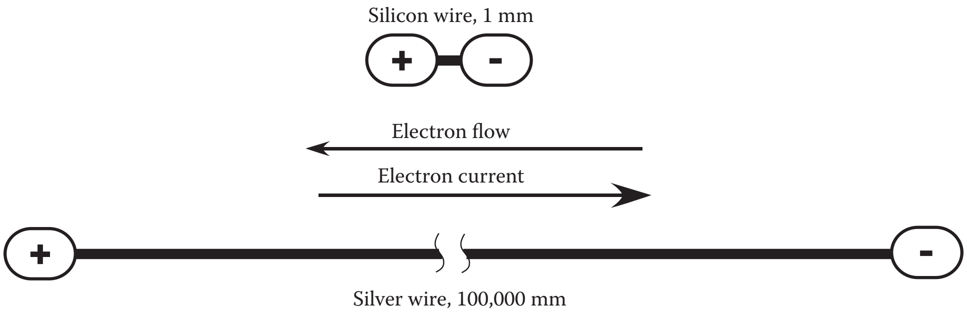

FIGURE 5.13 A silicon wire that is suddenly connected between two oppositely charged objects will allow electric current to flow between them, eventually making both neutral. A silver wire of the same diameter and 100,000 times longer will allow the same amount of current to flow as does the shorter silicon wire.

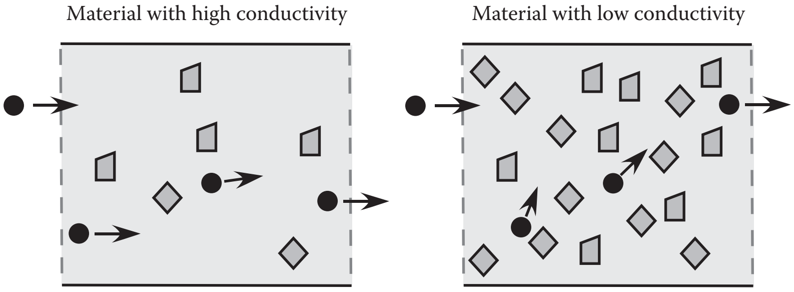

FIGURE 5.14 The number of obstructions in a material determines its electrical conductivity.

5.6 ELECTRICAL ENERGY AND VOLTAGE

We learned in Chapter 3 that accelerating an object through a distance by applying a force to the object increases its energy. The increased energy equals the work done on the object, and can be in the form of kinetic energy (energy of motion) or potential energy (energy of position).

Electric potential energy is the potential energy gained by a charged object if it is accelerated through an opposing electric force. If an object has positive electric potential energy, this means it is located at a position where it has the potential to be pushed to a new position by the existing electric field. It is measured in energy units, joules (J).

Consider two parallel metal plates, which are oppositely charged, as in **Figure 5.15**. If a single proton, which has charge $+e$, is placed between the plates, it will "feel" a force directed toward the negative plate. Let us say that the proton begins at the negative plate, and you use your hand to overcome the electric force and push the proton to the positive plate. You did physical work on the proton, although this is a very small amount of work,[1] because a proton has a very small charge. Now the proton, being at the plus plate, has the potential to be pushed by the electric field back to the minus plate if you release it; that is, the proton has electrical potential energy by virtue of its location. We specify a charge's potential energy using the concept of ***voltage***.

Voltage is a measure of a charged object's change in electric potential energy that is associated with moving from one location to another.

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[1] The work equals 0.16×10^{-18}J, or 0.16aJ, which is sometimes called one electron-volt.

