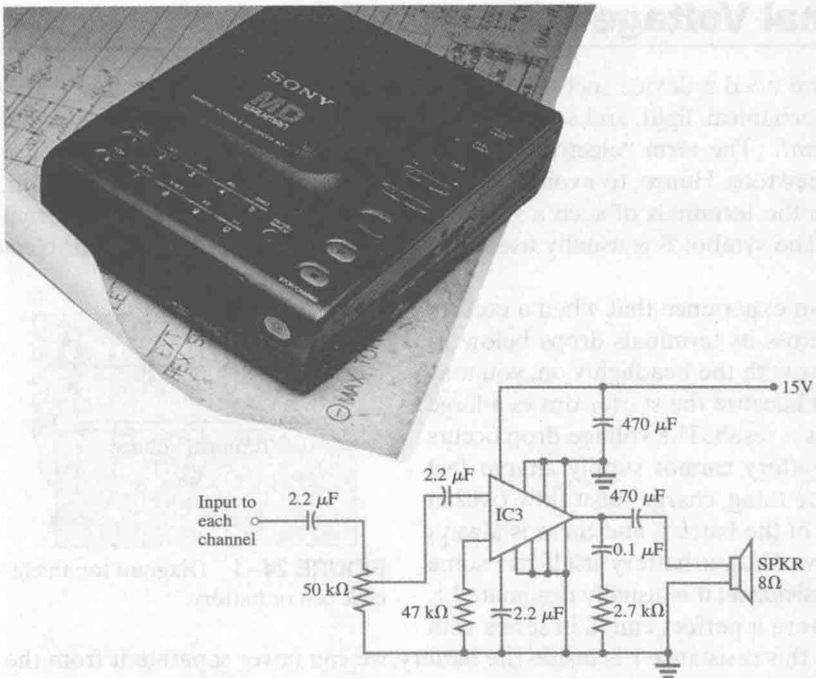

This "Walkman" contains circuits within it that are dc, at least in part. (The audio signal is ac.) The circuit diagram below shows a possible amplifier circuit (actually, two identical circuits are used, one for each stereo channel). Although the large triangle is an amplifier circuit board containing transistors (not discussed in this book), the other circuit elements are ones we have met, resistors and capacitors, and we discuss them in circuits in this chapter.

CHAPTER 24

DC Circuits

Electric circuits are basic parts of all electronic gear from radio and TV sets to computers and automobiles. Scientific measurements, from physics to biology and medicine, make use of electric circuits. In Chapter 23, we discussed the basic principles of electric current. Now we will apply these principles to analyze dc circuits and to understand the operation of a number of useful instruments.†

When we draw a diagram for a circuit, we represent batteries, capacitors, and resistors by the symbols shown in Table 24–1. Wires whose resistance is negligible compared to other resistance in the circuit are drawn simply as straight lines. Some circuit diagrams show a ground symbol ($\frac{\;}{\top}$ or $\downarrow$) which may mean a real connection to the ground, perhaps via a metal pipe, or it may simply mean a common connection, such as the frame of a car.

TABLE 24–1
Symbols for Circuit Elements

Symbol	Device
$-\vert\!\vdash$	Battery
$\dashv\vdash$	Capacitor
$-\!\wedge\!\!\vee\!\!\wedge\!\!\vee\!-$	Resistor
——	Wire with negligible resistance
$\frac{\;}{\top}$ or $\downarrow$	Ground

For the most part in this chapter, except in Section 24–4, we will be interested in circuits operating in their steady state—that is, 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 rather a short time later 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.

24–1 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, light, and so on) into electric energy. Such a device is called a *source* of *electromotive force* or of *emf*. (The term "electromotive force" is a misnomer since it does not refer to a "force" that is measured in newtons. Hence, to avoid confusion, we prefer to use the abbreviation, 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 it with E for electric field).

You may have noticed in your own experience that when a current is drawn from a battery, the voltage across its terminals drops below its rated emf. 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 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 flow (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 then modeled as if it were a perfect emf $\mathscr{E}$ in series with a resistor r, as shown in Fig. 24–1. Since this resistance r is inside the battery, we can never separate it from the battery. The two points a and b in the diagram 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 naturally from the battery there is an internal drop in voltage equal to Ir. Thus the terminal voltage (the actual voltage delivered) is†

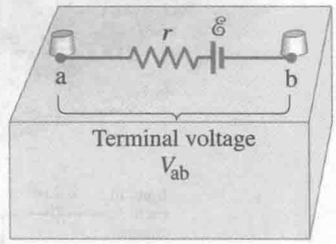

FIGURE 24–1 Diagram for an electric cell or battery.

$$V_{ab} = \mathscr{E} - Ir.$$

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.) Car batteries have even lower internal resistance.

EXAMPLE 24–1 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. 24–2. 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.

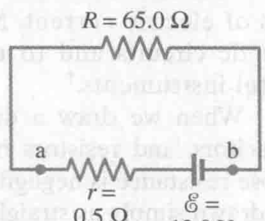

FIGURE 24–2 Example 24–1.

SOLUTION (*a*) From the equation above relating emf $\mathscr{E}$ to terminal voltage, we have

$$V_{ab} = \mathscr{E} - Ir,$$

where $V_{ab} = IR$ (Eq. 23–2). Hence $IR = \mathscr{E} - Ir$ or $\mathscr{E} = I(R + r)$, and so

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

(*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 is

$$P_R = I^2R = (0.183\text{ A})^2(65.0\,\Omega) = 2.18\text{ W}$$
$$P_r = I^2r = (0.183\text{ A})^2(0.5\,\Omega) = 0.02\text{ W}.$$

† When a battery is being charged, a current is forced to pass through it and we have to write $V_{ab} = \mathscr{E} + Ir$. See Example 24–10.

In much of what follows, unless stated otherwise, we assume that the battery's internal resistance is negligible, and that the battery voltage given is its terminal voltage, which we will usually write simply as V rather than V_{ab}.

24–2 Resistors in Series and in Parallel

When two or more resistors are connected end to end as shown in Fig. 24–3, they are said to be connected in **series**. The resistors could be simple resistors as were pictured in Fig. 23–10, or they could be lightbulbs, heating elements, or other resistive devices. Any charge that passes through R_1 in Fig. 24–3a will also pass through R_2 and then R_3. Hence the same current I passes through each resistor. (If it did not, this would imply that charge was accumulating at some point in the circuit, which does not happen in the steady state.) We let V represent the voltage across all three resistors. We assume all other resistance in the circuit can be ignored, and so V equals the terminal voltage of the battery. We let V_1, V_2, and V_3 be the potential differences across each of the resistors, R_1, R_2, and R_3, respectively, as shown in Fig. 24–3a. From $V = IR$, we can write $V_1 = IR_1$, $V_2 = IR_2$, and $V_3 = IR_3$. Because the resistors are connected end to end, energy conservation tells us that the total voltage V is equal to the sum of the voltages across each resistor:

$$V = V_1 + V_2 + V_3 = IR_1 + IR_2 + IR_3. \qquad \text{[series]} \qquad \textbf{(24–1)}$$

To see in more detail why this is true, note that an electric charge q passing through R loses potential energy by qV_1. In passing through R_2 and R_3, the potential energy U decreases by qV_2 and qV_3, for a total $\Delta U = qV_1 + qV_2 + qV_3$; this sum must equal the energy given to q by the battery, qV, so that energy is conserved. Hence $qV = q(V_1 + V_2 + V_3)$, and so $V = V_1 + V_2 + V_3$, which is Eq. 24–1.

Now let us determine the equivalent single resistance R_{eq} that would draw the same current as our combination; see Fig. 24–3c. Such a single resistance R_{eq} would be related to V by

$$V = IR_{eq}.$$

We equate this expression with Eq. 24–1, $V = I(R_1 + R_2 + R_3)$, and find

$$R_{eq} = R_1 + R_2 + R_3. \qquad \text{[series]} \qquad \textbf{(24–2)}$$

This is, in fact, what we expect. When we put several resistances in series, the total resistance is the sum of the separate resistances. This applies to any number of resistances in series. Note that when you add more resistance to the circuit, the current will decrease. For example, if a 12-V battery is connected to a 4-Ω resistor, the current will be 3 A. But if the 12-V battery is connected to three 4-Ω resistors in series, the total resistance is 12 Ω and the current will be only 1 A.

