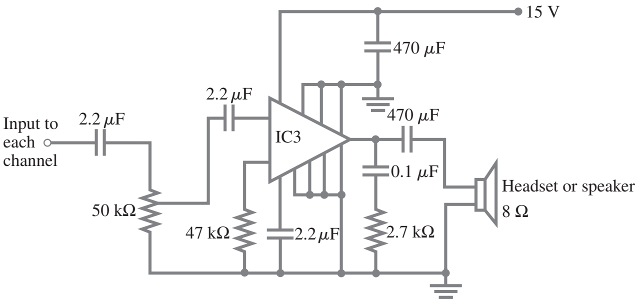
This cell phone has an attachment that measures a person's blood sugar level, and plots it over a period of days. All electronic devices contain circuits that are dc, at least in part. The circuit diagram below shows a possible amplifier circuit for an audio output (cell phone ear piece). We have already met two of the circuit elements shown: resistors and capacitors, and we discuss them in circuits in this Chapter. (The large triangle is an amplifier chip containing transistors.) We also discuss how voltmeters and ammeters work, and how measurements affect the quantity being measured.



CHAPTER

19 DC Circuits

CONTENTS

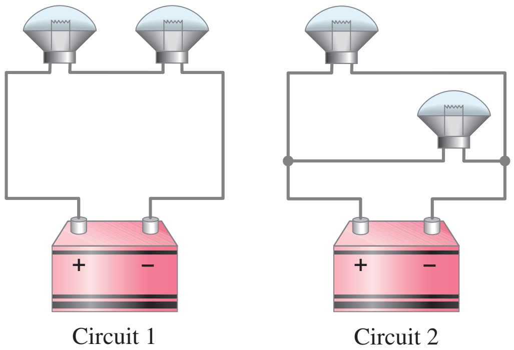
TABLE 19–1 Symbols for Circuit Elements

Symbol	Device
⊣⊢	Battery
⊣⊢ or ⊣(	Capacitor
-\/\/\/-	Resistor
——	Wire with negligible resistance
⁄ —	Switch
⏚ or ⏚	Ground

CHAPTER-OPENING QUESTION—Guess now!

The automobile headlight bulbs shown in the circuits here are identical. The battery connection which produces more light is

(a) circuit 1.
(b) circuit 2.
(c) both the same.
(d) not enough information.



Electric circuits are basic parts of all electronic devices from cell phones and TV sets to computers and automobiles. Scientific measurements—whether in physics, biology, or medicine—make use of electric circuits. In Chapter 18, we discussed the basic principles of electric current. Now we apply these principles to analyze dc circuits involving combinations of batteries, resistors, and capacitors. We also study the operation of some useful instruments.†

When we draw a diagram for a circuit, we represent batteries, capacitors, and resistors by the symbols shown in Table 19–1. Wires whose resistance is negligible compared with other resistance in the circuit are drawn as straight lines. A ground symbol (⏚ or ⏚) may mean a real connection to the ground, perhaps via a metal pipe, or it may mean a common connection, such as the frame of a car.

For the most part in this Chapter, except in Section 19–6 on *RC* circuits, we will be interested in circuits operating in their steady state. We won't be looking at a circuit at the moment a change is made in it, such as when a battery or resistor is connected or disconnected, but only when the currents have reached their steady values.

†AC circuits that contain only a voltage source and resistors can be analyzed like the dc circuits in this Chapter. However, ac circuits that contain capacitors and other circuit elements are more complicated, and we discuss them in Chapter 21.

19–1 EMF and Terminal Voltage

To have current in an electric circuit, we need a device such as a battery or an electric generator that transforms one type of energy (chemical, mechanical, or light, for example) into electric energy. Such a device is called a **source** of **electromotive force**† or of **emf**. The *potential difference* between the terminals of such a source, when no current flows to an external circuit, is called the **emf** of the source. The symbol $\mathscr{E}$ is usually used for emf (don't confuse $\mathscr{E}$ with E for electric field), and its unit is volts.