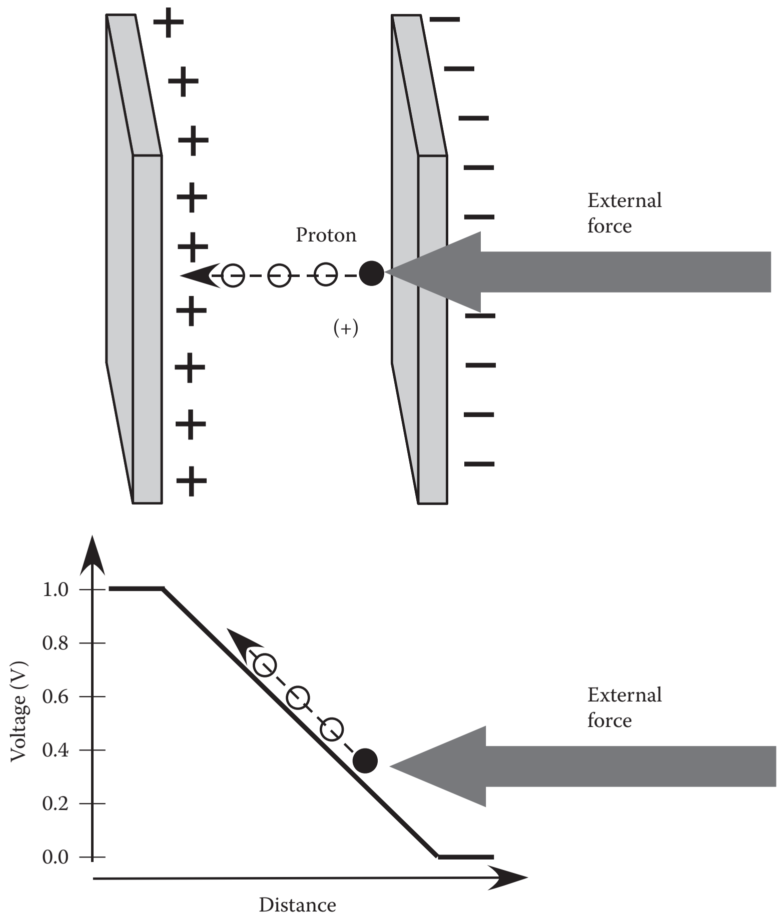

FIGURE 5.15 A proton between oppositely charge plates. An external force pushes the proton toward the plus plate, doing work on the proton and moving it to a location of higher voltage.

Voltage is not specified in terms of the amount of charge on an object, but in terms of the electrical environment around the object. We say that the positive plate on the left is at higher voltage than is the negative plate on the right. The voltage at an object depends only on its position in an electric field.

Consider a situation in which you have a small object—call it the "test object"—having 1 C ($6.2\times10^{18}e$) of positive charge on it, and you move it by hand from the negative plate to the positive plate in Figure 5.15. If it requires doing 1 J of work to move the test object from one plate to the other, then we say that the voltage between the plates equals one ***volt***. The symbol for volt is V.

Volt: One joule of energy, or work, will move 1 C of charge through 1 V. That is,
$1\text{J} = 1\text{C}\cdot\ 1\text{V}$

The relationship between voltage, potential energy, and charge is:

$$\textit{electrical potential energy}\ (\text{J}) = \textit{charge}\ (\text{C})\cdot\ \textit{voltage}\ (\text{V})$$

$$\textit{voltage}\ (\text{V}) = \frac{\textit{electrical potential energy}\ (\text{J})}{\textit{charge}\ (\text{C})}$$

For example, pushing an object having a net charge of 3 C between two plates with a voltage of 9 V between them requires $3\text{ C} \times 9\text{ V} = 27\text{ J}$.

A simple analogy helps us understand this relationship of voltage, charge, and energy. Say that a certain hill is 20 feet high, and you carry a bucket of water to its top. This requires you to expend a certain amount of energy while increasing the potential energy of the water. If you were to carry two buckets up the same hill, it would require twice as much energy. If the hill were twice as high, it would require twice as much energy to carry up the same number of buckets. The height of the hill is analogous to voltage, whereas the amount of water is analogous to charge. To determine the potential energy, you must know both.

We can summarize the above discussion by the following principle:

ELECTRICITY PRINCIPLE (IV)

Electrical energy is required to move a charged object when its motion is being opposed by an electric force. The amount of required energy equals the number of coulombs of charge on the object multiplied by the voltage between the object's starting and ending locations. That is,

$$\textit{number of joules} = (\textit{number of coulombs}) \times (\textit{voltage})$$
$$\textit{potential energy}\,(\mathrm{J}) = \textit{charge}\,(\mathrm{C}) \times \textit{voltage}\,(\mathrm{V})$$

THINK AGAIN

It is tempting to use the phrase "voltage difference," but this is redundant. Why is that so?

