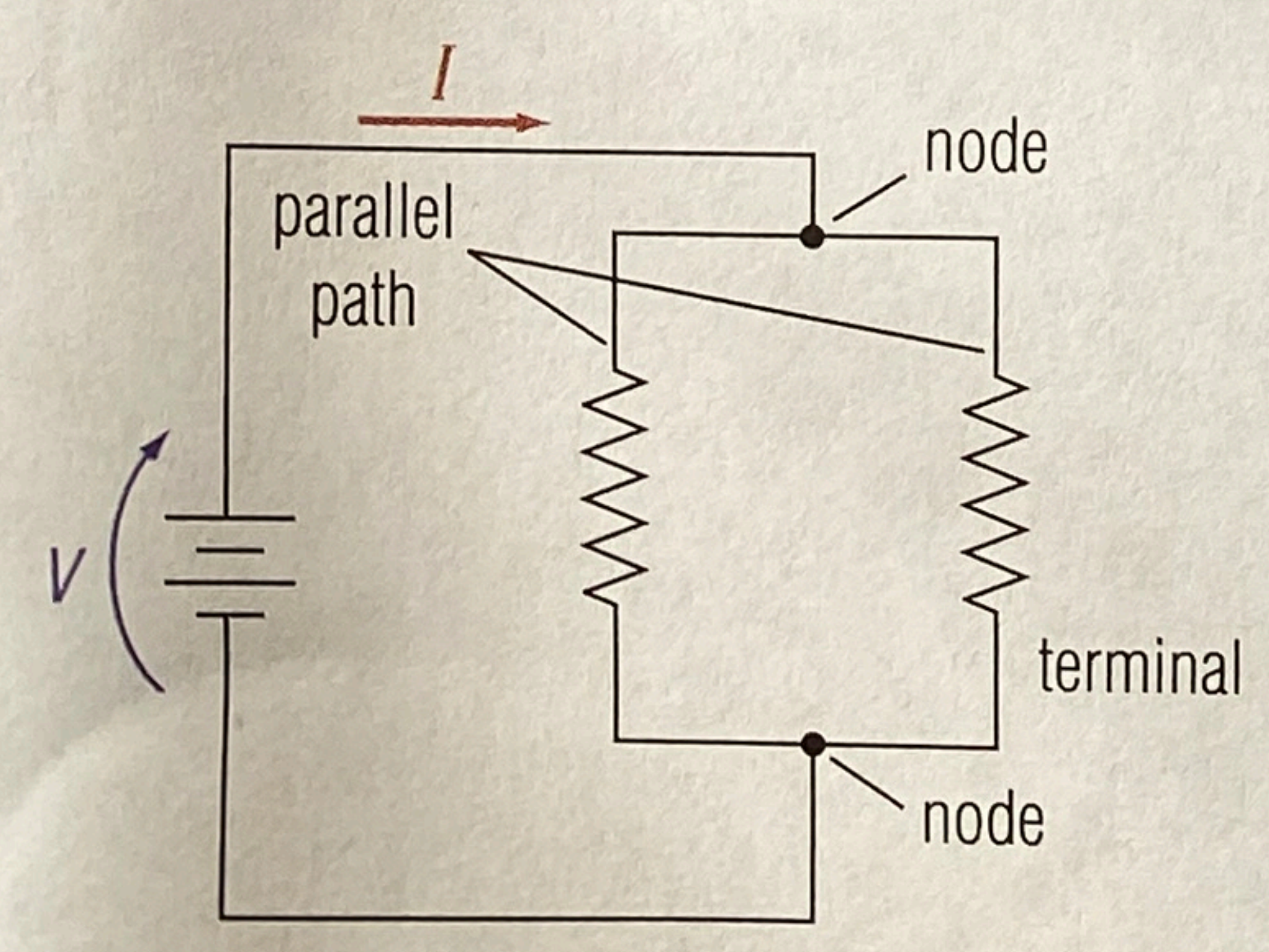
Solution:

Begin at the positive terminal of the battery, and proceed in the direction of the current. You first come to two resistors in series. Replace them with an equivalent resistor of resistance R_1:

$$R_1 = 0.5\,\Omega + 0.5\,\Omega = 1\,\Omega$$



20-20 Simplifying a resistance circuit, from Figure 20-19



20-21 A node is a junction in a circuit where current divides or converges.

Circuit (b) is the result. Now notice that there are three resistors in parallel. Replace them with R_2:

$$\frac{1}{R_2} = \frac{1}{6\,\Omega} + \frac{1}{6\,\Omega} + \frac{1}{6\,\Omega}$$

$$\frac{1}{R_2} = \frac{3}{6\,\Omega} = \frac{1}{2\,\Omega}$$

$$R_2 = 2\,\Omega$$

Circuit (c) is the result. Notice the three resistors in series. Replace them with R_3:

$$R_3 = 1\,\Omega + 2\,\Omega + 8\,\Omega$$

$$R_3 = 11\,\Omega$$

Now you have circuit (d). You have reached the complicated parallel arrangement. Simplify the left branch first. The parallel resistors can be replaced with R_4:

$$\frac{1}{R_4} = \frac{1}{4\,\Omega} + \frac{1}{4\,\Omega}$$

$$\frac{1}{R_4} = \frac{2}{4\,\Omega} = \frac{1}{2\,\Omega}$$

$$R_4 = 2\,\Omega$$

The branch now has two series resistors. Replace them with R_5:

$$R_5 = 2\,\Omega + 6\,\Omega = 8\,\Omega$$

The parallel circuit segment is now two parallel resistors. Replace them with R_6:

$$\frac{1}{R_6} = \frac{1}{8\,\Omega} + \frac{1}{2\,\Omega}$$

$$\frac{1}{R_6} = \frac{1}{8\,\Omega} + \frac{4}{8\,\Omega} = \frac{5}{8\,\Omega}$$

$$R_6 = 1.6\,\Omega$$

The circuit (g) shows the result of these operations. Since the two remaining resistors are in series, you can replace them with R_{eq}:

$$R_{eq} = 11\,\Omega + 1.6\,\Omega$$

$$R_{eq} = 12.6\,\Omega$$

The circuit (h) contains one equivalent resistor. Circuit simplification may take a long time, but it is not hard if you consistently apply the proper rules.

In complicated circuits, it is sometimes difficult to tell where the parallel part of a circuit begins. The place where a current divides or converges is called a **node** and is represented on a circuit diagram by a connection dot. Parallel paths begin and end at a node, as in Figure 20-21.

20.13 Kirchhoff's Rules

The rules for current and potential difference in series and parallel circuits can be summed up by two general rules called **Kirchhoff's rules**:

1. The sum of voltage drops in a simple *closed* path equals the sum of voltage rises in the path. A simple closed path does not contain any cross-connecting paths. In other words, the algebraic sum of the voltage drops and the voltage rises in the path is zero.
2. The sum of currents entering a node equals the sum of currents leaving the node. In other words, the algebraic sum of the currents entering and leaving a node is zero.

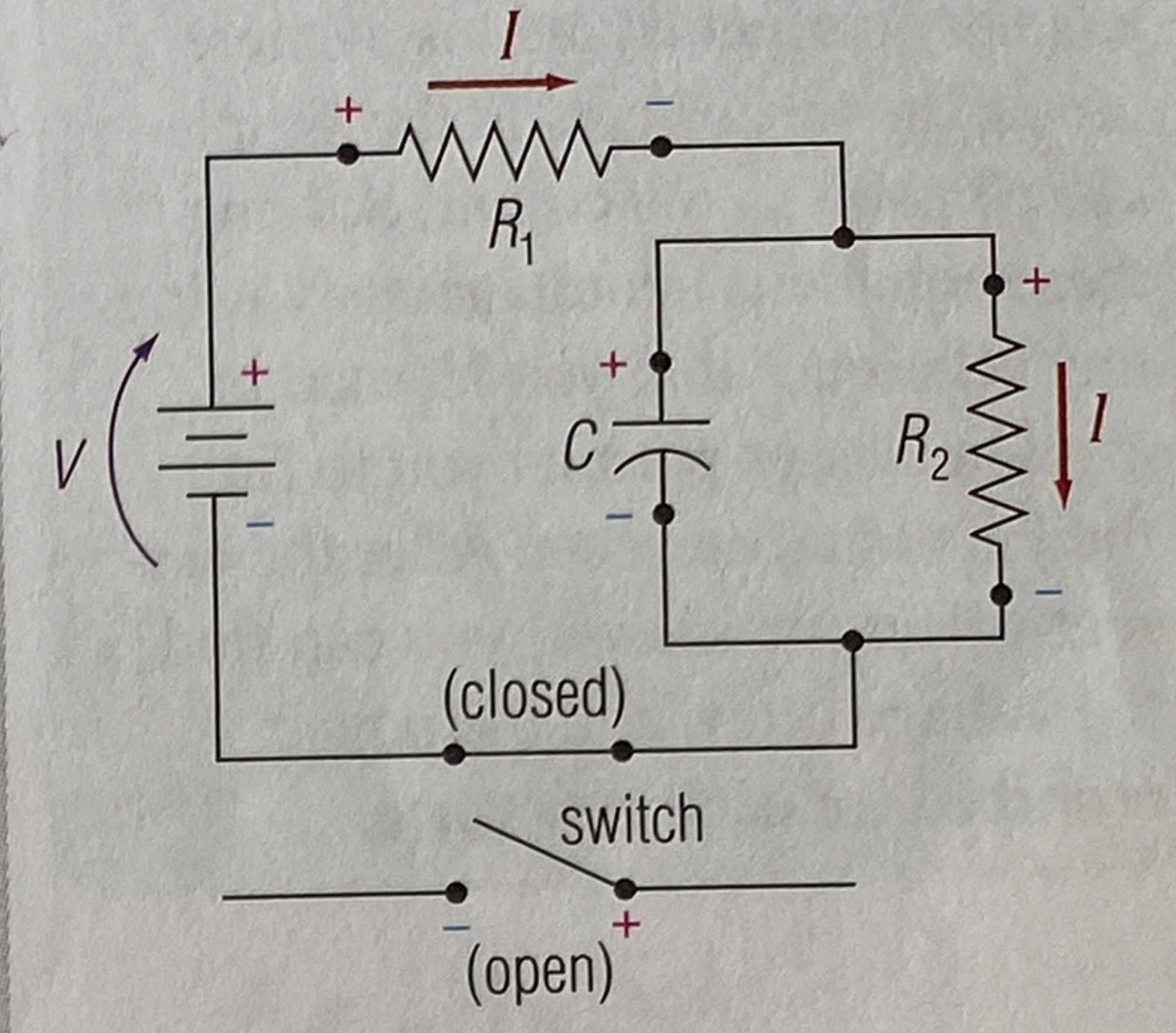
For these laws to be valid, the rules for positive and negative signs must be consistent. To be consistent, you should begin the analysis of any circuit diagram by assigning positive and negative sides to each circuit component (Figure 20-22). Start with the positive side of the voltage source (the battery in this instance), and proceed in the direction of the current. Mark the first side of any circuit component you reach positive, and mark the other side negative. In this way current always flows from positive to negative.

Notice in Figure 20-22 that the current crosses all voltage drops (the resistors) from positive to negative. For all components in a circuit other than the source, the potential is higher at the current inlet of the component and lower at the outlet. This is understandable since current flows down the potential "hill." The potential difference, ΔV, for these components is therefore negative:

$$\Delta V = V_{\text{out}} - V_{\text{in}}$$

However, the current crosses the source of voltage (the battery) from negative to positive. This is consistent with what you know already. The purpose of voltage sources is to supply a high electrical potential. The potential difference across a source is therefore positive in the direction of current flow.

Gustav Kirchhoff (1824–87) was a Prussian physicist known for his work on electrical currents and spectral analysis.