Another simple way to connect resistors is in **parallel**, so that the current from the source splits into

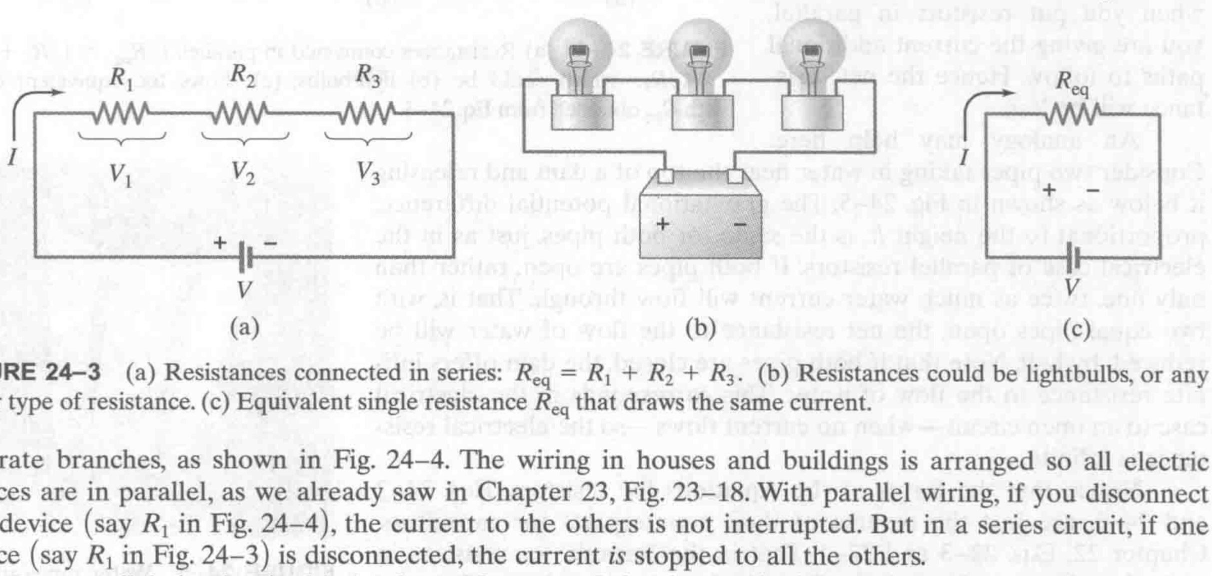

FIGURE 24–3 (a) Resistances connected in series: $R_{eq} = R_1 + R_2 + R_3$. (b) Resistances could be lightbulbs, or any other type of resistance. (c) Equivalent single resistance R_{eq} that draws the same current.

separate branches, as shown in Fig. 24–4. The wiring in houses and buildings is arranged so all electric devices are in parallel, as we already saw in Chapter 23, Fig. 23–18. With parallel wiring, if you disconnect one device (say R_1 in Fig. 24–4), the current to the others is not interrupted. But in a series circuit, if one device (say R_1 in Fig. 24–3) is disconnected, the current *is* stopped to all the others.

In a parallel circuit, Fig. 24–4a, the total current I that leaves the battery breaks into three branches. We let I_1, I_2, and I_3 be the currents through each of the resistors, R_1, R_2, and R_3, respectively. Because electric charge is conserved, the current flowing into a junction (where different wires or conductors meet) must equal the current flowing out of the junction. Thus, in Fig. 24–4a,

$$I = I_1 + I_2 + I_3. \qquad \text{[parallel]}$$

When resistors are connected in parallel, each experiences the same voltage. (Indeed, any two points in a circuit connected by a wire of negligible resistance are at the same potential.) Hence the full voltage of the battery is applied to each resistor in Fig. 24–4a, so

$$I_1 = \frac{V}{R_1}, \quad I_2 = \frac{V}{R_2}, \quad \text{and} \quad I_3 = \frac{V}{R_3}.$$

Let us now determine what single resistor R_{eq} (Fig. 24–4c) will draw the same current I as these three resistances in parallel. This equivalent resistance R_{eq} must satisfy

$$I = \frac{V}{R_{eq}}.$$

We now combine the equations above:

$$I = I_1 + I_2 + I_3,$$

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

When we divide out the V from each term, we have

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}. \qquad \text{[parallel]} \qquad (24\text{–}3)$$

For example, suppose you connect two 4-Ω loudspeakers to a single set of output terminals of your stereo amplifier or receiver. (Ignore the other channel for a moment—our two speakers are both connected to the left channel, say.) The equivalent resistance will then be found from

$$\frac{1}{R_{eq}} = \frac{1}{4\,\Omega} + \frac{1}{4\,\Omega} = \frac{2}{4\,\Omega} = \frac{1}{2\,\Omega},$$

and so $R_{eq} = 2\,\Omega$. Thus the net resistance is *less* than that of each single resistance. This may at first seem surprising. But remember that when you put resistors in parallel, you are giving the current additional paths to follow. Hence the net resistance will be less.

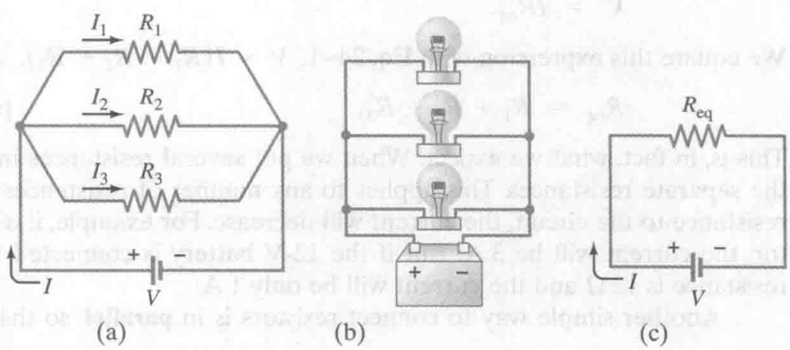

FIGURE 24–4 (a) Resistances connected in parallel: $1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$, which could be (b) lightbulbs; (c) shows the equivalent circuit with R_{eq} obtained from Eq. 24–3.

An analogy may help here. Consider two pipes taking in water near the top of a dam and releasing it below as shown in Fig. 24–5. The gravitational potential difference, proportional to the height h, is the same for both pipes, just as in the electrical case of parallel resistors. If both pipes are open, rather than only one, twice as much water current will flow through. That is, with two equal pipes open, the net resistance to the flow of water will be reduced, by half. Note that if both pipes are closed, the dam offers infinite resistance to the flow of water. This corresponds in the electrical case to an open circuit—when no current flows—so the electrical resistance is infinite.

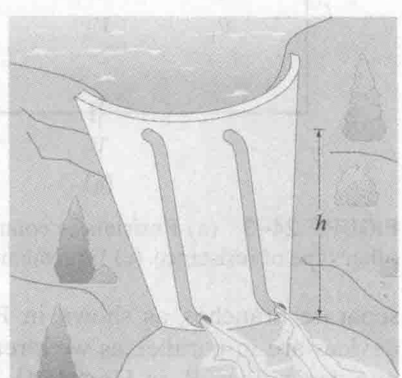

FIGURE 24–5 Water pipes in parallel—analogy to electric currents in parallel.

Notice that the forms of the equations for resistors, Eqs. 24–2 and 24–3, are just the reverse of their counterparts for capacitors, Chapter 22, Eqs. 22–3 and 22–4. That is, the formula for resistors in series has the same form as the formula for capacitors in parallel, and vice versa.