5.6.1 Voltage Sources—Batteries

A battery is a device that creates a voltage between two locations, which are called terminals. As discussed above, a charged object experiences a potential energy difference between these two locations that is equal to the charge (in coulombs) times the voltage difference. A simple way to think of a battery is to imagine two chambers with an impenetrable, nonconducting barrier separating them, as in **Figure 5.16a**. One chamber (the minus side) has an excess of electrons and the other chamber (the plus side) has a deficit of electrons. The barrier effectively blocks any electrical attraction directly through the barrier between charged particles in opposite sides. Yet a negatively charged test object placed near the battery minus terminal feels forces pushing it away from the minus terminal and pulling it toward the plus terminal.

Figure 5.16a is not a realistic drawing of a typical battery's shape. Figure 5.16b shows a more typical battery with conducting metal wires attached to terminals. The wire provides a conduit for electrons to move in. Electrons within the wire feel an attractive force along the direction of the wire that leads to the plus side. In the figure, an electron is symbolized by a minus sign (–). A region where there is a deficit of electrons is represented by a plus sign (+). One chamber (the minus side) has an excess of electrons and the other chamber (the plus side) has a deficit of electrons. When allowed to flow, some of the electrons from the minus side will rush out of this side because of the electric forces being exerted by the remaining electrons. If given a pathway, such as a metal wire, they will move along the path and enter the plus chamber to which they are attracted.

Figure 5.16b is a simple example of an ***electric circuit***, meaning a group of connected objects through which electrons can flow. Electric current will flow steadily

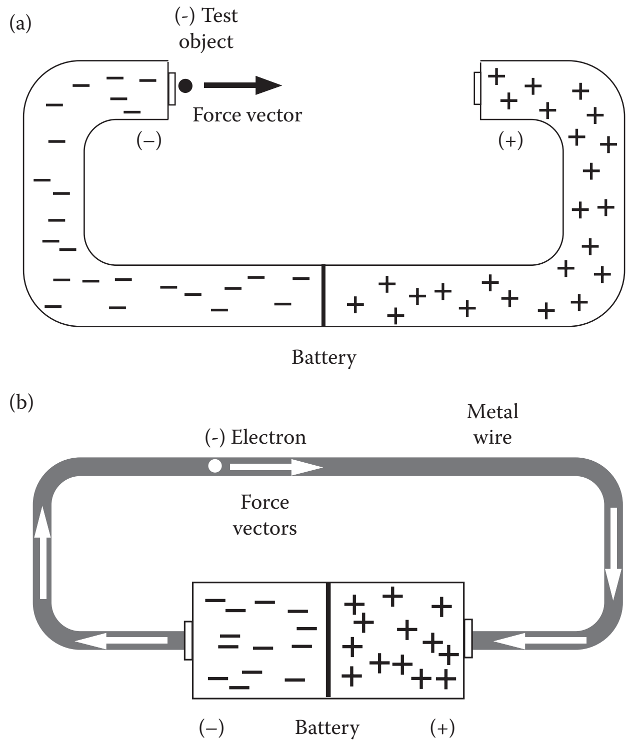

FIGURE 5.16 (a) Simple concept of a battery. (b) Metal conducting wires allow electrons to escape the minus side of the battery and move to its plus side.

only if there is an unbroken path of conducting material between two locations of unequal voltage.

THINK AGAIN

In circuits, only the minus-charged objects (electrons) move through wires. Plus-charged physical objects do not move through wires.

A battery provides positive potential energy to a plus-charged object and negative potential energy to a minus-charged object. A helpful analogy is a skater on a skateboard ramp, as in **Figure 5.17**, with the height providing positive potential energy. The battery has a wire connected between the plus end (B) and the minus end (A). If

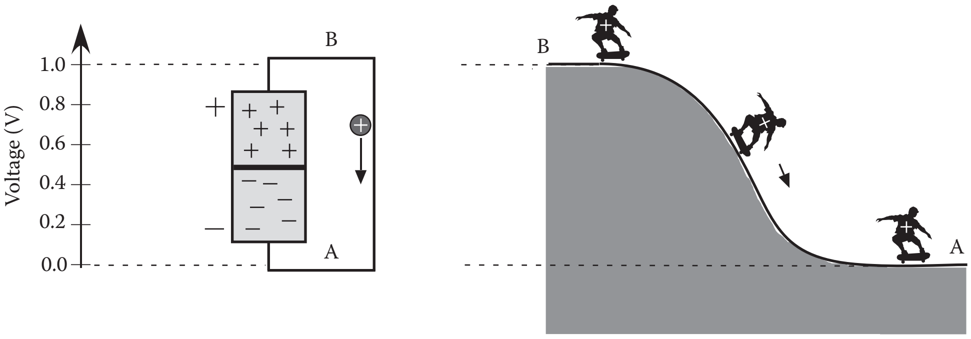

FIGURE 5.17 Skater analogy for motion of a plus charge in the presence of a voltage created by a battery.