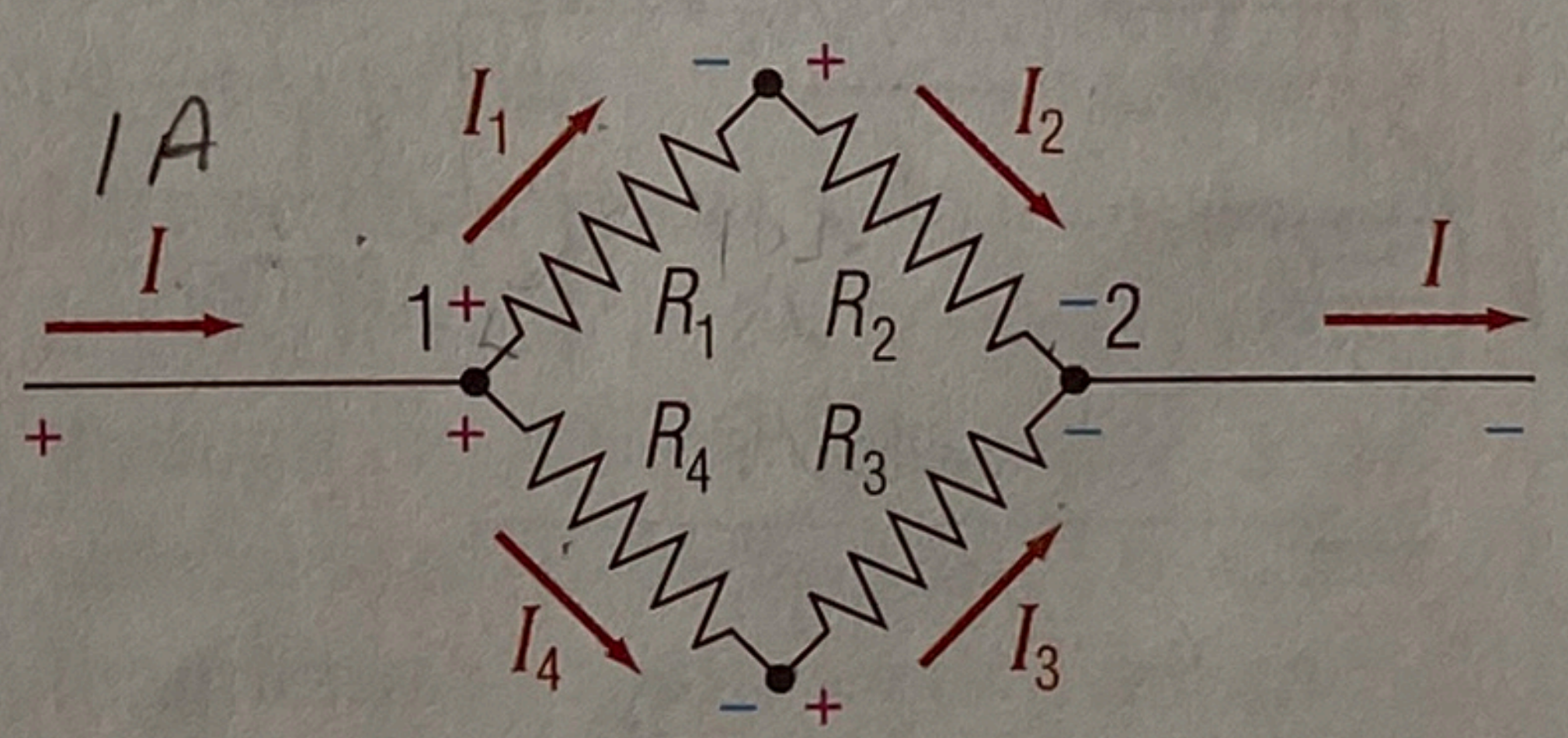


20-22 Assigning positive and negative polarities in a circuit

Problem-Solving Strategy 20.6

When applying Kirchhoff's voltage rule, remember that voltage *rises* across voltage sources (ΔV is positive) and *drops* across other circuit components (ΔV is negative) for conventional current flow. The opposite is true for negative (electron) current flow.

All R = 10 Ω



20-23 Current leaving a node must equal the current entering a node.

EXAMPLE 20-2

Using Kirchhoff's Rules

Figure 20-23 shows a circuit segment. If all the resistors have a resistance of 10 Ω, and the total current (I) is 1 A, find the current through each resistor.

Solution:

Use Kirchhoff's current rule to find the relationships among the currents. At node 1,

$$I = I_1 + I_4$$
$$1\text{ A} = I_1 + I_4.$$

At node 2,

$$I_2 + I_3 = I$$
$$I_2 + I_3 = 1\text{ A}.$$

You obtained no new information from node 2. That will be the case as long as there are no nodes between nodes 1 and 2. You can get more specific information from Kirchhoff's voltage rule. The only *closed* path in the figure is the path that goes through R_1, R_2, R_3, and R_4 in that order or the reverse order. Kirchhoff's voltage rule gives

$$V_1 + V_2 + V_3 + V_4 = 0\text{ V},$$

since there is no voltage source along the path. Note that V_1 and V_2 are negative and the other two voltages are positive along the specified path, according to the convention we are using. Apply Ohm's law to find these voltage drops.

$$(-I_1R_1) + (-I_2R_2) + I_3R_3 + I_4R_4 = 0\text{ V}. \qquad (1)$$

Since R_1 and R_2 are in series, and R_3 and R_4 are in series, then the currents through the respective pairs of resistors are equal. Therefore,

$$I_1 = I_2 = I_{1,2} \text{ and } I_3 = I_4 = I_{3,4}.$$

Substitute for currents and rearrange terms in Equation (1):

$$I_{3,4}(R_3 + R_4) = I_{1,2}(R_1 + R_2)$$

$$I_{3,4}(10\,\Omega + 10\,\Omega) = I_{1,2}(10\,\Omega + 10\,\Omega)$$

$$I_{3,4} = I_{1,2}$$

Then, $I_1 = I_2 = I_3 = I_4$.

To find the values of the currents, use the results of the current rule at node 1.

$$1\text{ A} = I_1 + I_4 = I_{1,2} + I_{3,4}$$

$$1\text{ A} = I_{1,2} + I_{1,2} = 2\,I_{1,2}$$

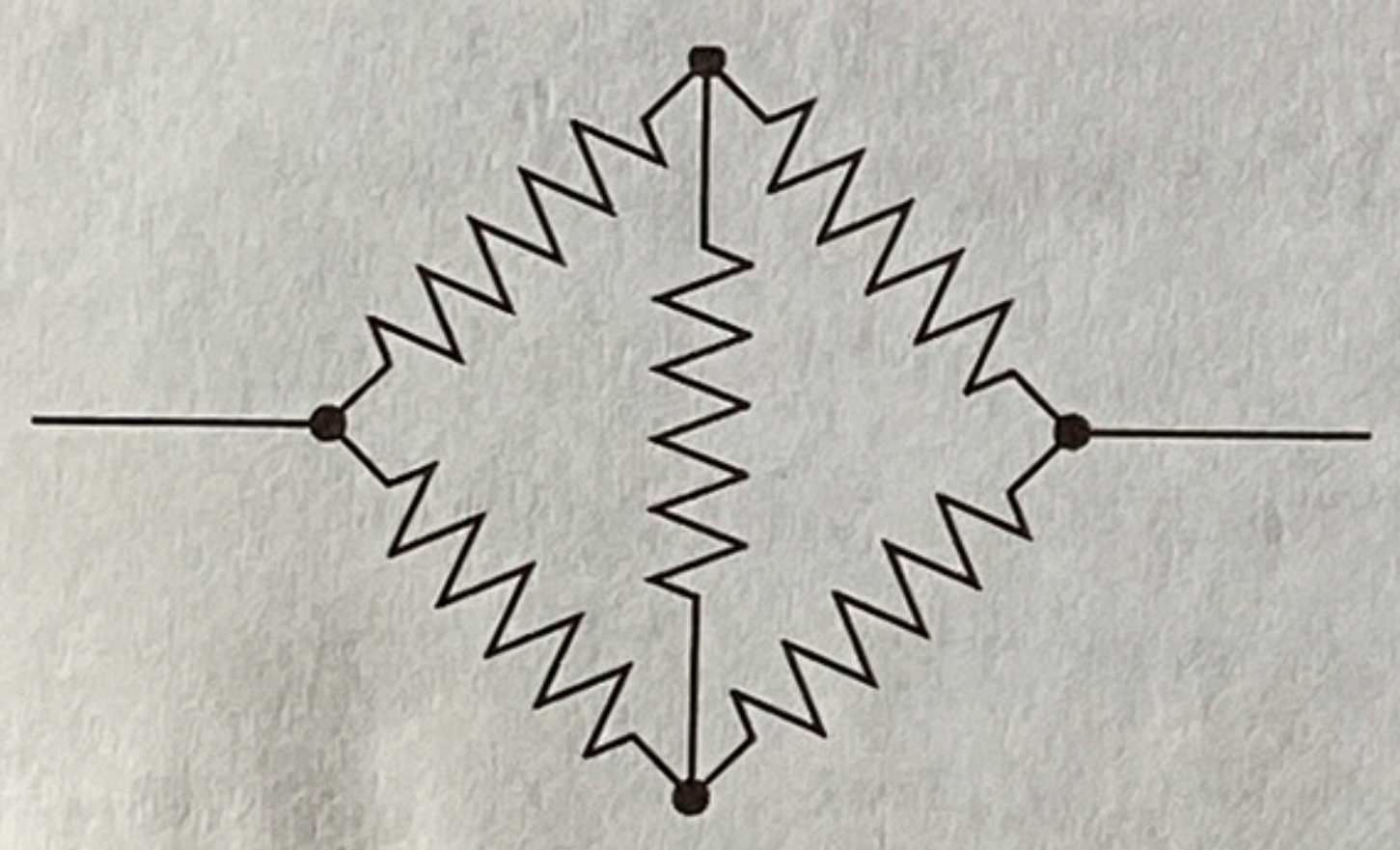
$$I_{1,2} = 0.5\text{ A}$$

$$I_1 = I_2 = I_3 = I_4 = 0.5\text{ A}$$

The current through every resistor is 0.5 A.

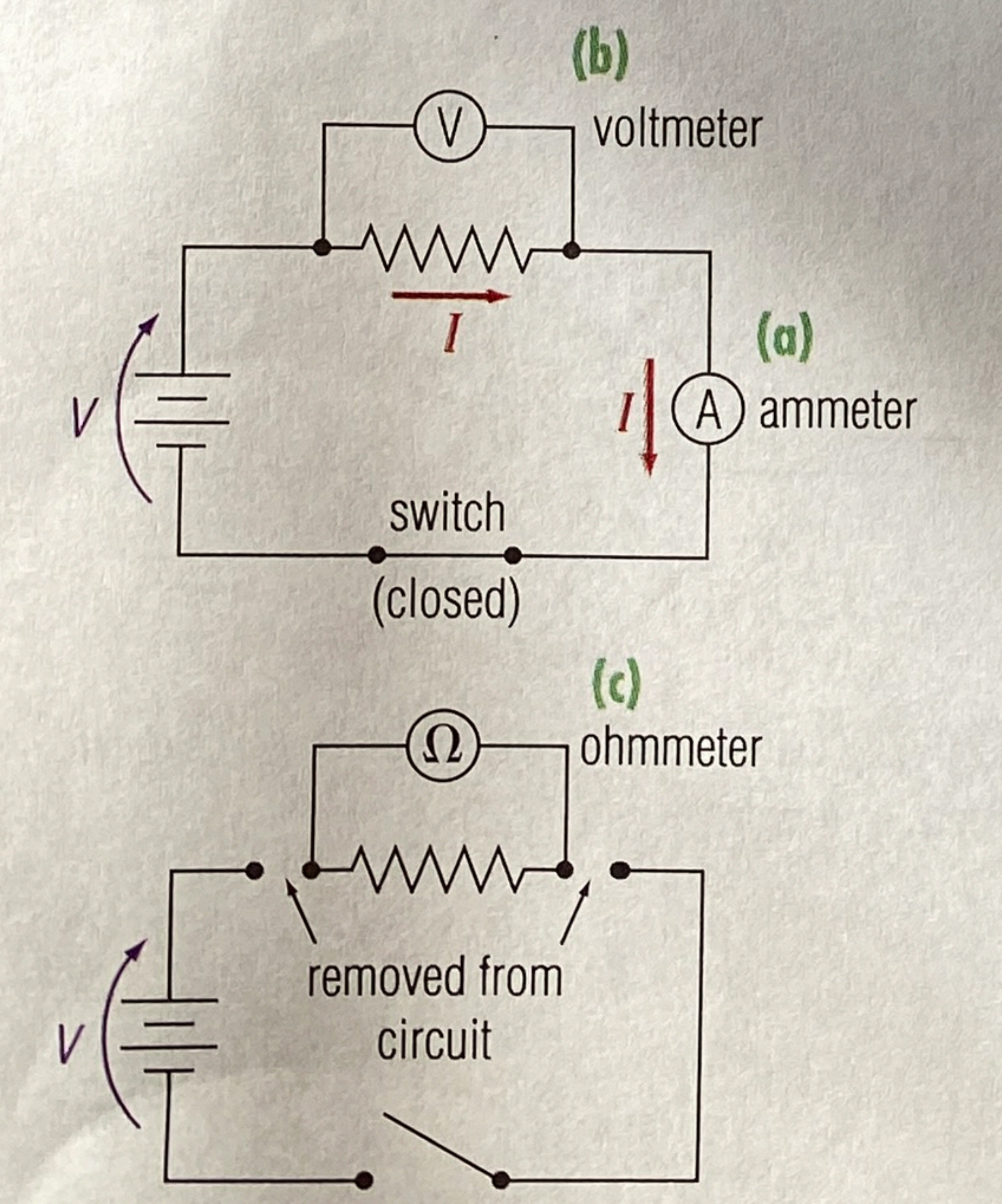
Problem-Solving Strategy 20.7

Kirchhoff's rules are used to generate as many current equations as there are unknown currents in the simple closed paths in the circuit. Solving these equations simultaneously using the techniques that you learned in algebra classes permits you to find the individual currents. After the current values are known, you can find the voltage drops and the power absorbed for each resistance.