* 24–3 Kirchhoff's Rules

In the last few Examples we have been able to find the currents flowing in circuits by combining resistances in series and parallel. This technique can be used for many circuits. However, some circuits are too complicated for that analysis. For example, we cannot find the currents flowing in each part of the circuit shown in Fig. 24–6 simply by combining resistances as we did before.

To deal with such complicated circuits, we use Kirchhoff's rules, devised by G. R. Kirchhoff (1824–1887) in the mid-nineteenth century. There are two of them, and they are simply convenient applications of the laws of conservation of charge and energy. **Kirchhoff's first** or **junction rule** is based on the conservation of charge, and we already used it in deriving the rule for parallel resistors. It states that

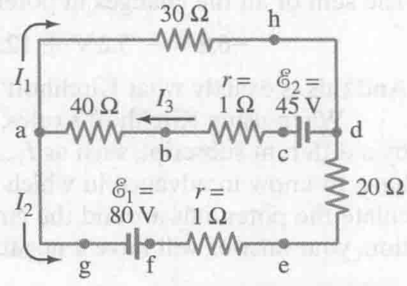

FIGURE 24–6 Currents can be calculated using Kirchhoff's rules.

> **at any junction point, the sum of all currents entering the junction must equal the sum of all currents leaving the junction.**

That is, what goes in must come out. For example, at the junction point a in Fig. 24–6, I_3 is entering whereas I_1 and I_2 are leaving. Thus Kirchhoff's junction rule states that $I_3 = I_1 + I_2$.

Kirchhoff's second or **loop rule** is based on the conservation of energy. It states

> **the sum of the changes in potential around any closed path of a circuit must be zero.**

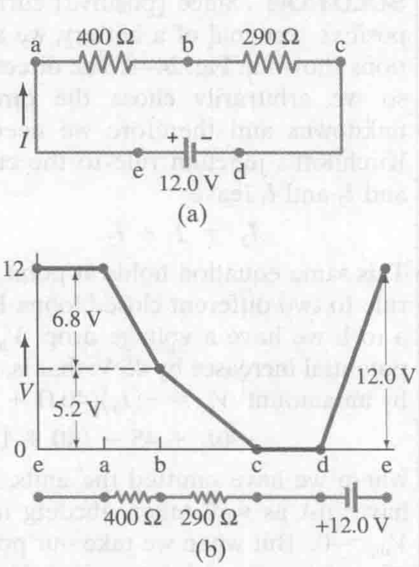

FIGURE 24–7 Changes in potential around the circuit in (a) are plotted in (b).

To see why this should hold, consider a rough analogy with the potential energy of a roller coaster on its track. When it starts from the station, it has a particular potential energy. As it climbs the first hill, its potential energy increases and reaches a peak at the top. As it descends the other side, its potential energy decreases and reaches a local minimum at the bottom of the hill. As the roller coaster continues on its path, its potential energy goes through more changes. But when it arrives back at the starting point, it has exactly as much potential energy as it had when it started at this point. Another way of saying this is that there was as much uphill as there was downhill.

Similar reasoning can be applied to an electric circuit. We will do the circuit of Fig. 24–6 shortly but first we consider the simpler circuit in Fig. 24–7. The current in this circuit is $I = (12.0\,\mathrm{V})/(690\,\Omega) = 0.017\,\mathrm{A}$. The positive side of the battery, point e in Fig. 24–7a, is at a high potential compared to point d at the negative side of the battery. That is, point e is like the top of a hill for a roller coaster. We can now follow the current around the circuit starting at any point we choose. Let us start at point e and follow a positive test charge completely around this circuit. As we go, we will note all changes in potential. When the test charge returns to point e, the potential there will be the same as when we started, so the total change in potential will be zero. It is useful to plot the changes in voltage around the circuit, and we do this in Fig. 24–7b; point d is arbitrarily taken as zero. As our positive test charge goes from point e to point a, there is no change in potential since there is no source of potential nor any resistance. However, as the charge passes through the 400-Ω resistor to get to point b, there is a decrease in potential of $V = IR = (0.017\,\mathrm{A})(400\,\Omega) = 6.8\,\mathrm{V}$. In effect, the positive test charge is flowing "downhill" since it is heading toward the negative terminal of the battery. This is indicated in the graph of Fig. 24–7b. The decrease in potential between the two ends of a resistor ($= IR$) is called a **voltage drop**. Because this is a *decrease* in potential, we use a *negative* sign when applying Kirchhoff's loop rule; that is,

$$V_{\mathrm{ba}} = V_{\mathrm{b}} - V_{\mathrm{a}} = -6.8\,\mathrm{V}.$$

As the charge proceeds from b to c there is another voltage drop of $(0.017\,\mathrm{A}) \times (290\,\Omega) = 5.2\,\mathrm{V}$, and since this is a decrease in potential, we write

$$V_{\mathrm{cb}} = -5.2\,\mathrm{V}.$$

There is no change in potential as our test charge moves from c to d. But when it moves from d, which is the negative or low potential side of the battery, to point e which is the positive terminal, the potential *increases* by 12.0 V. That is,

$$V_{ed} = +12.0\,\text{V}.$$

The sum of all the changes in potential in going around the circuit of Fig. 24–7 is

$$-6.8\,\text{V} - 5.2\,\text{V} + 12.0\,\text{V} = 0.$$

And this is exactly what Kirchhoff's loop rule said it would be.

When using Kirchhoff's rules, we will designate the current in each separate branch of the given circuit by a different subscript, such as I_1, I_2, and I_3 in Fig. 24–8 (this is the same circuit as in Fig. 24–6). You do not have to know in advance in which direction these currents actually are moving. You make a guess and calculate the potentials around the circuit for that direction. If the current actually flows in the opposite direction, your answer will have a negative sign.

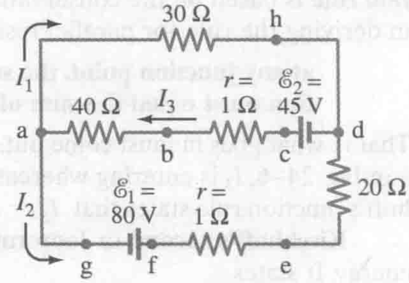

FIGURE 24–8 Currents can be calculated using Kirchhoff's rules. See Example 24–2.

EXAMPLE 24–2 Using Kirchhoff's rules. Calculate the currents I_1, I_2, and I_3 in each of the branches of the circuit in Fig. 24–8.

SOLUTION Since (positive) current tends to move away from the positive terminal of a battery, we assume I_2 and I_3 to have the directions shown in Fig. 24–8. The direction of I_1 is not obvious in advance, so we arbitrarily chose the direction indicated. We have three unknowns and therefore we need three equations. We first apply Kirchhoff's junction rule to the currents at point a, where I_3 enters and I_2 and I_1 leave:

$$I_3 = I_1 + I_2. \qquad (a)$$

This same equation holds at point d, so we get no new information there. We now apply Kirchhoff's loop rule to two different closed loops. First we apply it to the loop ahdcba. We start (and end) at point a. From a to h we have a voltage drop $V_{ha} = -(I_1)(30\,\Omega)$. From h to d there is no change, but from d to c the potential increases by 45 V: that is, $V_{cd} = +45\,\text{V}$. From c to a the voltage drops through the two resistances by an amount $V_{ac} = -(I_3)(40\,\Omega + 1\,\Omega)$. Thus we have $V_{ha} + V_{cd} + V_{ac} = 0$, or

$$-30I_1 + 45 - (40 + 1)I_3 = 0 \qquad (b)$$

where we have omitted the units. For our second loop, we take the complete circuit ahdefga. (We could have just as well taken abcdefg instead.) Again we start at point a and have $V_{ha} = -(I_1)(30\,\Omega)$, and $V_{dh} = 0$. But when we take our positive test charge from d to e, it actually is going uphill, against the flow of current—or at least against the *assumed* direction of the current, which is what counts in this calculation. Thus $V_{ed} = I_2(20\,\Omega)$ has a *positive* sign. Similarly, $V_{fe} = I_2(1\,\Omega)$. From f to g there is a decrease in potential of 80 V since we go from the high potential terminal of the battery to the low. Thus $V_{gf} = -80\,\text{V}$. Finally, $V_{ag} = 0$, and the sum of the potential charges around this loop is then

$$-30I_1 + (20 + 1)I_2 - 80 = 0. \qquad (c)$$

The physics is now done. The rest is algebra. We have three equations—labeled (a), (b), and (c)—in three unknowns. From Eq. (c) we have

$$I_2 = \frac{80 + 30I_1}{21} = 3.8 + 1.4I_1. \qquad (d)$$

From Eq. (b) we have

$$I_3 = \frac{45 - 30I_1}{41} = 1.1 - 0.73I_1. \qquad (e)$$

We substitute these into Eq. (a) and solve for I_1:

$$I_1 = I_3 - I_2 = 1.1 - 0.73I_1 - 3.8 - 1.4I_1$$
$$3.1I_1 = -2.7$$
$$I_1 = -0.87\,\text{A}.$$