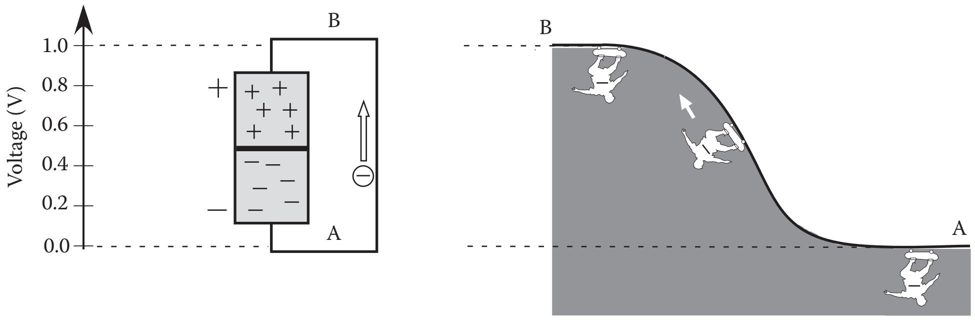

FIGURE 5.18 A pretend skater analogy for motion of a minus charge in the presence of a voltage created by a battery.

a plus-charged object is located at position B, it will be pushed toward the A position. This is analogous to the skater at the top of a ramp going downhill under the force of gravity. The skater had potential energy at the top of the ramp and kinetic energy at the bottom of the ramp.

In the case of gravity, there is only one type of skater—all skaters go downhill under the force of gravity. In contrast, in the case of electric forces, there are two types of "skater"—one plus and one minus charged. Whereas the plus objects go "downhill" with respect to the voltage difference, negatively charged objects go "uphill" with respect to the voltage. Although for this there is no physical analogy using gravity, we can make up a pretend analogy, as in **Figure 5.18**. A new type of skater, called here a negative skater, is drawn with a minus sign on her shirt and inverted compared with an ordinary skater. It is drawn inverted to remind us that we are talking only about a pretend analogy. This negative skater would move uphill naturally, without making any effort, just as an ordinary skater naturally moves downhill.

THINK AGAIN

In the case of electric forces there is a third type of object—neutral objects. What would be the motion of the analogous "neutral skater" on the ramp in this case?

If conducting wires are connected to the battery terminals, as in **Figure 5.19**, each wire is brought to the same voltage as the corresponding terminal. The connected plates now act as extensions of the battery terminals. If a 1-V battery is connected in this way to a pair of metal plates, as in Figure 5.19a, a voltage equal to 1 V is created between the plates. To move a test charge from the negative plate to the positive plate requires applying an external force. If the test object contains 6.2×10^{18} excess protons, or 1 C of charge, then to move it from the negative plate to the positive plate requires doing 1 J of work.

If you make the wires shorter, as in Figure 5.19b, the voltage between the plates still equals 1 V. Therefore, if you apply an external force to move the same test object from the minus terminal to the plus terminal, it still requires 1 J of work. The amount of work does not depend on what path you use in moving the charge. The voltage and the work depend only on voltages at the starting and ending locations of the charged object.

You would need nearly the same amount of energy to move the test object from the plus plate to the minus plate as is needed to move the object from the battery's plus side