20-24 A circuit segment that cannot be simplified into an equivalent resistance

This example could have been done as easily by using equivalent resistances to calculate the voltage drop across the segment and then using that value in Ohm's law to find the current in each branch. However, some circuits cannot be simplified using equivalent resistances because there are multiple paths that the current can follow. For example, the circuit segment in Figure 20-24 would have to be analyzed using Kirchhoff's rules.



20-25 Electrical schematics showing the connections and symbols for using (a) an ammeter, (b) a voltmeter, and (c) an ohmmeter

20.14 Electrical Instruments

To calculate any quantity associated with a circuit, you must have some information. You will usually obtain this information by using instruments to detect the basic quantities. An **ammeter** measures current. A **galvanometer** is a sensitive ammeter for detecting very small currents. Devices to measure current must be connected to the energized circuit in series with the current being measured.

An **ohmmeter** measures resistance. It is not connected in a circuit because it contains its own source of potential difference. An ohmmeter can be connected to a single component, a circuit segment, or an entire circuit, as long as there is no outside source of voltage present that could damage the instrument.

A **voltmeter** measures the voltage drop or rise across an energized circuit component. The instrument is connected to the circuit in parallel with the component for which the voltage is being measured.

20-26 An ammeter, a voltmeter, and a galvanometer; the analog and digital multimeters (in back and right) can act as an ohmmeter as well as an ammeter and a voltmeter.

20.15 Resistance Bridges

Figure 20-27a demonstrates the analysis of a somewhat complicated resistance circuit. Such a circuit is called a **bridge circuit** and is commonly used to accurately measure temperatures using a *resistance temperature detector (RTD)*. This circuit segment consists of two standard resistors, one precise variable resistor, and a galvanometer. The unknown resistor, labeled R_x (e.g., the RTD), is connected as Figure 20-27a shows. The *variable resistor* is adjusted until the galvanometer detects no current. Now the circuit is analyzed using Kirchhoff's rules. In Figure 20-27b, the potential difference rule for the left-hand path gives

$$-I_1R_x + I_2R_3 = 0\text{ V}$$

$$I_1R_x = I_2R_3. \tag{20.9}$$

For the right-hand path in Figure 20-27b, the potential difference rule gives

$$-I_1R_1 + I_2R_2 = 0\text{ V}$$

$$I_1R_1 = I_2R_2. \tag{20.10}$$

Now divide Equation 20.9 by Equation 20.10:

$$\frac{I_1R_x}{I_1R_1} = \frac{I_2R_3}{I_2R_2}$$

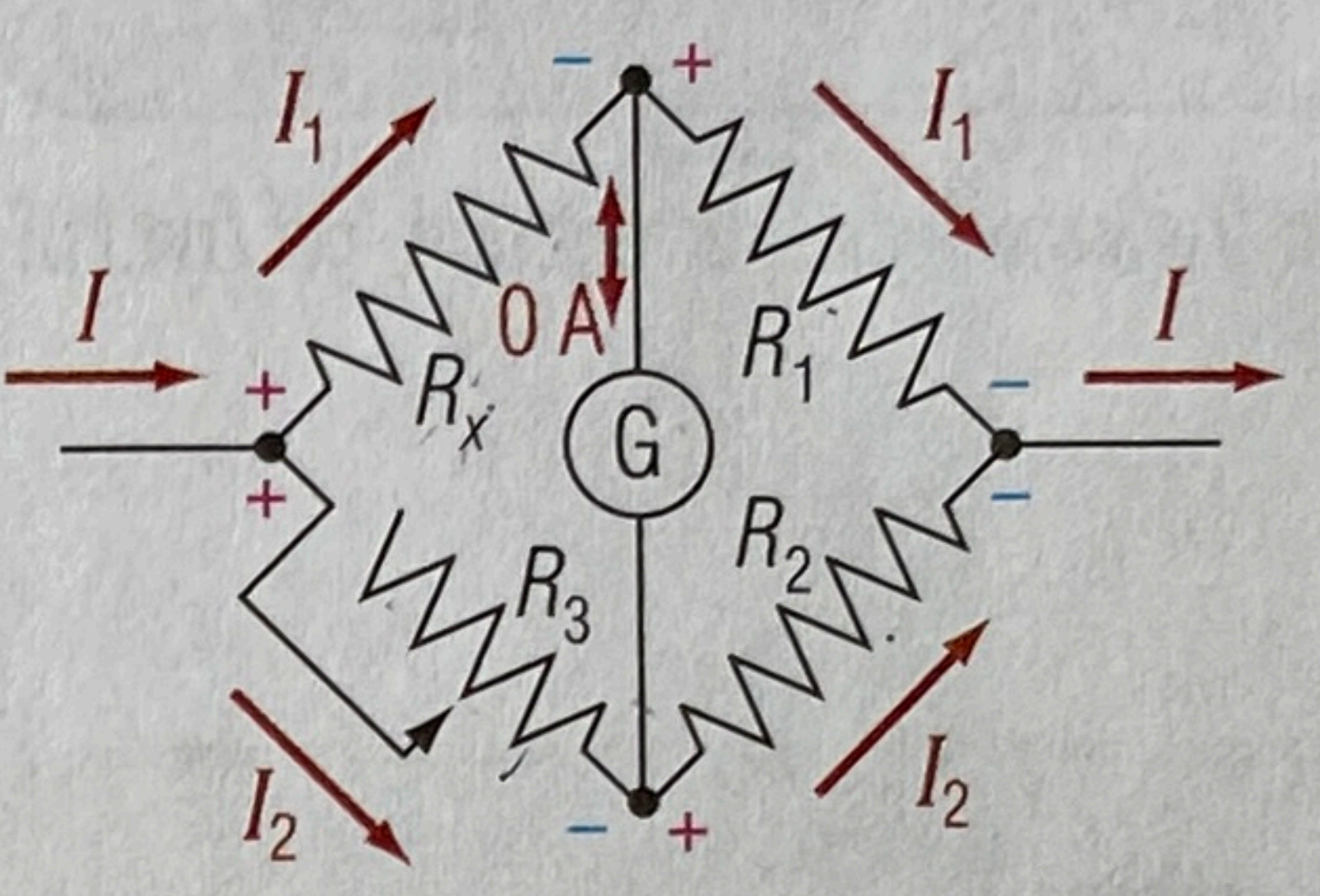
$$\frac{R_x}{R_1} = \frac{R_3}{R_2}$$

$$R_x = \frac{R_1R_3}{R_2} \tag{20.11}$$

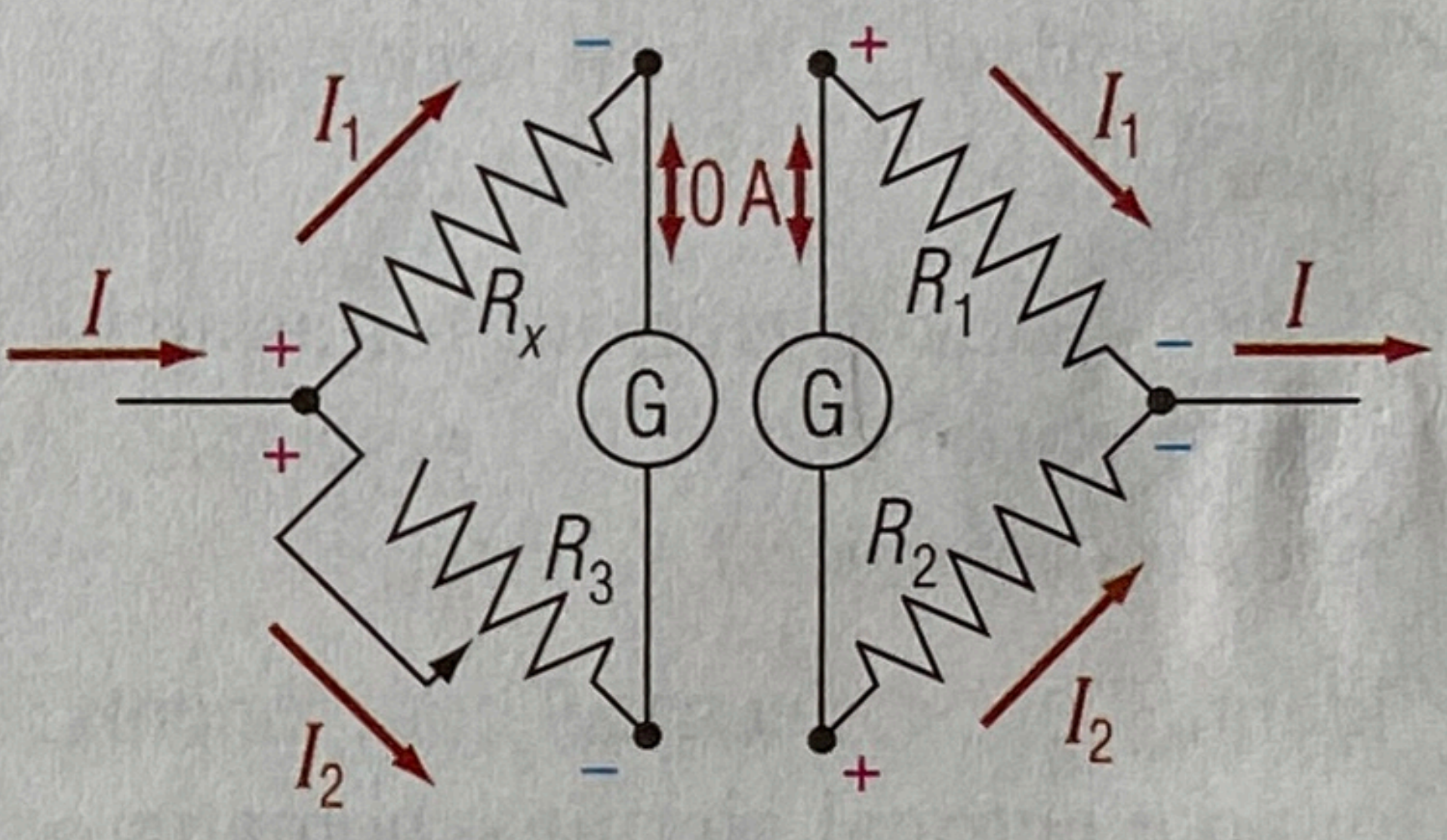
Equation 20.11 can give the unknown resistance precisely, and it requires only simple calculations.

A more detailed discussion of the various electrical meters and their uses is provided in Appendix E of the Lab Manual.

G = galvanometer
= measures current



20-27a A resistance bridge circuit segment



20-27b A resistance bridge broken down into two equivalent closed paths for analysis using Kirchhoff's current rule

A **variable resistor**, , is capable of providing any resistance between two preset values by changing the length of the current path through the resistor. Typically, a variable resistor is constructed of a very long length of wire coiled around a support. A metal "wiper" is connected to one end of the circuit, and one end of the resistor's wire coil is connected to the other end of the circuit. As the current flows through the wiper resting on the wire coil, the current path length varies depending how far the wiper is from the connected end of the coil. Such a variable resistor is called a **rheostat**.

TABLE 20-3

RTD Resistance Data

Temperature (°C)	RTD (Ω)†
0	1000.0
10	1039.0
20	1077.9
30	1116.7
40	1155.4
50	1194.0
60	1232.4
70	1270.8
80	1309.0
90	1347.1
100	1385.1

†URL: http://www.weedinstrument.com/pdf/rvt.PDF

20B Objectives

After completing this section, I can

- ✓ differentiate between series and parallel electrical circuits.
- ✓ discuss the conventions for assigning potential drops and potential rises in a simple DC circuit.
- ✓ identify basic electrical components in an electrical circuit schematic.
- ✓ determine the equivalent resistance for various arrangements of resistors in a simple DC circuit.
- ✓ analyze simple DC circuits using Kirchhoff's rules.
- ✓ describe the purpose of basic electrical instruments and how to make connections when using them.
- ✓ find an unknown resistance using a resistance bridge circuit.