The negative sign indicates that the direction of I_1 is actually opposite to that initially assumed and shown in Fig. 24–8. Note that the answer automatically comes out in amperes because all values were in volts and ohms. From Eq. (d) we have

$$I_2 = 3.8 + 1.4I_1 = 2.6\text{ A},$$

and from Eq. (*e*)

$$I_3 = 1.1 - 0.73I_1 = 1.7\text{ A}.$$

This completes the solution.

PROBLEM SOLVING Kirchhoff's Rules

1. Label + and − for each battery. The long side of a battery symbol is +.
2. Label the current in each branch of the circuit with a symbol and an arrow (as in Fig. 24–8): The direction of the arrow can be chosen arbitrarily. If the current is actually in the opposite direction, it will come out with a minus sign in the solution.
3. Apply Kirchhoff's junction rule at one or more junctions, and the loop rule for one or more loops. You will need as many independent equations as there are unknowns. You may write down more equations than this, but you will find that some of the equations will be redundant (that is, not be independent in the sense of providing new information). You may use $V = IR$ for each resistor, which sometimes will reduce the number of unknowns.
4. In applying the loop rule, follow each loop in one direction only. Pay careful attention to subscripts, and to signs:
   (a) For a resistor, the sign of the potential difference is negative if your chosen loop direction is the same as the chosen current direction through that resistor; the sign is positive if you are moving opposite to the chosen current direction.
   (b) For a battery, the sign of the potential difference is positive if your loop direction moves from the negative terminal toward the positive; the sign is negative if you are moving from the positive terminal toward the negative terminal.
5. Solve the equations algebraically for the unknowns. Be careful in manipulating equations not to err with signs. At the end, check your answers by plugging them into the original equations, or even by using any additional equations not used previously (either loop or junction rule equations).

EXAMPLE 24–3 Wheatstone bridge. A wheatstone bridge is a type of "bridge circuit" used to make measurements of resistance. The unknown resistance to be measured, R_x, is placed in the circuit with accurately known resistances R_1, R_2, and R_3. One of these, R_3, is a variable resistor which is adjusted so that when the switch is closed momentarily, the ammeter Ⓐ shows zero current flow. (We will see later in this Chapter how an ammeter works.) (*a*) Determine R_x in terms of R_1, R_2, and R_3. (*b*) If a Wheatstone bridge is "balanced" when $R_1 = 630\,\Omega$, $R_2 = 972\,\Omega$, and $R_3 = 42.6\,\Omega$, what is the value of the unknown resistance?

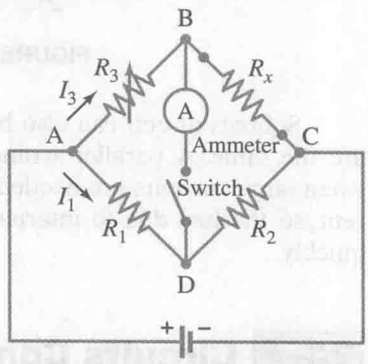

FIGURE 24–9 Example 24–3, Wheatstone bridge.

SOLUTION (*a*) We are told that R_3 has been adjusted until no current flows through the ammeter. Hence points B and D in Fig. 24–9 are at the same potential, so $V_{AB} = V_{AD}$ or

$$I_3 R_3 = I_1 R_1.$$

I_1 is the current that passes through R_1 and also through R_2 when the bridge is balanced; I_3 is the current through R_3 and R_x. When the bridge is balanced the voltage across R_x equals that across R_2, so

$$I_3 R_x = I_1 R_2.$$

We divide these two equations and find

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

In practice, the ammeter is very sensitive, and so when R_3 is being adjusted the switch is closed only momentarily to check if the current is zero or not.

(*b*) $$R_x = \frac{R_2}{R_1}R_3 = \left(\frac{972\Omega}{630\Omega}\right)(42.6\Omega) = 65.7\Omega.$$

EMFs in Series and in Parallel; Charging a Battery

When two or more sources of emf, such as batteries, are arranged in series, as in Fig. 24–10a, the total voltage is the algebraic sum of their respective voltages. On the other hand, when a 20-V and a 12-V battery are connected oppositely, as shown in Fig. 24–10b, the net voltage V_{ca} is 8 V. That is, a positive test charge moved from a to b gains in potential by 20 V, but when it passes from b to c it drops by 12 V. So the net change is 20 V − 12 V = 8 V. You might think that connecting batteries in reverse like this would be wasteful. And for most purposes that would be true. But such a reverse arrangement is precisely how a battery charger works. In Fig. 24–10b, the 20-V source is charging up the 12-V battery. Because of its greater voltage, the 20-V source is forcing charge back into the 12-V battery: electrons are being forced into its negative terminal and removed from its positive terminal. An automobile alternator keeps the car battery charged in the same way. A voltmeter placed across the terminals of a (12-V) car battery with the engine running fairly fast can tell you whether or not the alternator is charging the battery. If it is, the voltmeter reads 13 or 14 V. If the battery is not being charged, the voltage will be 12 V, or less if the battery is discharging. Car batteries can be recharged, but other batteries may not be rechargeable, since the chemical reactions in many cannot be reversed. In such cases, the arrangement of Fig. 24–10b would simply waste energy.

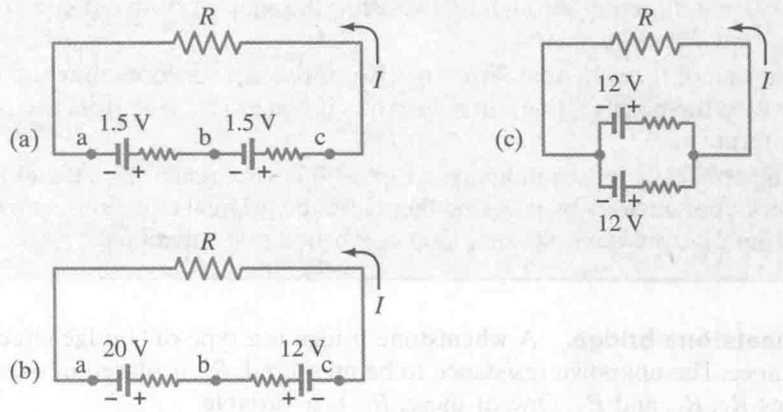

FIGURE 24–10 Batteries in series, (a) and (b), and in parallel, (c).

Sources of emf can also be arranged in parallel, Fig. 24–10c, which is useful normally only if the emfs are the same. A parallel arrangement is not used to increase voltage, but rather to provide more energy when large currents are needed. Each of the cells in parallel has to produce only a fraction of the total current, so the loss due to internal resistance is less than for a single cell; and the batteries will go dead less quickly.

* 24–4 Circuits Containing Resistor and Capacitor (*RC* Circuits)

Our study of circuits in this chapter has, until now, dealt with steady currents that don't change in time. Now we examine circuits that contain both resistance and capacitance. Such a circuit is called an ***RC* circuit**. *RC* circuits are common in everyday life: they are used to control the speed of a car's windshield wiper, and the timing of the change of a traffic light from red to green. They are used in camera flashes and in heart pacemakers.