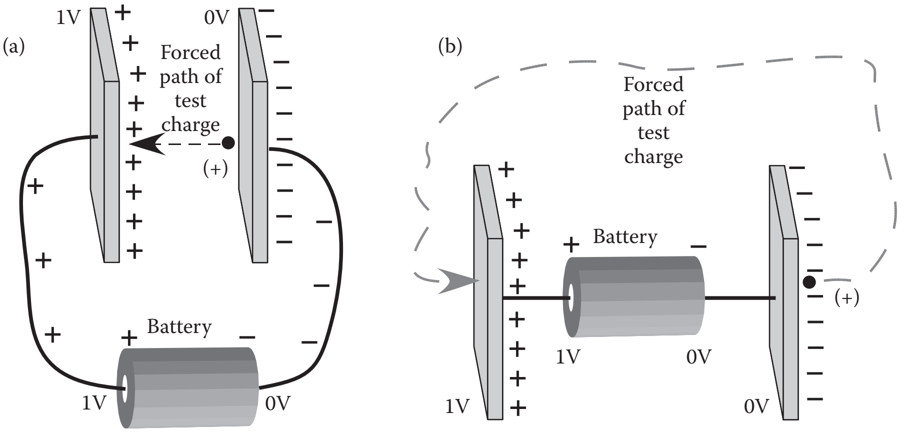

FIGURE 5.19 (a) A 1 V battery connected to a pair of metal plates creates a voltage equal to 1 V between the plates. If an outside agent (not shown) pushes a plus-charged object toward the plus plate, the agent does work on the object, increasing the object's energy. (b) The amount of work required in moving the object from the minus to the plus plate does not depend on the locations of the plates, nor on the path taken by the object when the agent pushes it.

to the battery's minus side. This means that the voltage is nearly equal everywhere on the plus wire and the plus plate. Also, the voltage is nearly equal everywhere on the minus wire and minus plate. The two voltages differ by the amount of voltage provided by the battery. We can summarize as:

Rule: For an object made with a material having very high electrical conductivity (such as copper), the voltage is nearly equal everywhere on the object.

5.6.2 Energy Stored in a Battery

In **Figure 5.20**, a positive test object is located near the plus plate. In this case, rather than requiring an outside agent to do work on the test object, the test object can do work on an outside agent. If you put your hand between the test object and the minus plate, the test object would exert a force on your hand toward the minus plate. If you allowed the test object to push your hand toward the minus plate, the test object would be doing work on your hand.

From this, we can see that a battery stores energy, which can be transferred to other objects, such as your hand. To recharge a spent battery, we use a battery charger to push many electrons into its minus end, and pull electrons out of its plus end. Clearly, this requires us to do work on the electric charges. The energy stored is electric potential energy, which has the potential (ability) to be released later to do work, such as running a computer or an electric motor.

The voltage provided by an outlet in a house is typically 120 or 240 V. Such large voltages are needed when large forces must be created, such as for driving the drum of a washing machine. In contrast, in a device like a computer, where large forces are not required, smaller voltages are used—12 V for a laptop battery.

5.6.3 Energy Stored in a Capacitor

The combination of two metal plates we have been discussing makes a device called a ***capacitor***. The name arises from the capacity of the device to store charge. **Figure 5.21** shows a sequence of events, using a battery, a capacitor, and two electrical switches.

QUICK QUESTION 5.4

If the test object in Figure 5.20 carried a charge of plus 5 C, and the battery was 1.5 V, how much work (in joules) would the test object do as it pushed your hand toward the minus plate?

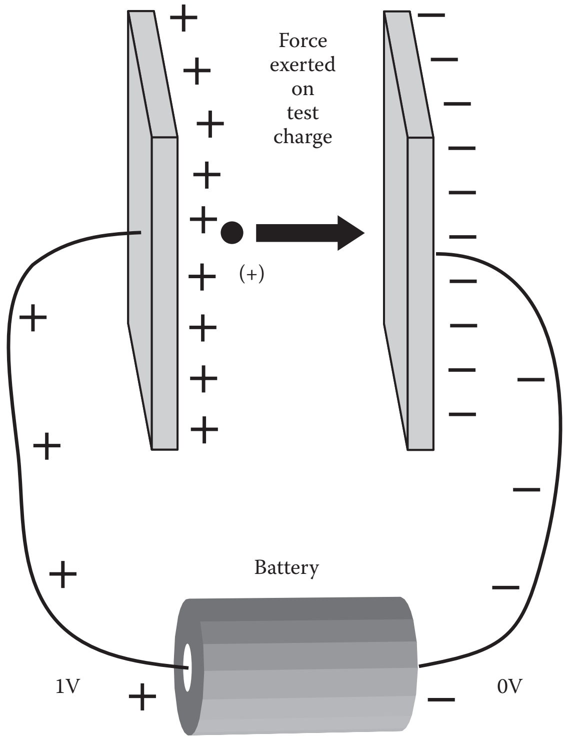

FIGURE 5.20 A 1 V battery connected to a pair of metal plates creates 1 V of voltage between the plates. If a positive test charge (the solid dot) is located near the plus plate, it will feel a force pushing it toward the minus plate.

QUICK QUESTION 5.5

In Figure 5.21b, charge is not flowing. Why not?