EXAMPLE 20-3

Circuit Analysis: The RTD Bridge

Refer to Figure 20-27a on the previous page. In order to accurately measure the temperature in a cooled-down nuclear reactor plant pipe, an RTD is monitored using the following bridge resistance readings: $R_1 = 1500.\ \Omega$ and $R_2 = 2500.\ \Omega$. The variable resistor, R_3, is adjusted to a value of 1796.5 Ω in order to zero the galvanometer reading. (a) What is the resistance of the RTD (R_{RTD}) for the temperature in the reactor pipe? (b) What is the temperature in the pipe?

a. Substituting the values of the known resistances into Equation 20.11, you have

$$R_{\mathrm{RTD}} = \frac{R_1R_3}{R_2}$$

$$R_{\mathrm{RTD}} = \frac{(1500.\cancel{\Omega})(1796.5\ \Omega)}{2500.\cancel{\Omega}}$$

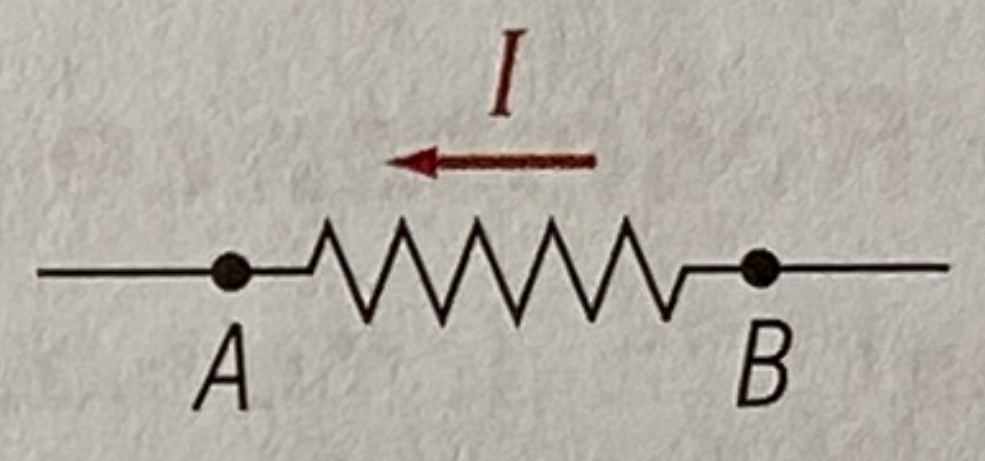
$$R_{\mathrm{RTD}} \cong 1078\ \Omega.$$

b. According to Table 20-3, the piping temperature is 20 °C.

20B Section Review

1. Is the switch for your kitchen ceiling light arranged in series or parallel with the light fixture? Explain your answer.

2. Which point is at the higher potential in the figure? Explain.



3. State Kirchhoff's voltage rule and his current rule in your own words.

4. List the three basic electrical instruments, how they are connected when in use, and the condition of the circuit/component when a measurement is being taken (i.e., energized/de-energized, connected/disconnected to a circuit, etc.)

5. What kind of circuit is used to find the value of an unknown resistance in the circuit by balancing the currents flowing through its two branches?

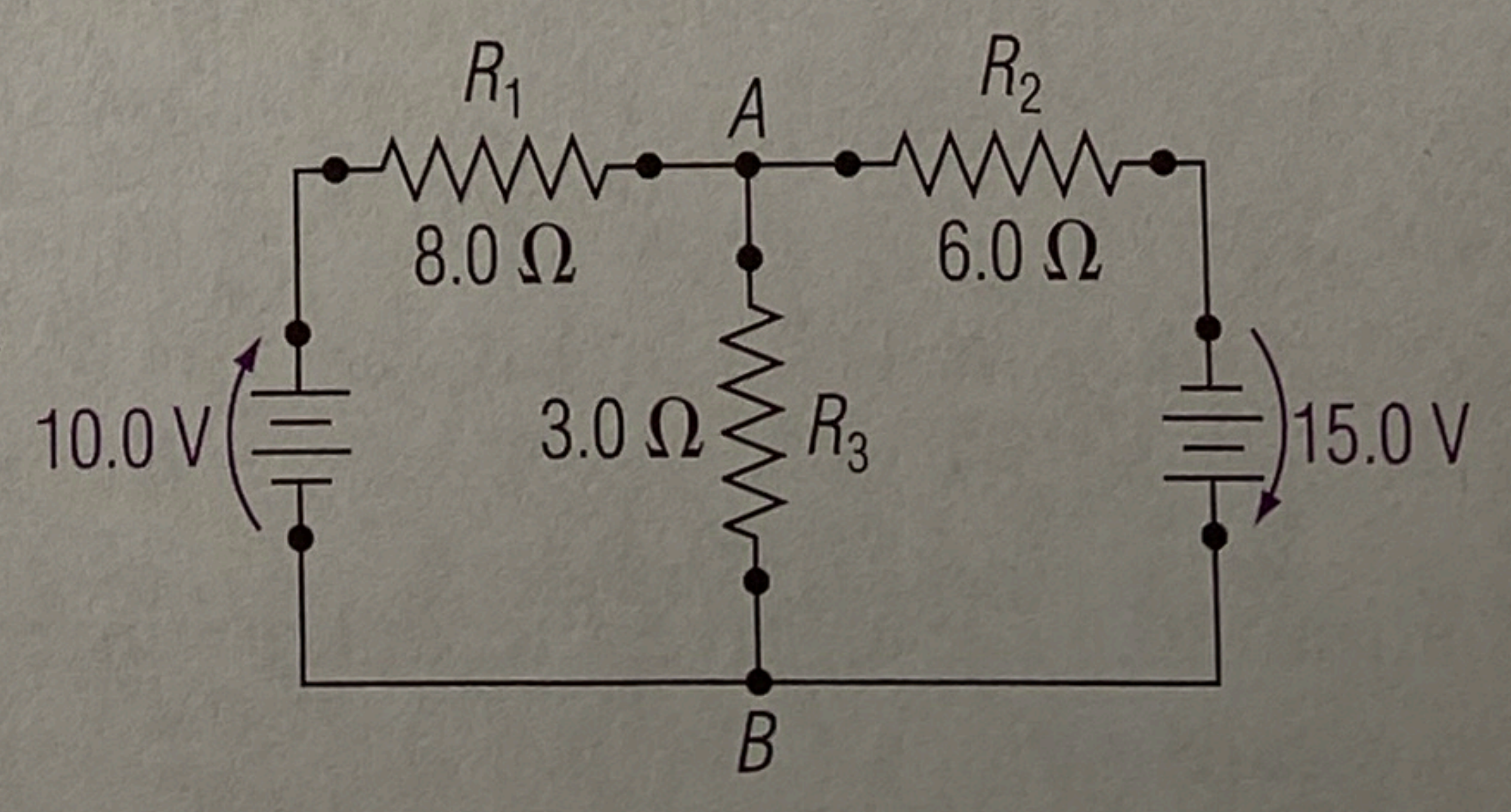
✪6. What is the equivalent resistance of the resistors 1 MΩ, 100. Ω, and 1.00 Ω

a. in series? (Assume all resistors have a 5% tolerance for rounding purposes. See Appendix A in the Lab Manual for a discussion of manufacturer's tolerances.)

b. in parallel?

✪7. For each case in Question 6, is the order of magnitude of the equivalent resistance closer to the largest or the smallest resistance?

✪8. Using Kirchhoff's rules, determine the current through and the voltage drop across each resistor in the accompanying figure.



20C SEMICONDUCTORS AND TRANSISTORS

20.16 Vacuum Tubes

The fastest growing area of technology today is semiconductor electronics. Scientists and engineers are striving to make devices that are smaller, faster, more energy efficient, and more powerful. Perhaps the most surprising fact about electronics is its youthfulness. Only a little more than a century ago this discipline was unknown. Now, we would feel helpless without our calculators, computers, cell phones, GPS navigation, wireless data devices, and digital video systems.

The electronic age began with the invention of the light bulb. In 1883, in an attempt to reduce blackening on the inside of the bulb, Thomas Edison introduced a loop of wire into the bulb. He discovered that if he made the loop positive with respect to the filament, a current began to flow. If he made the loop negative with respect to the filament, no current flowed. This behavior is called the **Edison effect**. The current was surprising, considering that the bulb contained a vacuum. The charge apparently traveled through the space between the filament and the loop *without requiring a physical conductor*. A few years later, in 1897, J. J. Thomson discovered the electron, explaining the Edison effect. You will learn more about J. J. Thomson's experiment in Chapter 21.

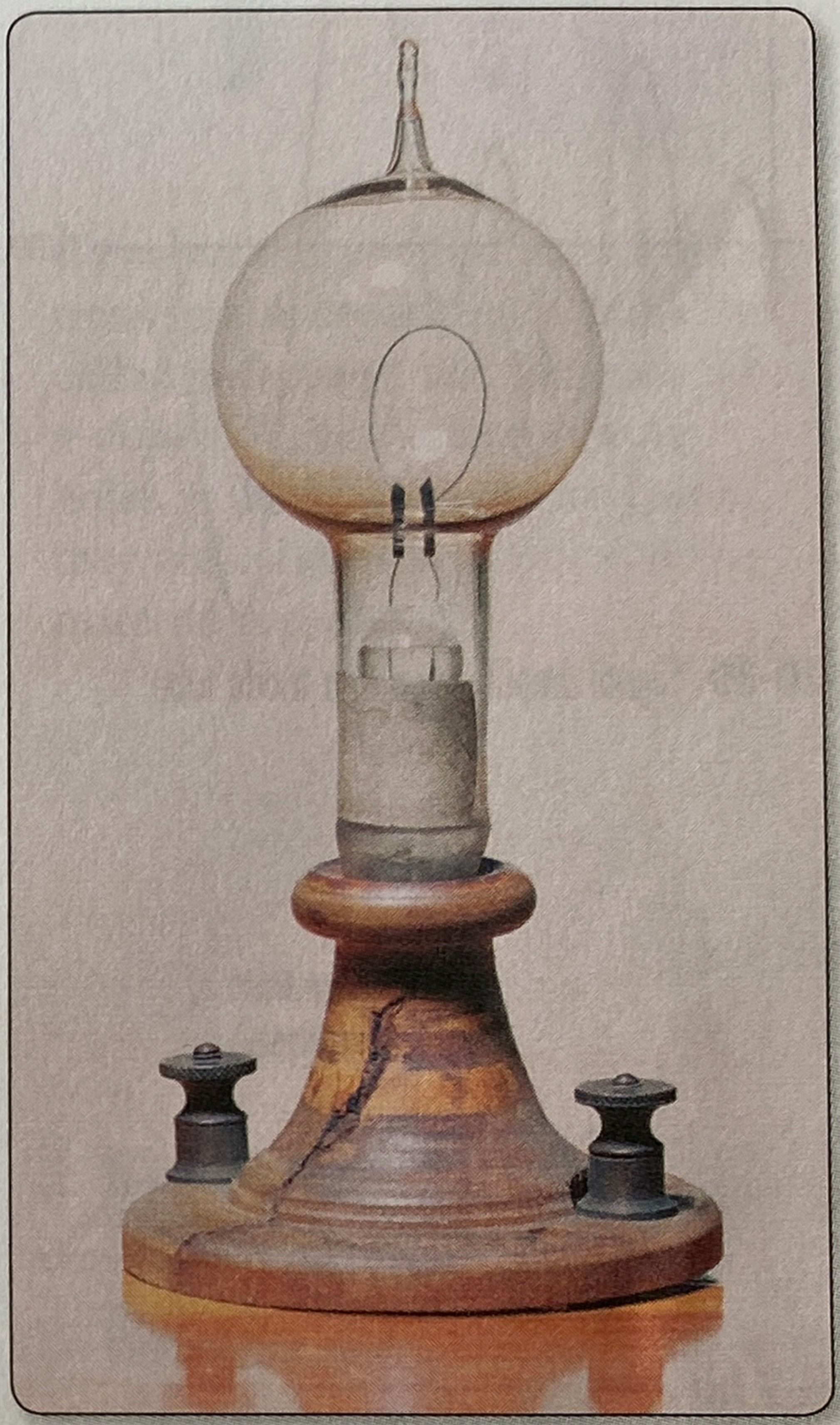
The electrical resistance of the filament causes its temperature to rise until it emits electrons, similar to evaporation in a boiling liquid. This escape is called *thermionic emission*. The free electrons were drawn to the positively charged loop along electric field lines, producing a current. A negatively charged loop repelled the free electrons, so no electrons could reach the loop, and no current flowed.

In 1904 John Fleming placed a filament and a metal plate, connected to exterior wires, in an evacuated, sealed glass tube similar to Edison's. This device, and any other arrangement of conductors in an evacuated envelope, is called a **vacuum tube**. Because his vacuum tube, containing a filament and a plate, allowed electricity to pass in only one direction, Fleming called it a *valve*, since its action was like a check valve in a water pipe. Such devices came to be called **diodes** because they contained two electrodes.

In 1906 the American inventor Lee De Forest developed the **triode**, a vacuum tube that could be used to detect and amplify weak electrical currents, particularly signals from sound and radio waves. The triode is a vacuum tube containing three elements: a filament, a plate, and a control grid between the filament and the plate. The control grid is usually given a negative charge so that few electrons from the filament will be able to reach the plate. Electrons will be repelled by even a slightly negative control grid. If the control grid is attached to a varying current, such as an audio signal, it will vary in charge. Even a slight change in control grid charge can allow the free electrons to reach the plate or block their path, depending on the direction of the change. Thus, a small change in the grid current produces a large change in the plate current. Controlling a large current with a small one is called *amplification*. De Forest's triode vacuum tube is recognized as the first step in the development of modern electronics.