Let us now examine the simple *RC* circuit shown in Fig. 24–11a. When the switch S is closed, current immediately begins to flow through the circuit. Electrons will flow out from the negative terminal of the battery, through the resistor *R*, and accumulate on the upper plate of the capacitor. And electrons will flow into the positive terminal of the battery, leaving a positive charge on the other plate of the capacitor. As charge accumulates on the capacitor, the potential difference across it increases; and the current is reduced until eventually the voltage across the capacitor equals the emf of the battery, $\mathscr{E}$. There is then no potential difference across the resistor, and no further current flows. The charge Q on the capacitor thus increases gradually as shown in Fig. 24–11b and reaches a maximum value equal to $C\mathscr{E}$ (Eq. 22–1, $Q_{\max} = CV_{\text{ba}} = C\mathscr{E}$). The mathematical form of this curve—that is, Q as a function of time—can be derived using conservation of energy (or Kirchhoff's loop rule). The emf $\mathscr{E}$ of the battery will equal the sum of the voltage drops across the resistor (IR) and the capacitor (Q/C):

$$\mathscr{E} = IR + \frac{Q}{C}. \qquad \textbf{(24–4)}$$

The resistance R includes all resistance in the circuit, including the internal resistance of the battery; I is the current in the circuit at any instant, and Q is the charge on the capacitor at that same instant. Although $\mathscr{E}$, R, and C are constants, both Q and I are functions of time. The rate at which charge flows through the resistor $(I = dQ/dt)$ is equal to the rate at which charge accumulates on the capacitor. Thus we can write

$$\mathscr{E} = R\frac{dQ}{dt} + \frac{1}{C}Q.$$

This equation can be solved by rearranging it:

$$\frac{dQ}{C\mathscr{E} - Q} = \frac{dt}{RC}.$$

We now integrate from $t = 0$, when $Q = 0$, to time t when a charge Q is on the capacitor:

$$\int_0^Q \frac{dQ}{C\mathscr{E} - Q} = \frac{1}{RC}\int_0^t dt$$

$$-\ln(C\mathscr{E} - Q) - (-\ln C\mathscr{E}) = \frac{t}{RC}$$

or

$$\ln(C\mathscr{E} - Q) - \ln(C\mathscr{E}) = -\frac{t}{RC}$$

so

$$\ln\left(1 - \frac{Q}{C\mathscr{E}}\right) = -\frac{t}{RC}.$$

We take the exponential of both sides

$$1 - \frac{Q}{C\mathscr{E}} = e^{-t/RC}$$

or

$$Q = C\mathscr{E}\left(1 - e^{-t/RC}\right). \qquad \textbf{(24–5a)}$$

The potential difference across the capacitor is $V_C = Q/C$, so

$$V_C = \mathscr{E}\left(1 - e^{-t/RC}\right) \qquad \textbf{(24–5b)}$$

From Eqs. 24–5 we see that the charge Q on the capacitor, and the voltage V_C across it, increase from zero at $t = 0$ to maximum values $Q_{\max} = C\mathscr{E}$ and $V_C = \mathscr{E}$ after a very long time. The quantity RC that appears in the exponent is called the **time constant** τ of the circuit:

$$\tau = RC.$$

(The units of RC are $\Omega \cdot \text{F} = (\text{V/A})(\text{C/V}) = \text{C}/(\text{C/s}) = \text{s}$.) It represents the time required for the capacitor to reach $(1 - e^{-1}) = 0.63$ or 63 percent of its full charge. Thus the product RC is a measure of how quickly the

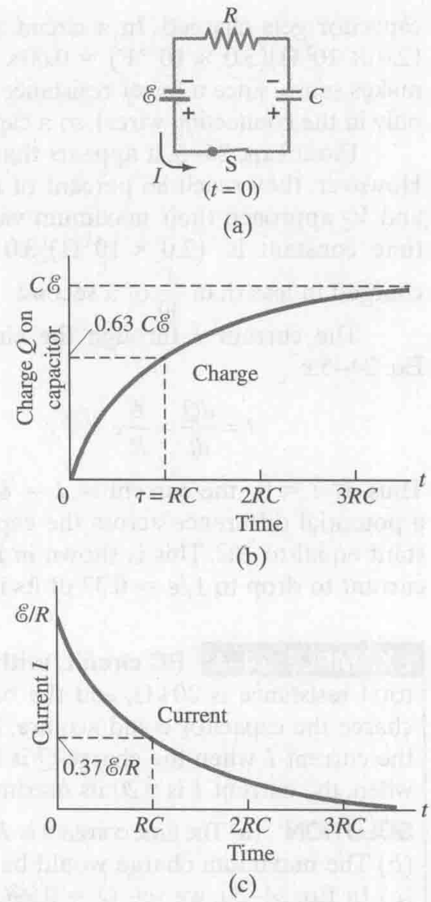

FIGURE 24–11 For the RC circuit shown in (a), the charge on the capacitor increases with time as shown in (b), and the current through the resistor decreases with time as shown in (c).

capacitor gets charged. In a circuit, for example, where $R = 200\,\mathrm{k\Omega}$ and $C = 3.0\,\mu\mathrm{F}$, the time constant is $(2.0 \times 10^5\,\Omega)(3.0 \times 10^{-6}\,\mathrm{F}) = 0.60\,\mathrm{s}$. If the resistance is much lower, the time constant is much smaller. This makes sense, since a lower resistance will retard the flow of charge less. All circuits contain some resistance (if only in the connecting wires), so a capacitor never can be charged instantaneously when connected to a battery.

From Eqs. 24–5, it appears that Q and V_C never quite reach their maximum values within a finite time. However, they reach 86 percent of maximum in $2RC$, 95 percent in $3RC$, 98 percent in $4RC$, and so on. Q and V_C approach their maximum values asymptotically. For example, if $R = 20\,\mathrm{k\Omega}$ and $C = 0.30\,\mu\mathrm{F}$, the time constant is $(2.0 \times 10^4\,\Omega)(3.0 \times 10^{-7}\,\mathrm{F}) = 6.0 \times 10^{-3}\,\mathrm{s}$. So the capacitor is more than 98 percent charged in less than $\frac{1}{40}$ of a second.

The current I through the circuit of Fig. 24–11a at any time t can be obtained by differentiating Eq. 24–5a:

$$I = \frac{dQ}{dt} = \frac{\mathscr{E}}{R} e^{-t/RC}. \qquad \textbf{(24–6)}$$

Thus, at $t = 0$, the current is $I = \mathscr{E}/R$, as expected for a circuit containing only a resistor (there is not yet a potential difference across the capacitor). The current then drops exponentially in time with a time constant equal to RC. This is shown in Fig. 24–11c. The time constant RC represents the time required for the current to drop to $1/e \approx 0.37$ of its initial value.

EXAMPLE 24–4 **RC circuit, with emf.** The capacitance in the circuit of Fig. 24–11a is $C = 0.30\,\mu\mathrm{F}$, the total resistance is $20\,\mathrm{k\Omega}$, and the battery emf is 12 V. Determine (*a*) the time constant, (*b*) the maximum charge the capacitor could acquire, (*c*) the time it takes for the charge to reach 99 percent of this value, (*d*) the current I when the charge Q is half its maximum value, (*e*) the maximum current, and (*f*) the charge Q when, the current I is 0.20 its maximum value.

SOLUTION (*a*) The time constant is $RC = (2.0 \times 10^4\,\Omega)(3.0 \times 10^{-7}\,\mathrm{F}) = 6.0 \times 10^{-3}\,\mathrm{s}$.
(*b*) The maximum charge would be $Q = C\mathscr{E} = (3.0 \times 10^{-7}\,\mathrm{F})(12\,\mathrm{V}) = 3.6\,\mu\mathrm{C}$.
(*c*) In Eq. 24–5a, we set $Q = 0.99C\mathscr{E}$:

$$0.99\,\mathscr{E} = C\mathscr{E}(1 - e^{-t/RC}),$$

or

$$e^{-t/RC} = 1 - 0.99 = 0.01.$$

Then

$$\frac{t}{RC} = -\ln(0.01) = 4.6$$

so

$$t = 4.6RC = 28 \times 10^{-3}\,\mathrm{s}$$

or 28 ms (less than $\frac{1}{30}$ s).