CAUTION
Why battery voltage isn't perfectly constant

A battery is not a source of constant current—the current out of a battery varies according to the resistance in the circuit. A battery *is*, however, a nearly constant voltage source, but not perfectly constant as we now discuss. For example, if you start a car with the headlights on, you may notice the headlights dim. This happens because the starter draws a large current, and the battery voltage drops below its rated emf as a result. The voltage drop occurs because the chemical reactions in a battery cannot supply charge fast enough to maintain the full emf. For one thing, charge must move (within the electrolyte) between the electrodes of the battery, and there is always some hindrance to completely free flow. Thus, a battery itself has some resistance, which is called its **internal resistance**; it is usually designated r.

A real battery is modeled as if it were a perfect emf $\mathscr{E}$ in series with a resistor r, as shown in Fig. 19–1. Since this resistance r is inside the battery, we can never separate it from the battery. The two points a and b in Fig. 19–1 represent the two terminals of the battery. What we measure is the **terminal voltage** $V_{ab} = V_a - V_b$. When no current is drawn from the battery, the terminal voltage equals the emf, which is determined by the chemical reactions in the battery: $V_{ab} = \mathscr{E}$. However, when a current I flows from the battery there is an internal drop in voltage equal to Ir. Thus the terminal voltage (the actual voltage applied to a circuit) is

$$V_{ab} = \mathscr{E} - Ir. \qquad \text{[current } I \text{ flows from battery]} \qquad \textbf{(19–1)}$$

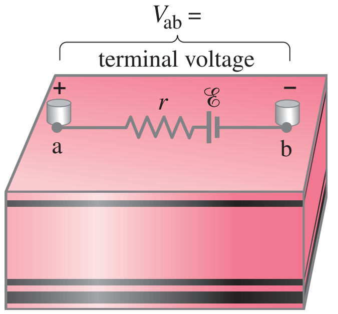
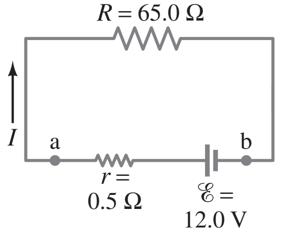


FIGURE 19–1 Diagram for an electric cell or battery.

For example, if a 12-V battery has an internal resistance of 0.1 Ω, then when 10 A flows from the battery, the terminal voltage is $12\text{ V} - (10\text{ A})(0.1\ \Omega) = 11\text{ V}$. The internal resistance of a battery is usually small. For example, an ordinary flashlight battery when fresh may have an internal resistance of perhaps 0.05 Ω. (However, as it ages and the electrolyte dries out, the internal resistance increases to many ohms.)

EXAMPLE 19–1 **Battery with internal resistance.** A 65.0-Ω resistor is connected to the terminals of a battery whose emf is 12.0 V and whose internal resistance is 0.5 Ω, Fig. 19–2. Calculate (*a*) the current in the circuit, (*b*) the terminal voltage of the battery, V_{ab}, and (*c*) the power dissipated in the resistor R and in the battery's internal resistance r.

FIGURE 19–2 Example 19–1.



APPROACH We first consider the battery as a whole, which is shown in Fig. 19–2 as an emf $\mathscr{E}$ and internal resistance r between points a and b. Then we apply $V = IR$ to the circuit itself.

SOLUTION (*a*) From Eq. 19–1, we have $V_{ab} = \mathscr{E} - Ir$. We apply Ohm's law (Eq. 18–2) to this battery and the resistance R of the circuit: $V_{ab} = IR$. Hence

$$\mathscr{E} - Ir = IR$$

or $\mathscr{E} = I(R + r)$. So

$$I = \frac{\mathscr{E}}{R + r} = \frac{12.0\text{ V}}{65.0\ \Omega + 0.5\ \Omega} = \frac{12.0\text{ V}}{65.5\ \Omega} = 0.183\text{ A}.$$

(*b*) The terminal voltage is

$$V_{ab} = \mathscr{E} - Ir = 12.0\text{ V} - (0.183\text{ A})(0.5\ \Omega) = 11.9\text{ V}.$$

(*c*) The power dissipated in R (Eq. 18–6) is

$$P_R = I^2R = (0.183\text{ A})^2(65.0\ \Omega) = 2.18\text{ W},$$

and in the battery's resistance r it is

$$P_r = I^2r = (0.183\text{ A})^2(0.5\ \Omega) = 0.02\text{ W}.$$

†The term "electromotive force" is a misnomer—it does not refer to a "force" that is measured in newtons. To avoid confusion, we use the abbreviation, emf.