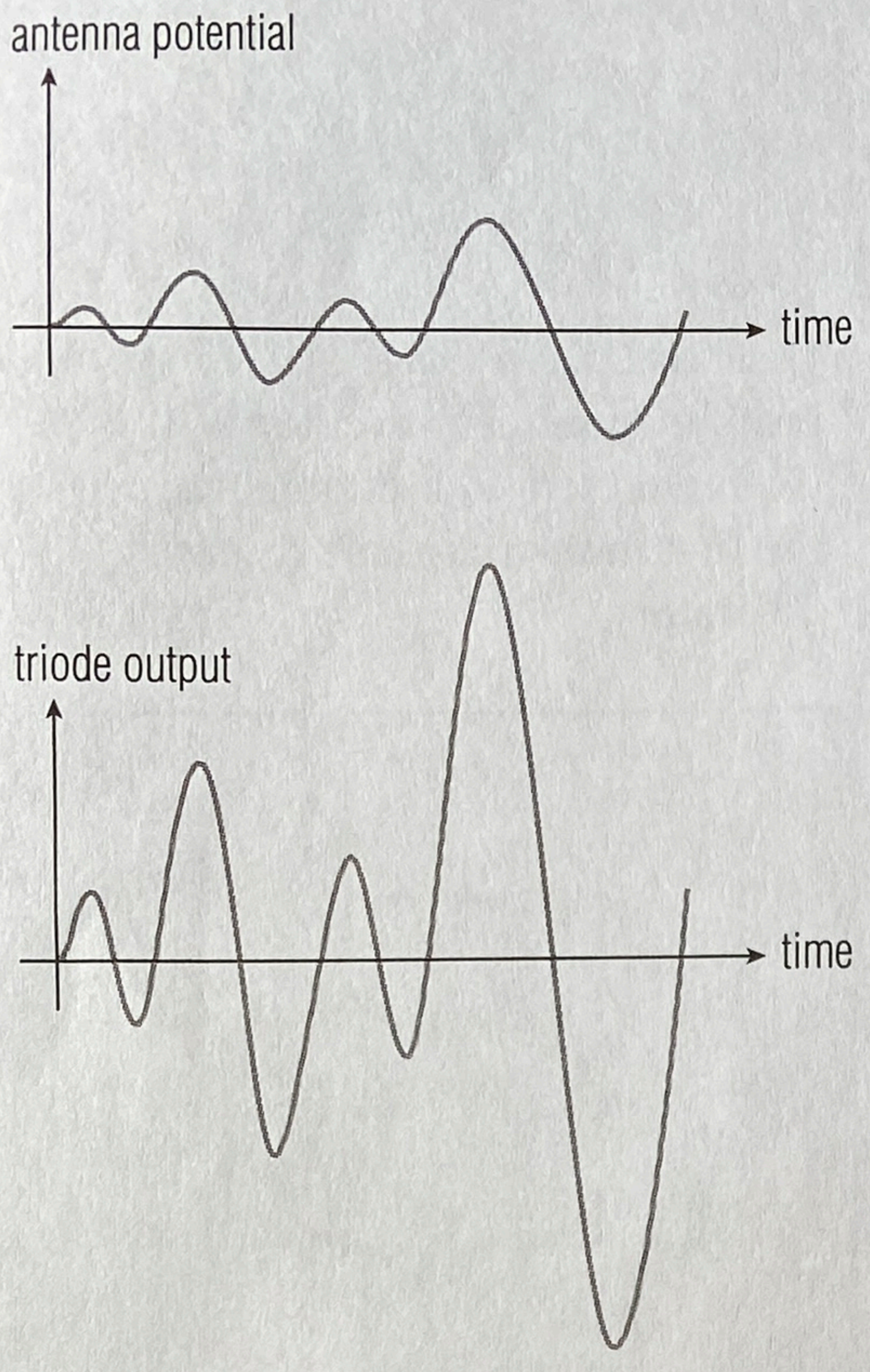
AT&T bought the patent to De Forest's triode and improved it for use in transcontinental telephone service. It was the basis of a successful expansion of telephone service nationwide. But vacuum tubes proved to be expensive to operate, generated lots of heat, and tended to be short-lived. AT&T researchers began to look for other technologies to replace them. This search eventually led to investigations involving semiconductor devices.

Thomas Edison (1847–1931) was a prolific American inventor who is often credited with establishing the first industrial-scale research laboratory.

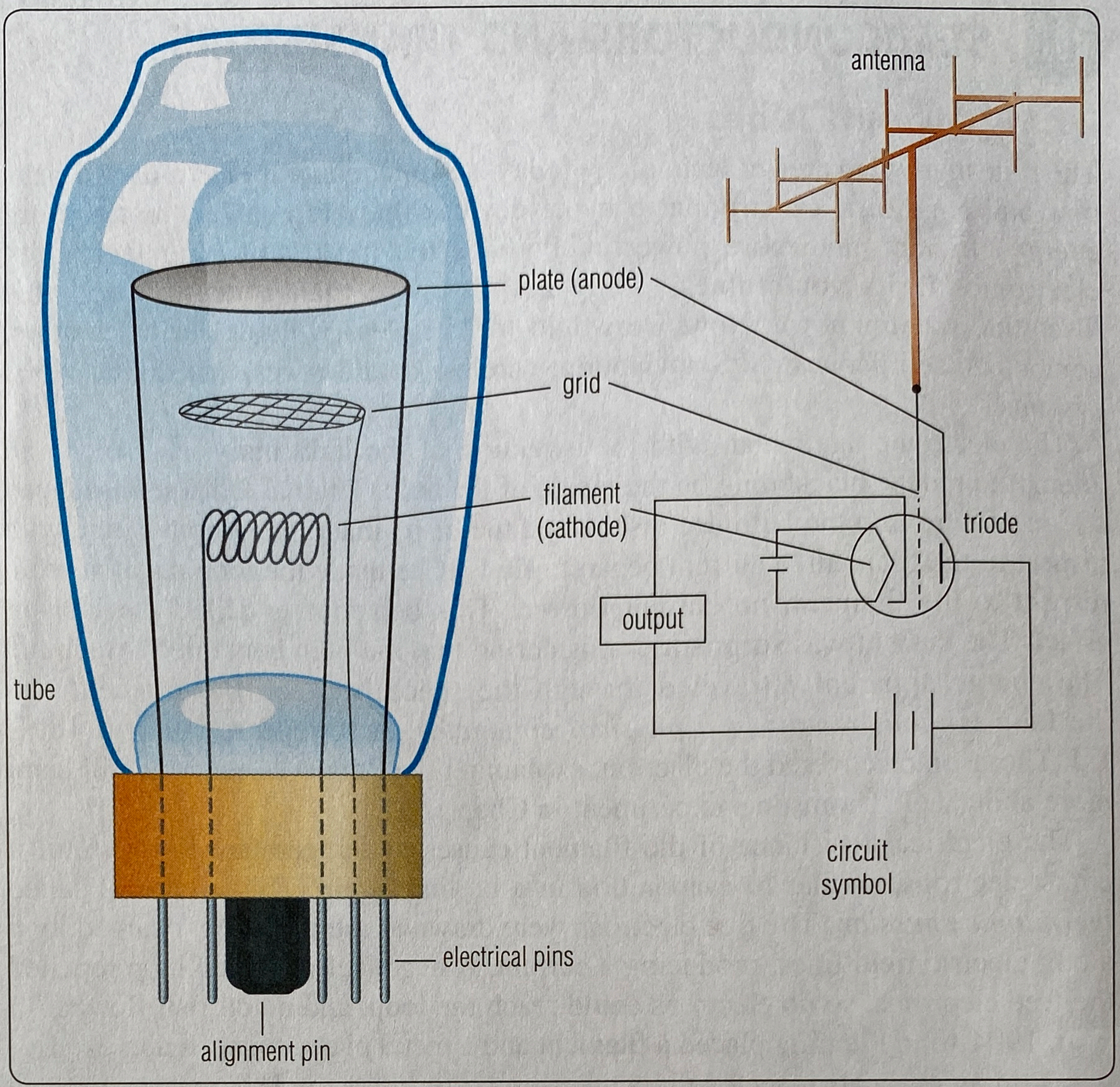


20-28 Edison's light bulb

John Ambrose Fleming (1849–1945) was an English physicist and electrical engineer who was a devout Christian and creationary scientist. He was one of the founders of the Evolution Protest Movement that eventually became the modern Creation Science Movement. He published several books about Creationism. Having no children, he left most of his estate to Christian charities.



20-30 Signal amplification in a triode tube



20-29 An electronic triode

20.17 Semiconductor Theory

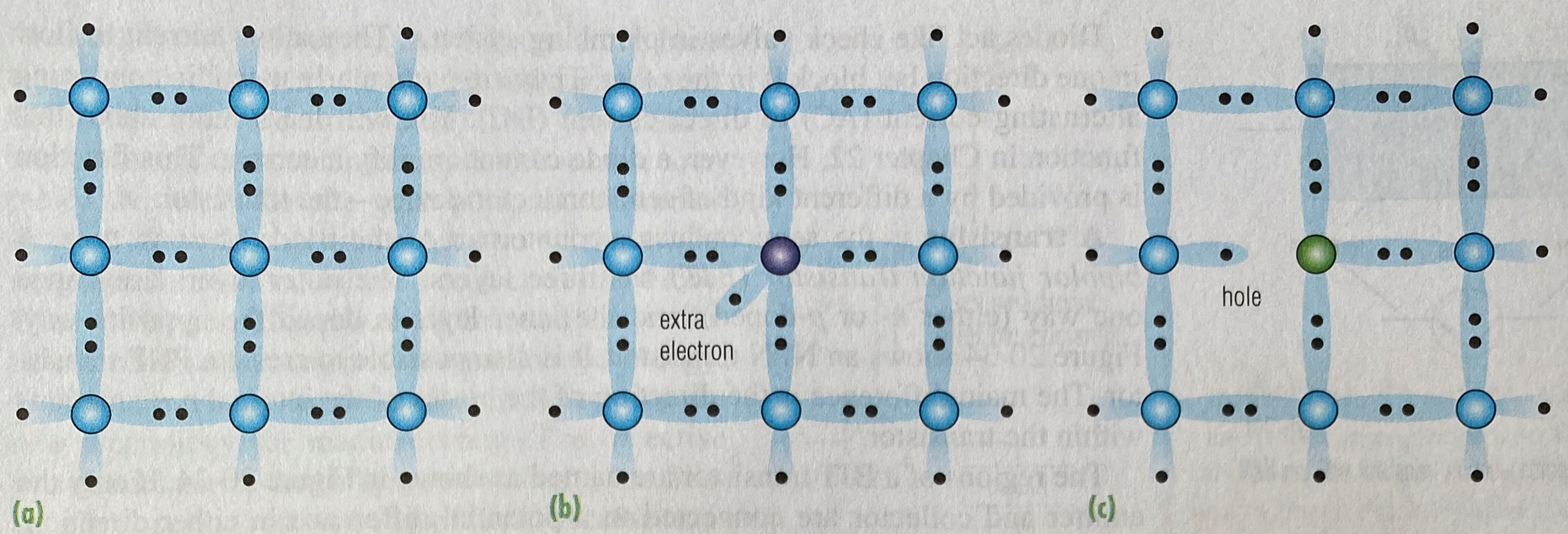
Electronic devices that have largely replaced vacuum tubes are made of semiconductor materials. The differences in electrical behavior of conductors, insulators, and semiconductors come from the kinds and strengths of the bonds that hold their atoms together.

Conductors usually are metals. Their atoms are bonded together by metallic bonds, in which the valence electrons are loosely held and can be shared by all the nuclei in the conductor. These electrons can move freely throughout the conductor's crystal structure. Therefore, even very small potential differences applied across the conductor can cause the electrons to move.

Insulator compounds, on the other hand, usually contain strong covalent bonds between their atoms. The electrons are shared between pairs of atoms and do not move at all through the material. A relatively large amount of energy is required to remove an electron from its bond. Therefore, even a large potential difference applied across an insulator produces little current.

Semiconductor compounds are formed from the metalloid elements that lie on the stair-step region of the periodic table (see Appendix H). These elements have lower *electronegativities* than the nonmetal elements that form insulator compounds, but higher electronegativities than metals. Electrical semiconductor compounds are composed mostly of one element, such as silicon. Silicon, like carbon, has four valence electrons and makes a rigid crystal lattice similar to diamond by forming four covalent bonds with four neighboring atoms. Consequently, silicon by itself is an excellent insulator, since all of its valence electrons are tied up in covalent bonds.