(*d*) From part (*b*) the maximum charge is $3.6\,\mu\mathrm{C}$. When the charge is half this value, $1.8\,\mu\mathrm{C}$, the current I in the circuit can be found using the original differential equation, or Eq. 24–4:

$$I = \frac{1}{R}\left(\mathscr{E} - \frac{Q}{C}\right) = \frac{1}{2.0 \times 10^4\,\Omega}\left(12\,\mathrm{V} - \frac{1.8 \times 10^{-6}\,\mathrm{C}}{0.30 \times 10^{-6}\,\mathrm{F}}\right) = 300\,\mu\mathrm{A}.$$

(*e*) The current is a maximum when there is no charge on the capacitor ($Q = 0$):

$$I_{\max} = \frac{\mathscr{E}}{R} = \frac{12\,\mathrm{V}}{2.0 \times 10^4\,\Omega} = 600\,\mu\mathrm{A}.$$

(*f*) Again using Eq. 24–4, with $I = 0.20I_{\max} = 120\,\mu\mathrm{A}$, we have
$Q = C(\mathscr{E} - IR) = (3.0 \times 10^{-7}\,\mathrm{F})[12\,\mathrm{V} - (1.2 \times 10^{-4}\,\mathrm{A})(2.0 \times 10^4\,\Omega)] = 2.9\,\mu\mathrm{C}$.

The circuit just discussed involved the *charging* of a capacitor by a battery through a resistance. Now let us look at another situation: when a capacitor is already charged (say to a voltage V_0), and it is allowed to *dis-*

charge through a resistance R as shown in Fig. 24–12a. (In this case there is no battery.) When the switch S is closed, charge begins to flow through resistor R from one side of the capacitor toward the other side, until the capacitor is fully discharged. The voltage across the resistor at any instant equals that across the capacitor:

$$IR = \frac{Q}{C}.$$

The rate at which charge leaves the capacitor equals the negative of the current in the resistor, $I = -dQ/dt$, because the capacitor is discharging (Q is decreasing). So we write the above equation as

$$-\frac{dQ}{dt}R = \frac{Q}{C}.$$

We rearrange this to

$$\frac{dQ}{Q} = -\frac{dt}{RC}$$

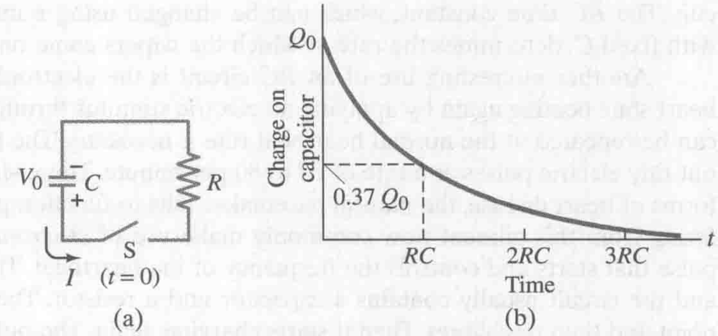

FIGURE 24–12 For the RC circuit shown in (a), the charge Q on the capacitor decreases with time, as shown in (b), after the switch S is closed at $t = 0$. The voltage across the capacitor follows the same curve since $V \propto Q$.

and integrate it from $t = 0$ when the charge on the capacitor is Q_0, to some time t when the charge is Q:

$$\ln\frac{Q}{Q_0} = -\frac{t}{RC}$$

or

$$Q = Q_0 e^{-t/RC}. \tag{24–7}$$

Thus the charge on the capacitor decreases exponentially in time with a time constant RC. This is shown in Fig. 24–12b. The current is

$$I = -\frac{dQ}{dt} = \frac{Q_0}{RC}e^{-t/RC} = I_0 e^{-t/RC}, \tag{24–8}$$

and it too is seen to decrease exponentially in time with the same time constant RC. Both the charge on the capacitor and the voltage across it ($V_C = Q/C$), as well as the current in the resistor, decrease to 37 percent of their original value in one time constant $t = \tau = RC$.

Applications of *RC* Circuits

The charging and discharging in an RC circuit can be used to produce voltage pulses at a regular frequency. The charge on the capacitor increases to a particular voltage, and then discharges. A simple way of initiating the discharge is by the use of a gas-filled tube that breaks down when the voltage across it reaches a certain value V_0. After the discharge is finished, the tube no longer conducts current and the recharging process repeats itself, starting at V_0'. Figure 24–13 shows a possible circuit, and the "sawtooth" voltage it produces.

An automobile turn signal indicator can be an application of a sawtooth oscillator circuit. Here the emf is supplied by the car battery ($\mathscr{E} = 12\,\text{V}$); the neon bulb, which flashes on at a rate of perhaps 2 cycles per second, is the turn signal indicator. The main component of the "flasher unit" is a moderately large capacitor.

The intermittent windshield wipers of a car can also use an RC cir-

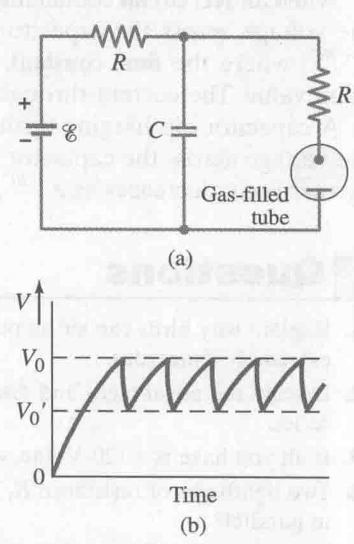

FIGURE 24–13 (a) An RC circuit, coupled with a gas-filled tube as a switch, can produce a repeating "sawtooth" voltage, as shown in (b).

cuit. The RC time constant, which can be changed using a multi-positioned switch for different values of R with fixed C, determines the rate at which the wipers come on.

Another interesting use of an RC circuit is the electronic heart pacemaker, which can make a stopped heart start beating again by applying an electric stimulus through electrodes attached to the chest. The stimulus can be repeated at the normal heartbeat rate if necessary. The heart itself contains *pacemaker* cells, which send out tiny electric pulses at a rate of 60 to 80 per minute. These signals induce the start of each heartbeat. In some forms of heart disease, the natural pacemaker fails to function properly, and the heart loses its beat. People suffering from this ailment now commonly make use of *electronic pacemakers* which produce a regular voltage pulse that starts and controls the frequency of the heartbeat. The electrodes are implanted in or near the heart and the circuit usually contains a capacitor and a resistor. The charge on the capacitor increases to a certain point and then discharges. Then it starts charging again. The pulsing rate depends on the values of R and C.

Summary

A device that transforms one type of energy into electrical energy is called a **source** of **emf**. A battery behaves like a source of emf in series with an **internal resistance**. The emf is the potential difference determined by the chemical reactions in the battery and equals the terminal voltage when no current is drawn. When a current is drawn, the voltage at the battery's terminals is less than its emf by an amount equal to the Ir drop across the internal resistance.

When resistances are connected in **series** (end to end), the equivalent resistance is the sum of the individual resistances:

$$R_{eq} = R_1 + R_2 + \cdots.$$

When resistors are connected in **parallel**, the reciprocal of the total resistance equals the sum of the reciprocals of the individual resistances:

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

In a parallel connection, the net resistance is less than any of the individual resistances.

Kirchhoff's rules are helpful in determining the currents and voltages in circuits. Kirchhoff's **junction rule** is based on conservation of electric charge and states that the sum of all currents entering any junction equals the sum of all currents leaving that junction. The second, or **loop rule**, is based on conservation of energy and states that the algebraic sum of the voltage changes around any closed path of the circuit must be zero.