Charge can flow through a switch only when it is closed. If a switch is open, it prevents charge from moving through that part of the circuit. In Figure 5.21a, switch 1 is suddenly closed, causing electrons in the minus side of the battery to "feel" a force along the wire toward the plus end of the battery. These electrons can travel only as far as the plate on the right, where a minus charge builds up. Electrons originally on the left plate feel repulsion from the electrons now on the right plate and an attraction to the plus end of the battery, so they flow to the plus terminal of the battery. In this case, there is no closed-loop circuit, as the capacitor breaks the circuit. Therefore, charge cannot flow indefinitely. The current continues only until the voltage across the two plates equals the voltage of the battery. Then charge ceases to flow.

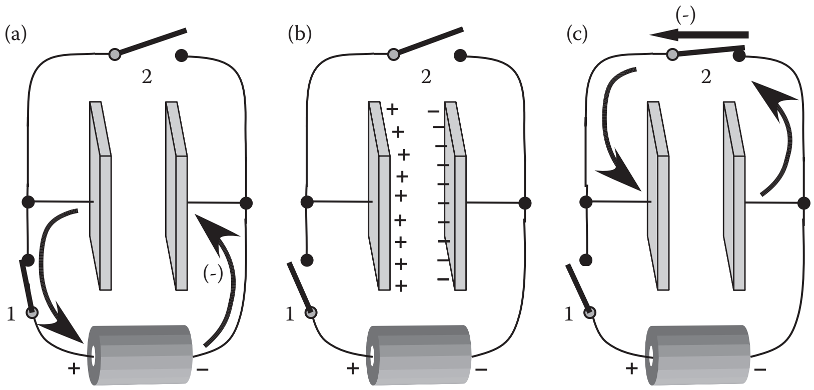

FIGURE 5.21 Capacitor circuit: (a) charging, (b) storing, and (c) discharging.

After this voltage equality is established at the two plates, switch 1 is opened, as in Figure 5.21b. Both switches are now open, and charge is prevented from moving. Charge, and therefore energy, is stored in the capacitor. To discharge the capacitor, switch 2 is closed, as in Figure 5.21c, allowing the minus charge to leave the right capacitor plate and flow to the left plate. This makes the plates neutral again.

A practical way to make a capacitor is to press a thin piece of paper or plastic, which acts as an insulator, between two smaller sheets of metal foil and then roll them up into a cylinder shape. Capacitors, in miniaturized form, are used in many electrical circuits, including those in electronic computer memory, as explained in Real-World Example 5.1.

REAL-WORLD EXAMPLE 5.1: CAPACITOR COMPUTER MEMORY

Data storage in computers is accomplished by means of capacitors. Electronic memory in a computer is random-access memory (**RAM**). This means that you can access the data in any individual memory location, or cell, without reading out the whole memory or some large block of it. This differs from, for example, compact-disk memory, which requires you to read out large blocks of data. Most of the memory in computers is dynamic RAM or DRAM, which can store a bit value for only about 1 millisecond. In DRAM, each bit value is represented by the amount of charge stored on a particular capacitor, as in Figure 5.21. The scheme for controlling the read-in, storing, and readout of charge is shown in **Figure 5.22**. The region enclosed by a dashed line is one cell of memory. Inside the memory cell is a capacitor and a switch, controlled by current passing from outside of the chip into the chip on the wire shown. The switch is a transistor device, whose operation will be examined in later chapters. For now, you can think of it as a mechanical switch.

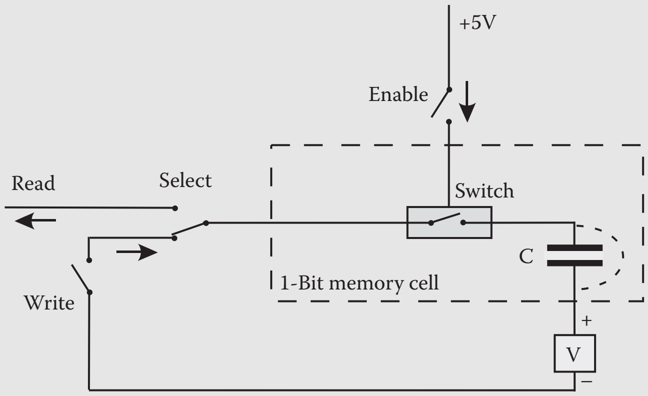

FIGURE 5.22 Capacitor-based memory cell.