The **electronegativity** of an element is a measure of how tightly an atom holds onto valence electrons when bonded to another element. Relatively high electronegativities are characteristic of nonmetal elements, and low ones are characteristic of metals.



20-31 A pure silicon crystal lattice (a), an *n*-doped crystal lattice (b), and a *p*-doped crystal lattice (c)

Elements that provide excess electrons in a semiconductor lattice are called *n-dopants*, and the material is *n-doped*. If the elements create holes in the semiconductor lattice, they are called *p-dopants*, and the material is *p-doped.*

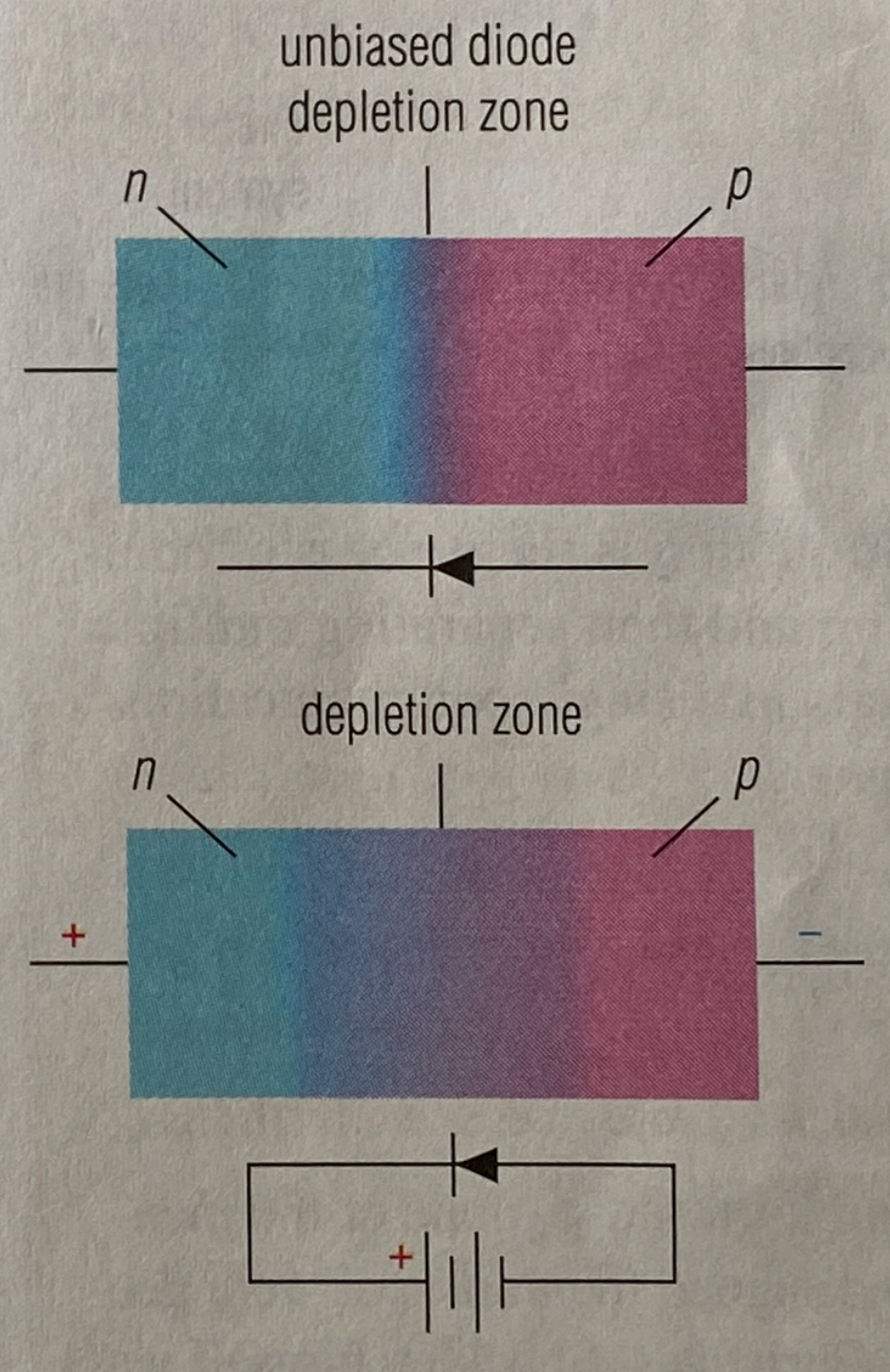
The silicon crystal lattice's conductivity can be increased in two ways. During manufacture, a small percentage of the silicon atoms can be replaced in the lattice with other atoms that have a different number of valence electrons. This process, called **doping**, creates points in the silicon lattice that have extra or missing electrons ("holes"). For example, if an element such as phosphorus, arsenic, or antimony, which all have five valence electrons, is used as the *dopant*, this produces points in the lattice where, after four covalent bonds form with adjacent silicon atoms, there is an unbonded electron left over, leaving a negatively charged point in the lattice. This kind of semiconductor compound is called an ***n*-type semiconductor**. If an element with only three valence electrons, such as boron, aluminum, or gallium, is used as the dopant, there are holes in the lattice with missing bonds, leaving atoms with a positive charge. This kind of material is called a ***p*-type semiconductor**.

When a potential difference is applied to an *n*-doped material, the unbonded electrons are pulled away from their atoms and drift down the electrical potential. With *p*-doped material, unbonded electrons jump from one hole to the next, leaving holes behind that appear to move in the opposite direction. By themselves, *n*-type and *p*-type semiconductors do conduct, although not very well. They make better resistors than conductors. However, unlike resistors, as a semiconductor's temperature increases, its resistance *decreases*.

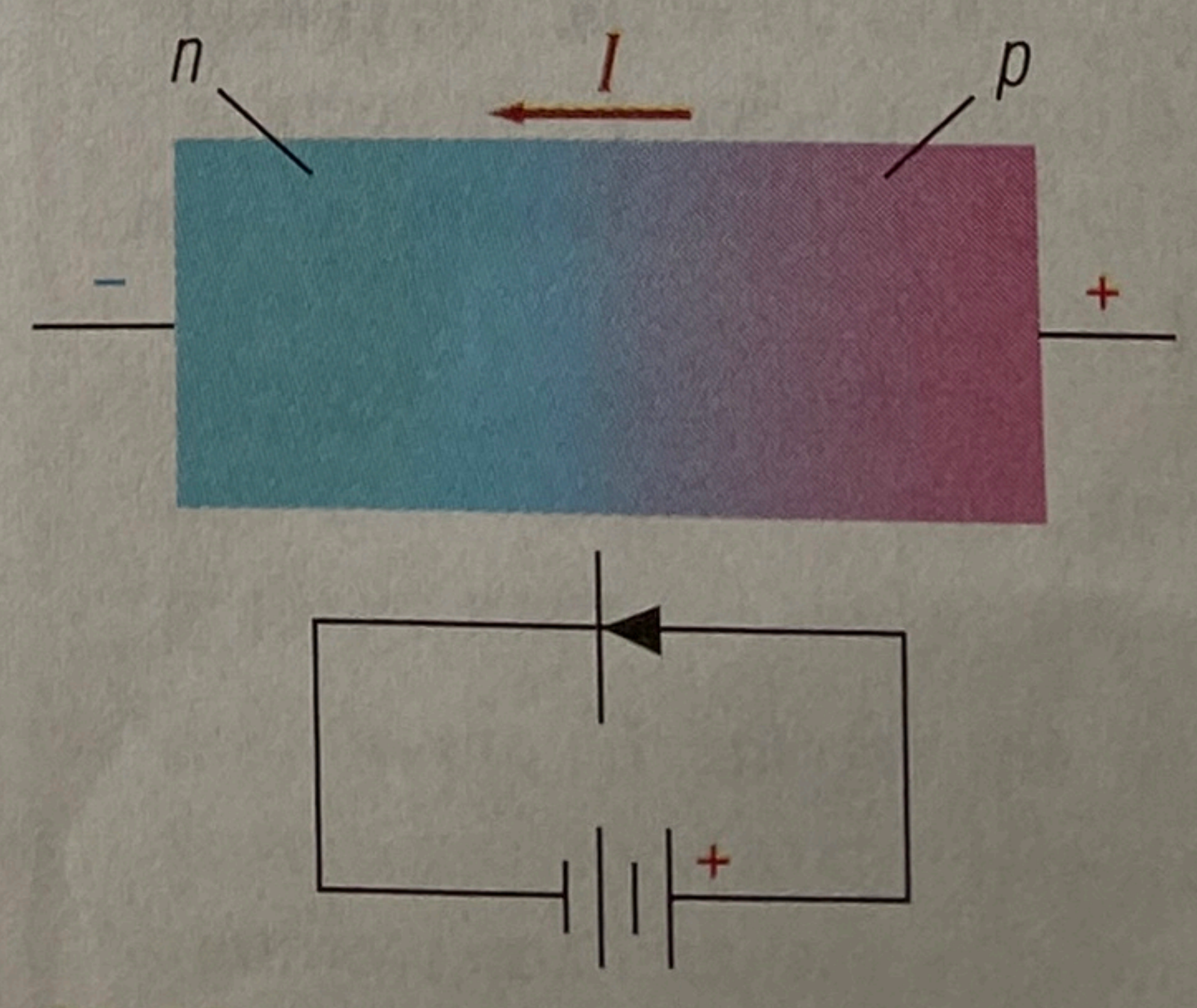
20.18 Semiconductor Devices

By themselves, *n*- and *p*-type semiconductor materials are not particularly useful, but when they are joined together, something interesting happens. The contact surface between the two materials is called a ***p-n* junction**. Some of the excess electrons from the *n*-doped material drift across the junction and fill the holes in the *p*-doped material. This leaves a neutral region between the two materials called the *depletion zone*. A device consisting of a single *p-n* junction between two doped semiconductor materials is called a diode, and it performs the same function as the vacuum tube diode. Let's see how it works.

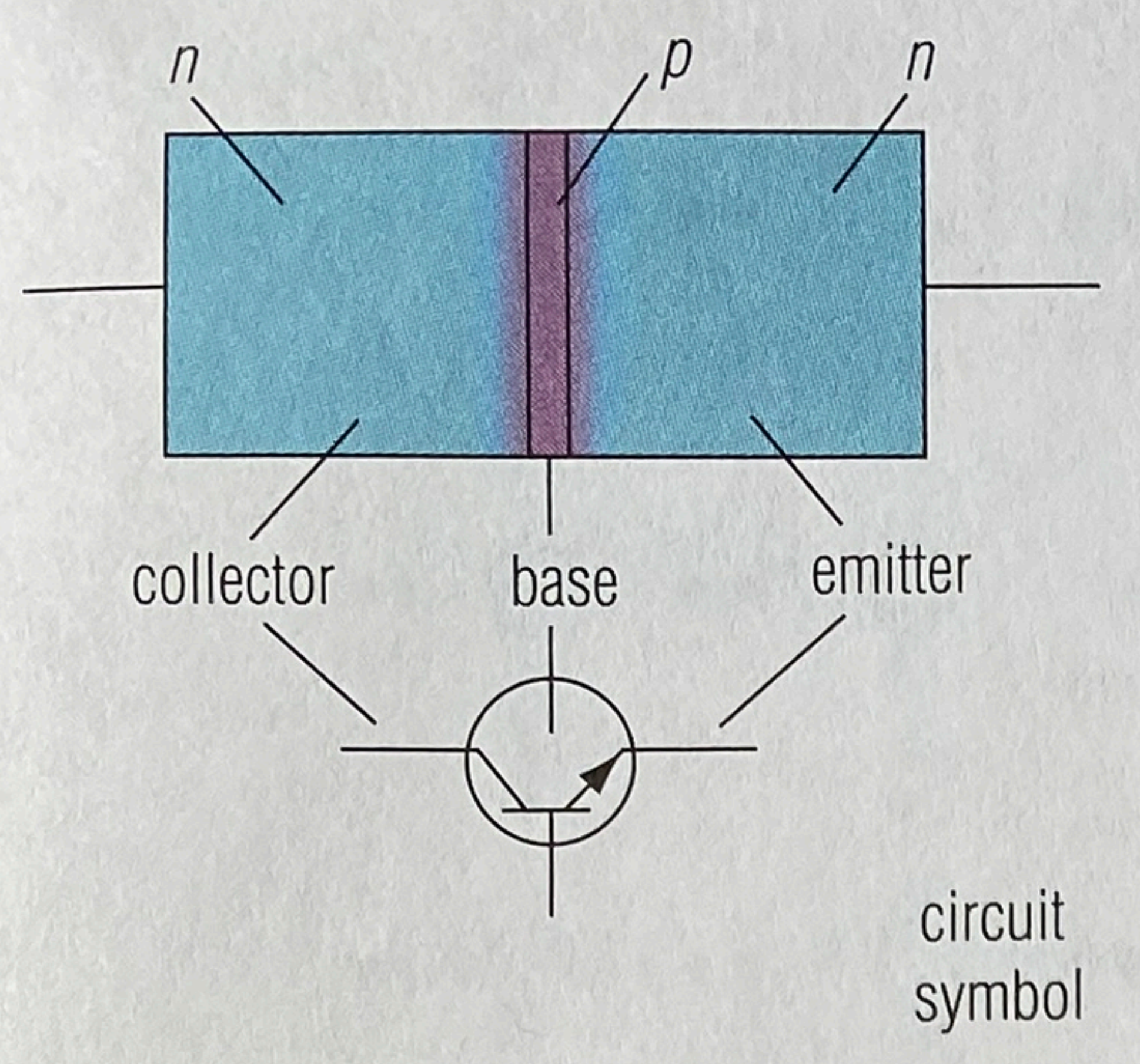
If a potential difference is applied to the diode so that the *n*-doped material is at the higher potential, the excess electrons in the *n*-doped material are attracted to the positive charge, and the holes in the *p*-doped material are attracted to the negative charge. The depletion region *increases* in size, and no current flows through the diode. The diode is said to be **reverse-biased**. However, if the polarity is reversed so that the *n*-material is at the lower potential and the *p*-material is at the higher potential, the electrons and holes are repelled toward the depletion zone until it disappears and charge carriers can move into the opposite materials. In this condition the diode conducts current and it is said to be **forward-biased**.