When an ***RC* circuit** containing a resistor R in series with a capacitance C is connected to a dc source of emf, the voltage across the capacitor rises gradually in time characterized by an exponential of the form $(1 - e^{-t/RC})$ where the **time constant**, $\tau = RC$, is the time it takes for the voltage to reach 63 percent of its maximum value. The current through the resistor decreases as $e^{-t/RC}$.

A capacitor discharging through a resistor is characterized by the same time constant: in a time $\tau = RC$, the voltage across the capacitor drops to 37 percent of its initial value. The charge on the capacitor, and voltage across it, decreases as $e^{-t/RC}$, as does the current.

Questions

1. Explain why birds can sit on power lines safely, while leaning a metal ladder up against one to fetch a stuck kite is extremely dangerous.
2. Discuss the advantages and disadvantages of Christmas tree lights connected in parallel versus those connected in series.
3. If all you have is a 120-V line, would it be possible to light several 6-V lamps without burning them out? How?
4. Two lightbulbs of resistance R_1 and R_2 $(>R_1)$ are connected in series. Which is brighter? What if they are connected in parallel?
5. Describe carefully the difference between emf and potential difference.
6. Household outlets are often double outlets. Are these connected in series or parallel? How do you know?
7. With two identical lightbulbs and two identical batteries, how would you arrange the bulbs and batteries in a circuit in order to get the maximum possible total power out. (Assume that the batteries have negligible internal resistance.)

8. Explain why Kirchhoff's junction rule is based on conservation of electric charge.
9. Explain why Kirchhoff's loop rule is a result of the conservation of energy.
10. How does the overall resistance of your room's electric circuit change when instead of having a single 60-W lightbulb on, you turn on an additional 100-W bulb?
11. Given the circuit shown in Fig. 24–14, use the words "increases," "decreases," or "stays the same" to complete the following statements:
    (*a*) If R_7 increases, the potential difference between A and E (assume no resistance in Ⓐ and $\mathscr{E}$) __________.
    (*b*) If R_7 increases, the potential difference between A and E (assume Ⓐ and $\mathscr{E}$ have resistance) __________.
    (*c*) If R_7 increases, the voltage drop across R_4 __________.
    (*d*) If R_2 decreases, the current through R_1 __________.
    (*e*) If R_2 decreases, the current through R_6 __________.
    (*f*) If R_2 decreases, the current through R_3 __________.
    (*g*) If R_5 increases, the voltage drop across R_2 __________.
    (*h*) If R_5 increases, the voltage drop across R_4 __________.
    (*i*) If R_2, R_5, and R_7 increase, $\mathscr{E}$ __________.

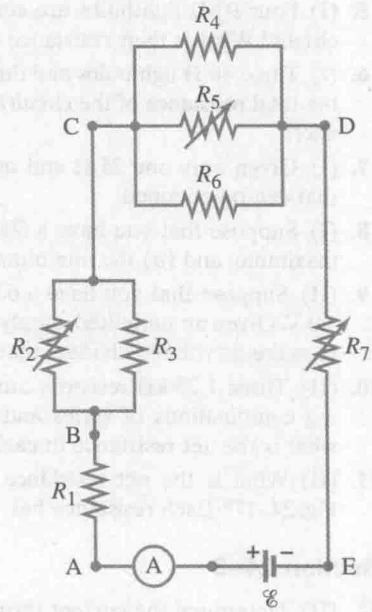

FIGURE 24–14 Question 11.

12. Why are batteries connected in series? Why in parallel? Does it matter if the batteries are nearly identical or not in either case?
13. Can the terminal voltage of a battery ever exceed its emf? Explain.
14. The 18-V source in Fig. 24–15 is "charging" the 12-V battery. Explain how it does this.
15. Explain in detail how you could measure the internal resistance of a battery.
16. Compare and discuss the formulas for the equivalent values for resistors and for capacitors when connected in series and in parallel.
17. Suppose that three identical capacitors are connected to a battery. Will they store more energy if connected in series or in parallel?
18. When applying Kirchhoff's loop rule (such as in Fig. 24–15), does the sign (or direction) of a battery's emf depend on the direction of current through the battery?
19. In an *RC* circuit, current flows from the battery until the capacitor is completely charged. Is the total energy supplied by the battery equal to the total energy stored by the capacitor? If not, where does the extra energy go?
20. Design a circuit in which two different switches of the type shown in Fig. 24–16 can be used to operate the same lightbulb from opposite sides of a room.

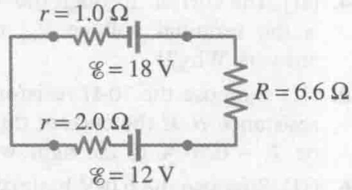

FIGURE 24–15 Questions 14 and 18; and Problem 24.

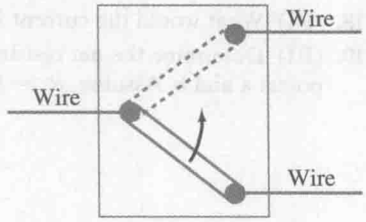

FIGURE 24–16 Question 20.

Problems

Section 24–1

1. (I) Calculate the terminal voltage for a battery with an internal resistance of 0.900 Ω and an emf of 8.50 V when the battery is connected in series with (*a*) a 68.0-Ω resistor, and (*b*) a 680-Ω resistor.
2. (I) Four 2.0-V cells are connected in series to a 12-Ω lightbulb. If the resulting current flow is 0.62 A, what is the internal resistance of each cell, assuming they are identical and neglecting the wires?
3. (II) A 1.5-V dry cell can be tested by connecting it to a low-resistance ammeter. It should be able to supply at least 25 A. What is the internal resistance of the cell in this case?
4. (II) What is the internal resistance of a 12.0-V car battery whose terminal voltage drops to 9.8 V when the starter draws 60 A? What is the resistance of the starter?

Section 24–2

In the following Problems neglect the internal resistance of a battery unless the Problem refers to it.

5. (I) Four 90-Ω lightbulbs are connected in series. What is the total resistance of the circuit? What is their resistance if they are connected in parallel?

6. (I) Three 40-Ω lightbulbs and three 80-Ω lightbulbs are connected in series. (*a*) What is the total resistance of the circuit? (*b*) What is their resistance if all six are wired in parallel?

7. (I) Given only one 25-Ω and one 70-Ω resistor, list all possible values of resistance that can be obtained.

8. (I) Suppose that you have a 500-Ω, a 900-Ω, and a 1.40-kΩ resistor. What is (*a*) the maximum, and (*b*) the mininium resistance you can obtain by combining these?

9. (II) Suppose that you have a 6.0-V battery and you wish to apply a voltage of only 4.0 V. Given an unlimited supply of 1.0-Ω resistors, how could you connect them so as to make a "voltage divider" that produced a 4.0-V output for a 6.0-V input?

10. (II) Three 1.20-kΩ resistors can be connected together in four different ways, making combinations of series and/or parallel circuits. What are these four ways and what is the net resistance in each case?

11. (II) What is the net resistance of the circuit connected to the battery in Fig. 24–17? Each resistance has $R = 2.8\ \text{k}\Omega$.

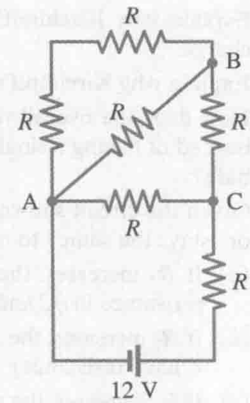

FIGURE 24–17 Problems 11 and 18.

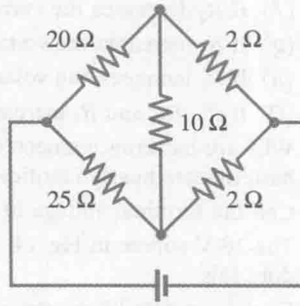

FIGURE 24–18 Problems 12 and 13.

*Section 24–3

*12. (II) Determine the current through each of the resistors in Fig. 24–18.