When the *Enable* switch is open, as shown in the figure, the capacitor is cut off from the rest of the world, and whatever charge is on the capacitor is stored there for a while. When the *Enable* switch is closed, then charge can be transferred to or from the capacitor, writing or reading a bit value. To write a bit value onto the capacitor, set the *Select* switch to *Write*, as shown. Then the position of the *Write* switch determines whether 1 is written (*Write* switch closed) or 0 is written (*Write* switch open). If, instead, you wish to read the bit value stored on the capacitor, set the *Select* switch to *Read*. Then any charge that is on the capacitor will flow into the *Read* circuit (not shown). Charge will not remain on a capacitor forever. There is a small, unintended leakage of charge between the plates, indicated in the figure by the dashed, curved line.

In a typical DRAM memory chip, millions or billions of cells each store one bit. **Figure 5.23** shows how this is done. Cells are arranged in rows, labeled Row 1, 2, 3, etc. This arrangement is called a memory array. There is a collection of *Enable* switches, arranged at the tops of columns labeled A, B, C, etc., in the figure. Each *Enable* switch controls one whole column of cells: when that switch is closed, every cell in the column below it is enabled. In the configuration shown, the *Enable* switch labeled “B” is closed. The other *Enable* switches are open. To select which individual cell will be accessed, a *Row Select* switch is used to connect the data *Read* or *Write* lines to only one row of cells. In the example shown, Row 1 is selected. Therefore, only one cell is both enabled and selected; this cell is indicated by a dashed oval. Now data can be read or written at this individual cell, leaving all other cells unaffected. To address other cells, we would use different combinations of *Enable* and *Row Select* switch settings.

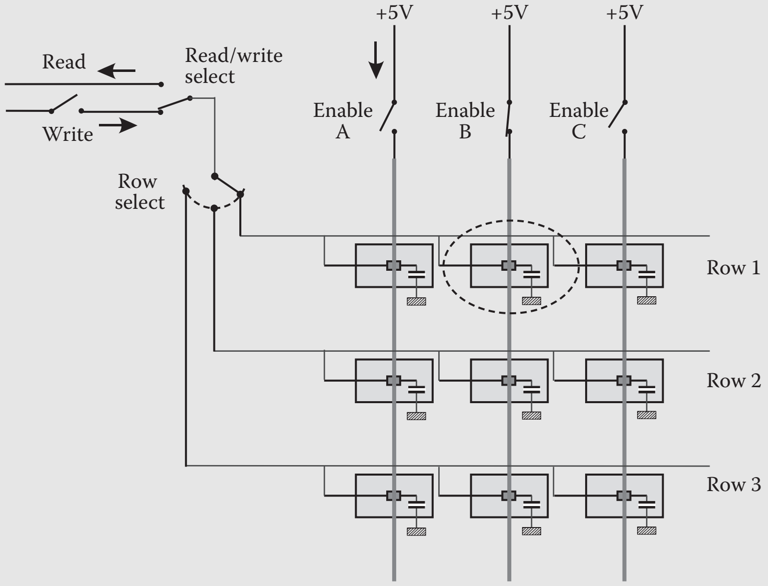

FIGURE 5.23 Addressing one cell in a dynamic random-access memory (DRAM) array.

In a semiconductor DRAM cell, electric charge does not stay on the capacitor forever. It “leaks” from one capacitor plate to the other, because the insulator material between them (a form of silicon) is not a perfect insulator. Every material has a nonzero conductivity, meaning it will conduct current at least weakly. Because of charge leakage, after 1-millisecond passes, each data bit value in the memory has to be rewritten. Imagine writing a 100-page novel on paper using disappearing ink, every letter of which has to be rewritten every thousandth of a second! DRAM is used because it is cheap to make in large quantities. A 500-megabyte DRAM chip might cost $40. That is 4 billion capacitors, at 0.000001 cents each.

5.7 RESISTORS, CONDUCTORS, AND OHM’S LAW

Recall from Section 5.5 that electrical conductivity is a material’s ability to conduct electric current. A term that is inversely related to conductivity is resistance. ***Electrical resistance*** is the ability of a wire or bar of any material to resist the flow of charge through it. Therefore a bar made of a material with low conductivity has high resistance.

Resistance is analogous to friction. For example, in Figure 5.13 the short silicon wire and the long silver wire have the same electrical resistance. This is because silver