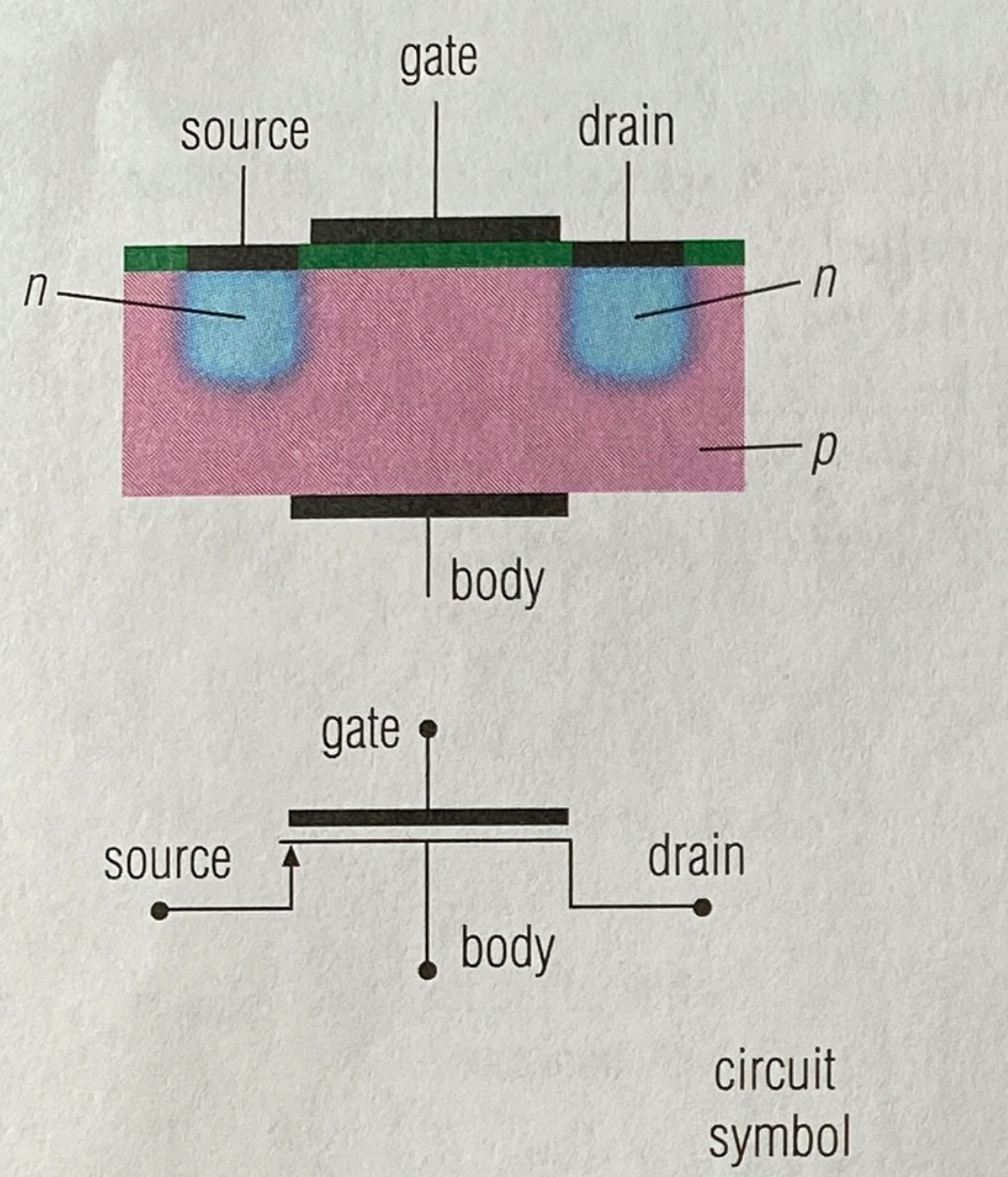
20-32 A reverse-biased diode



20-33 A forward-biased diode



20-34 A bipolar junction transistor with an NPN structure



20-35 A basic field-effect transistor (FET). There are many variations of the FET.

Multiplexing is the process of combining and then separating multiple signals in a single communications channel.

Dominion Science and Non-Christians

To our knowledge, none of the men who designed the transistor were genuine Christians. Shockley himself was an avowed atheist. How can the creative efforts of these men be considered dominion science—in keeping with the Dominion Mandate of Genesis 1:26–28?

Diodes act like check valves in plumbing systems. They allow current to flow in one direction but block it in the other. They are particularly useful in converting alternating current (AC) to direct current (DC). You will learn more about this function in Chapter 22. However, a diode cannot amplify a current. This function is provided by a different kind of semiconductor device—the transistor.

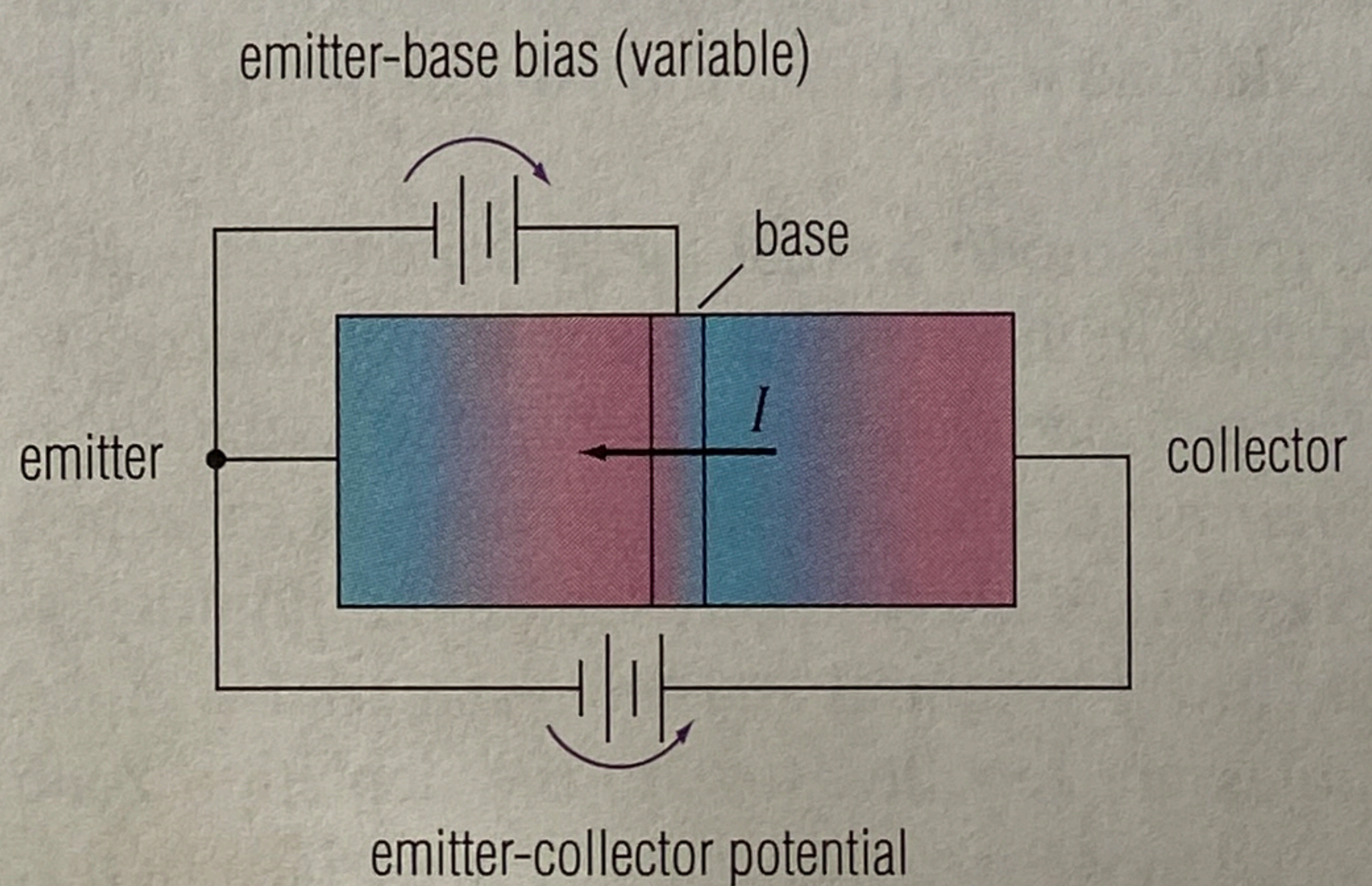
A **transistor** is the semiconductor counterpart to the triode vacuum tube. A *bipolar junction transistor (BJT)* has three layers. The outer layers are doped one way (either *n*- or *p*-doped), and the inner layer is doped the opposite way. Figure 20-34 shows an NPN transistor. It is also possible to create a PNP transistor. The main difference is the direction of the biases of the internal *p-n* junctions within the transistor.

The regions of a BJT transistor are named as shown in Figure 20-34. If only the emitter and collector are connected to a potential difference in either direction, there will be no current flowing through the transistor. No matter which end of the transistor is connected to the higher potential, the current will face a reverse-biased *p-n* junction at the base. However, if a small positive potential is applied to the narrow base region, holes are forced into the *n*-regions, which then begin to conduct. If the emitter contains more dopant atoms than the collector, the resulting current through them can be much larger than the small current through the base. The small base current controls the large collector-emitter current, allowing the transistor to act as an amplifier. This is particularly useful if a varying current signal from a microphone or a radio antenna is applied to the base. The weak signals can be greatly amplified.