*13. (II) If the 20-Ω resistor in Fig. 24–18 is shorted out (resistance = 0), what then would be the current through the 10-Ω resistor?

*14. (II) The current through the 4.0-kΩ resistor in Fig. 24–19 is 3.50 mA. What is the terminal voltage V_{ba} of the "unknown" battery? (There are two answers. Why?)

*15. (II) Suppose the 10-Ω resistor in Fig. 24–20 were replaced by an unknown resistance R. If the current through this unknown resistance is measured to be $I_2 = 0.90\ \text{A}$ to the right, what is the value of R? Assume $r = 1.0\ \Omega$.

*16. (II) Suppose the 6.0-V battery in Fig. 24–20 is replaced by an unknown emf $\mathscr{E}$. If the current through the 10-Ω resistor is $I_2 = 0.30\ \text{A}$ to the left, what is $\mathscr{E}$? Assume $r = 1.0\ \Omega$.

*17. (III) Determine the currents I_1, I_2, and I_3 in Fig. 24–20. Assume the internal resistance of each battery is $r = 1.0\ \Omega$. What is the terminal voltage of the 6.0-V battery?

*18. (III) What would the current I_1 be in Fig. 24–20 ($r = 1.0\ \Omega$) if the 18-Ω resistor were shorted out?

*19. (III) Determine the net resistance of the network shown in Fig. 24–21 (*a*) between points a and c, and (*b*) between points a and b. Assume $R' = R$. [*Hint*: Use symmetry.]

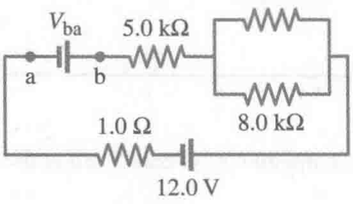

FIGURE 24–19 Problem 14.

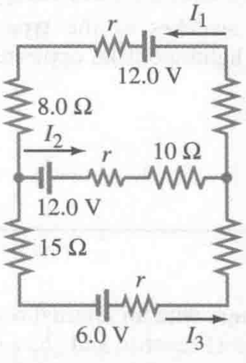

FIGURE 24–20 Problems 15, 16, 17 and18.

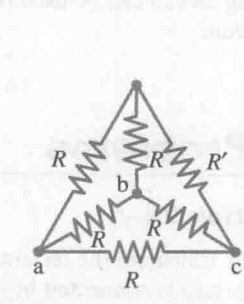

FIGURE 24–21 Problems 19

*20. (III) A voltage V is applied to n resistors connected in parallel. If the resistors are instead all connected in series with the applied voltage, show that the power transformed is decreased by a factor n^2.

*Section 24–4

*21. (II) In Fig. 24–11a, the total resistance is 15 kΩ, and the battery's emf is 24.0 V. If the time constant is measured to be 55 μs, calculate (*a*) the total capacitance of the circuit and (*b*) the time it takes for the voltage across the resistor to reach 16.0 V.

* **22.** (II) The RC circuit of Fig. 24–12a has $R = 6.7\,\mathrm{k\Omega}$ and $C = 6.0\,\mu\mathrm{F}$. The capacitor is at voltage V_0 at $t = 0$, when the switch is closed. How long does it take the capacitor to discharge to 1.0 percent of its initial voltage?

* **23.** (II) How long does it take for the energy stored in a capacitor in a series RC circuit (Fig. 24–11a) to reach half its maximum value? Express answer in terms of the time constant $\tau = RC$.

* **24.** (II) Two 6.0-μF capacitors, two 2.2-kΩ resistors, and a 12.0-V source are connected in series. Starting from the uncharged state, how long does it take for the current to drop from its initial value to 1.50 mA?

General Problems

25. Suppose that you wish to apply a 0.25-V potential difference between two points on the body. The resistance is about 2000 Ω, and you only have a 6.0-V battery. How can you connect up one or more resistors so that you can produce the desired voltage?

26. Suppose that a person's body resistance is 1100 Ω. (*a*) What current passes through the body when the person accidentally is connected to 110 V? (*b*) If there is an alternative path to ground whose resistance is 40 Ω, what current passes through the person? (*c*) If the voltage source can produce at most 1.5 A, how much current passes through the person in case (*b*)?

27. An unknown length of platinum wire 0.920 mm in diameter is placed as the unknown resistance in a Wheatstone bridge (Example 24–3 and Fig. 24–22). Arms 1 and 2 have resistance of 38.0 Ω and 46.0 Ω, respectively. Balance is achieved when R_3 is 3.48 Ω. How long is the platinum wire?

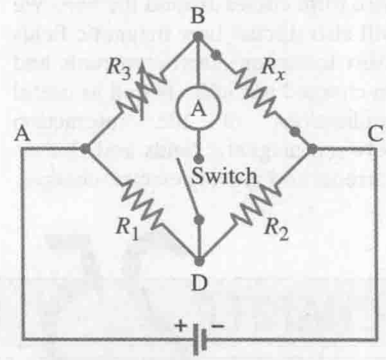

FIGURE 24–22 Wheatstone bridge. Problem 27.

28. A **potentiometer** is a device to precisely measure potential differences or emf, using a "null" technique. In the simple potentiometer circuit shown in Fig. 24–23, R' represents the total resistance of the resistor from A to B (which could be a long uniform "slide" wire), whereas R represents the resistance of only the part from A to the movable contact at C. When the unknown emf to be measured, $\mathscr{E}_x$, is placed into the circuit as shown, the movable contact C is moved until the galvanometer G gives a null reading (i.e., zero) when the switch S is closed. The resistance between A and C for this situation we call R_x. Next, a standard emf, $\mathscr{E}_s$, which is known precisely, is inserted into the circuit in place of $\mathscr{E}_x$ and again the contact C is moved until zero current flows through the galvanometer when the switch S is closed. The resistance between A and C now is called R_s. (*a*) Show that the unknown emf is given by

$$\mathscr{E}_x = \left(\frac{R_x}{R_s}\right)\mathscr{E}_s$$

where R_x, R_s, and $\mathscr{E}_s$ are all precisely known. The working battery is assumed to be fresh and give a constant voltage. (*b*) A slide-wire potentiometer is balanced against a 1.0182-V standard cell when the slide wire is set at 25.4 cm out of a total length of 100.0 cm. For an unknown source, the setting is 45.8 cm. What is the emf of the unknown? (*c*) The galvanometer of a potentiometer has an internal resistance of 30 Ω and can detect a current as small as 0.015 mA. What is the minimum uncertainty possible in measuring an unknown voltage? (*d*) Explain the advantage of using this "null" method of measuring emf.

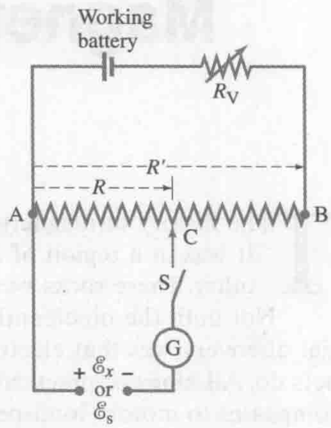

FIGURE 24–23 Potentiometer circuit. Problem 28.

29. Electronic devices often use an RC circuit to protect against power outages as shown in Fig. 24–24. (*a*) If the device is supposed to keep the supply voltage at least 70 percent of nominal for as long as 0.20 s, how big a resistance is needed? The capacitor is 14 μF. (*b*) Between which two terminals should the device be connected, a and b, b and c, or a and c?

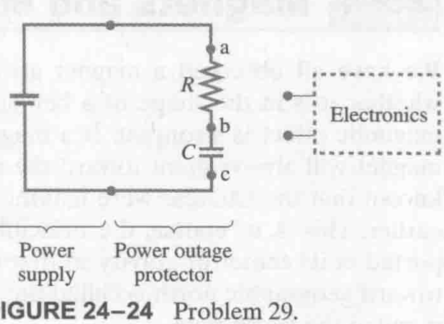

FIGURE 24–24 Problem 29.