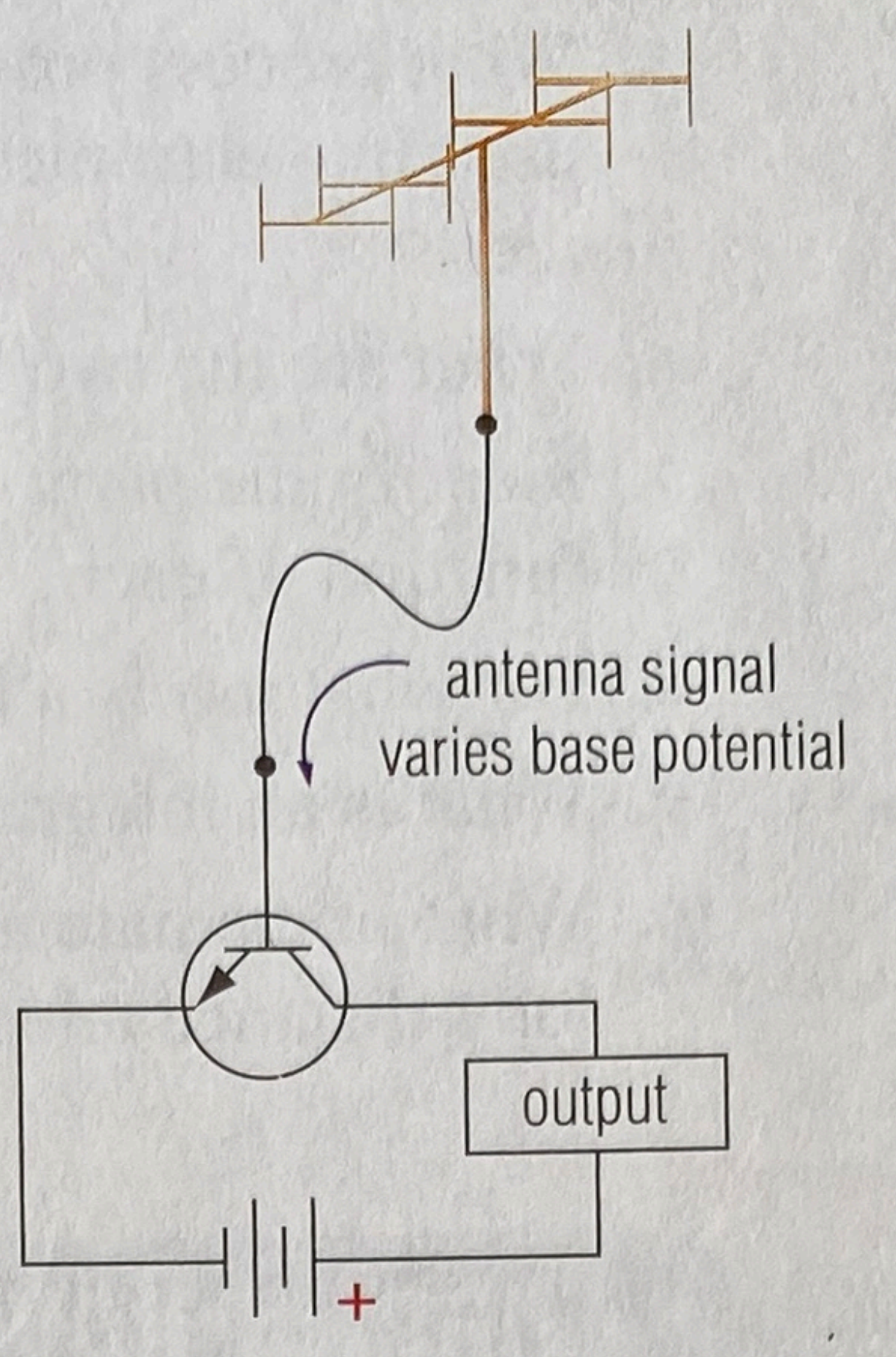
Another kind of transistor, called the *field-effect transistor (FET)*, utilizes *p-n* junctions differently to accomplish switching functions and amplification. The structure of a typical FET is shown in Figure 20-35. Current through the gate controls the size of the depletion region in the current channel between the source and the drain connections. Depending on the arrangement of the *n*- and *p*-doped materials used in the transistor, changes in the gate current cause the depletion region to expand, blocking current flow, or to shrink, allowing current to pass. FETs tend to be used as switches for external circuits. Some forms can control currents moving in either direction, which is useful for *multiplexing* circuits. The FET has largely replaced the BJT in modern electronics because of its better power efficiency.

20.19 Using Semiconductors to Solve Problems

The theoretical design for a field-effect transistor-like device was first developed by the Ukrainian emigrant physicist Julius Lilienfeld in 1925. Another field-effect device was described in a patent by the German electrical engineer Oskar Heil in 1935. However, no actual working models of these devices were built by these men. In 1945, a group of AT&T scientists at Bell Labs were assigned the task of developing a tubeless electronic amplifier—a solid-state device. In several stages of research and experimentation, plagued by interpersonal conflict, Bill Shockley, Walter Brattain, and John Bardeen developed several experimental models of a semiconductor amplifier. The most efficient design, developed by Shockley, eventually became the basis for the bipolar junction transistor. The name



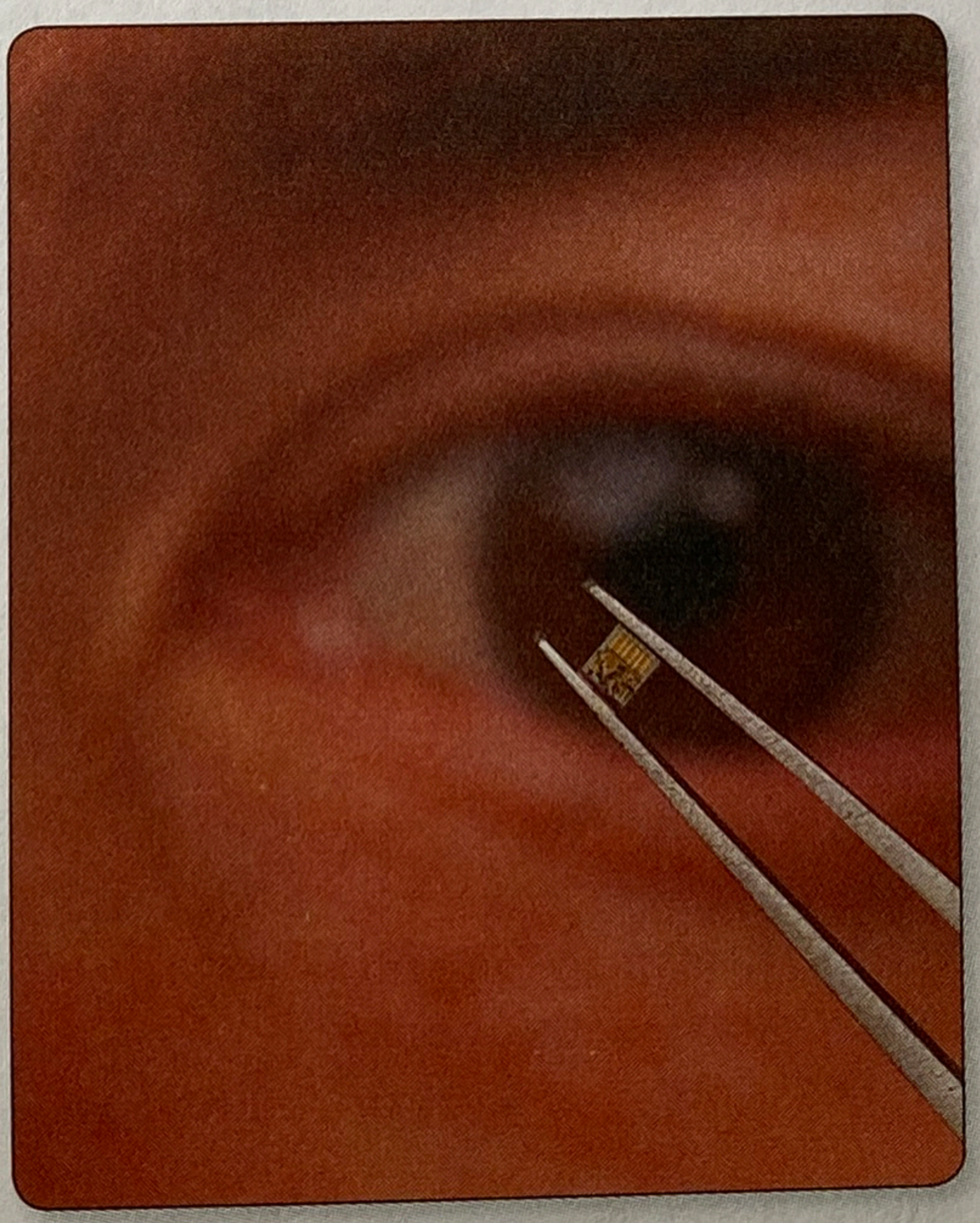
20-36 An NPN transistor in a circuit “transistor” was adopted by Bell Labs as a combination of words describing the variable resistance properties of the device (*trans*resistance). The *–istor* ending, used in many other contemporary device names, completed the word. Despite great personal resentment between Shockley and the other two scientists, the three briefly reunited in 1956 to receive the Nobel Prize in Physics. Their invention initiated the revolution in communications and information technology.



20-37 A transistor used as an amplifier

Bell Labs almost immediately began licensing the new technology for manufacturing. The objective was to miniaturize the bulky, power-hungry, and fragile telephone and radio tube amplifiers. Because transistors could act like switches, the huge, clacking mechanical telephone switching centers that filled many rooms were rapidly replaced by solid-state transistors fitting into the space of a cabinet. Telephone engineers had finally achieved their dream of replacing vacuum tubes with cooler, rugged amplifiers. Transcontinental and transoceanic telephone services became much more affordable, and the number of calls that could be made at one time jumped exponentially.

In 1952 a bright young engineer named Jack Kilby attended one of Bell Lab’s transistor symposiums. When he went to work for Texas Instruments a few years later, he was working on a problem that all electronics manufacturers were trying to solve—how to pack many transistors, wires, and other components like capacitors and resistors into the smallest possible space. Miniaturization, it seemed, had come up against an insurmountable obstacle. Kilby, working alone while the rest of the company was on an extended holiday, came up with the idea that all of the major circuit components could be made from semiconductors. Capacitors, resistors, switches, and amplifiers could all be constructed from appropriate combinations of *p-n* junctions and field-effect structures. His leap of inspiration was the realization that all of these devices could be built on a single base of semiconductor material and interconnected by properly doped semiconductor compounds. The company built a successful prototype of what came to be called an **integrated circuit (IC)** on a “chip” of germanium. In modern ICs, it is possible to concentrate tens of billions of circuit elements on a single chip. The IC is the basis for all microprocessors in use today. One of the benefits of this technology is instantaneous global telephone communications, of which the AT&T engineers back in 1907 could not have even dreamed.



20-38 A modern integrated circuit

20C Section Review

1. What material carries the current in a vacuum tube?
2. Describe thermionic emission.
3. How does a vacuum tube diode work?
4. How does a triode amplify a current signal?

Jack St. Clair Kilby (1923–2005) was an American engineer who flunked the entrance exam into MIT but went on to invent the integrated circuit, for which he received the Nobel Prize in Physics in 2000. He also received patents for inventing the handheld calculator and thermal printer.

Unknown to Kilby, Robert Noyce (1927–90) of Fairchild Semiconductor was also working on an integrated circuit. Although Kilby created the first working IC, Noyce’s design solved many practical problems, making it possible to mass-produce the device. Today, Kilby and Noyce are considered co-inventors of the IC.

20C Objectives

After completing this section, I can

- ✓ explain how simple vacuum tubes work.
- ✓ compare and contrast conductors, semiconductors, and insulators.
- ✓ describe how semiconductor doping establishes the properties of the material.
- ✓ explain how semiconductor junctions can be forward- or reverse-biased.
- ✓ describe the structure of simple semiconductor devices and identify their symbols in a circuit diagram.
- ✓ explain how a transistor amplifies a signal.
- ✓ summarize the historical invention of the transistor and integrated circuit.
- ✓ discuss the advantages that transistors provided to the telecommunications industry.

5. What process produces the different kinds of semiconductor materials used in electronic devices? What kinds of semiconductor materials are there?
6. What are the two kinds of current carriers in semiconductor materials?
7. Identify the parts of a bipolar junction transistor (BJT) and describe the function of each.
8. For what use is a field-effect transistor (FET) ideally suited?
9. What is an integrated circuit?

DS10. What immediate advantages did AT&T gain by using transistors in their long-distance telephone service?

Chapter Review

In Terms of Physics

current (I)	447	parallel	454
electrodynamics	447	voltage drop	454
ampere (A)	448	node	458
direct current (DC)	448	Kirchhoff's rules	459
polarity markings	448	ammeter	460
voltaic cell	449	galvanometer	460
galvanic cell	449	ohmmeter	460
electrode	449	voltmeter	460
circuit	450	bridge circuit	461
primary cell	450	rheostat	461
storage cell	450	Edison effect	463
battery	450	vacuum tube	463
dry cell	451	diode	463
resistivity (ρ)	451	triode	463
superconductor	451	doping	465
resistor	451	*n*-type semiconductor	465
resistance (R)	451	*p*-type semiconductor	465
Ohm's law	452	*p-n* junction	465
ohm (Ω)	452	reverse-biased	465
Joule's law	453	forward-biased	465
kilowatt-hour (kWh)	453	transistor	466
series	454	integrated circuit (IC)	467

Problem-Solving Strategies

20.1 (page 450) It is not normally necessary to keep track of which direction the moving charges are going. Just remember that current flows from the highest potential to the lowest potential in the external circuit.

20.2 (page 452) Ohm's law is true for a single circuit component, a segment of a circuit, or an entire circuit.

20.3 (page 453) Remember that the unit symbol indicates the kind of dimension of a property, while the variable (formula) symbol represents its numerical value.

20.4 (page 454) The symbol for a potential difference source has parallel lines of different lengths. The shorter line is conventionally the negative end of the source. Think of it as a minus sign.

20.5 (page 457) After summing the reciprocals of the parallel resistances, remember to take the reciprocal of the sum to find the total resistance.

20.6 (page 459) When applying Kirchhoff's voltage rule, remember that voltage *rises* across voltage sources (ΔV is positive) and *drops* across other circuit components (ΔV is negative) for conventional current flow. The opposite is true for negative (electron) current flow.

20.7 (page 460) Kirchhoff's rules are used to generate as many current equations as there are unknown currents in the simple closed paths in the circuit. Solving these equations simultaneously using the techniques that you learned in algebra classes permits you to find the individual currents. After the current values are known, you can find the voltage drops and the power absorbed for each resistance.