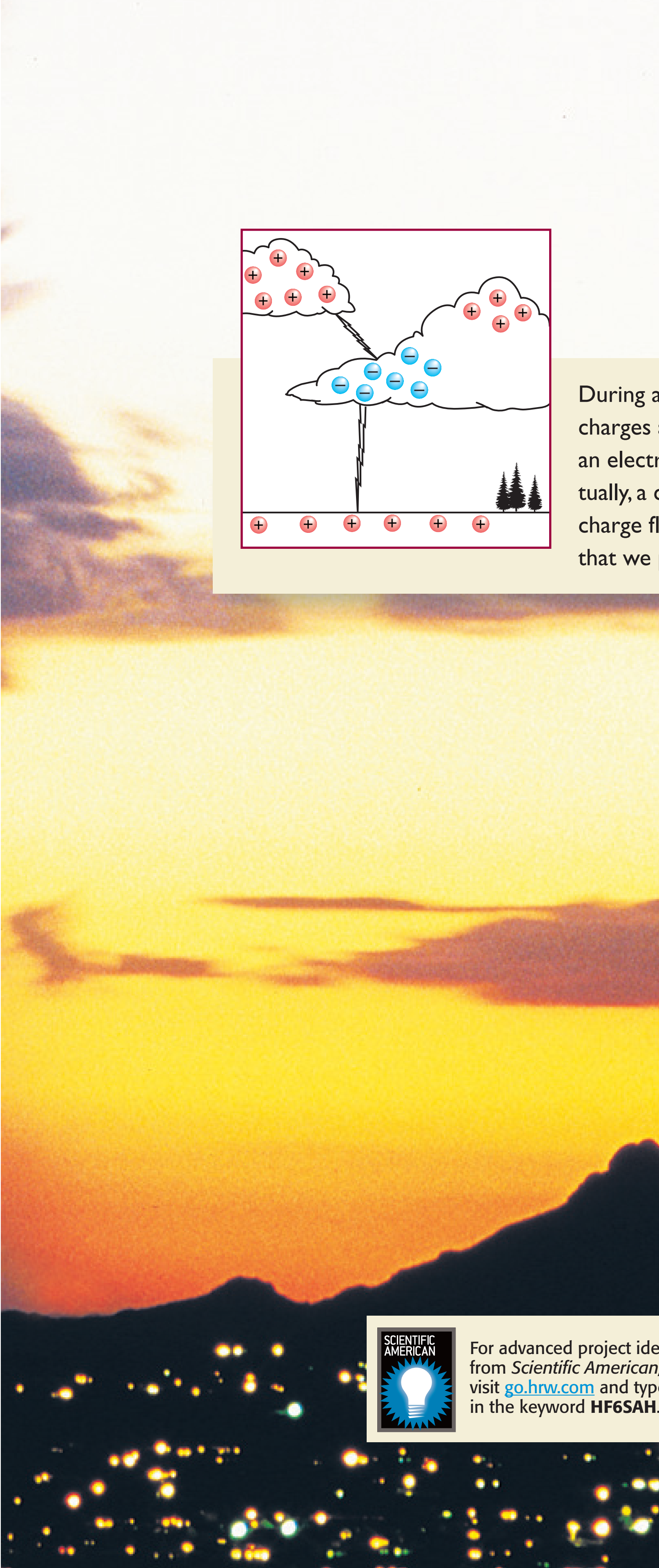

CHAPTER 17

Electrical Energy and Current

During a thunderstorm, particles that have different charges accumulate in different parts of a cloud to create an electric field between the cloud and the ground. Eventually, a critical *breakdown voltage* is reached, and electric charge flows between the cloud and the ground, an event that we perceive as lightning.

WHAT TO EXPECT

In this chapter, you will learn about electric potential and electrical energy and will learn about how capacitors can be used to store electrical energy. You will be introduced to electric current and resistance.

WHY IT MATTERS

The use of electrical energy is universal in our modern society. An understanding of electrical energy and the factors that affect its rate of use can help us use electric power more wisely.

CHAPTER PREVIEW

SCIENTIFIC AMERICAN

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SECTION 1

Electric Potential

SECTION OBJECTIVES

- **Distinguish between electrical potential energy, electric potential, and potential difference.**
- **Solve problems involving electrical energy and potential difference.**
- **Describe the energy conversions that occur in a battery.**

electrical potential energy

potential energy associated with a charge due to its position in an electric field

ELECTRICAL POTENTIAL ENERGY

You have learned that when two charges interact, there is an electric force between them. As with the gravitational force associated with an object's position relative to Earth, there is a potential energy associated with this force. This kind of potential energy is called **electrical potential energy.** Unlike gravitational potential energy, electrical potential energy results from the interaction of two objects' charges, not their masses.

Electrical potential energy is a component of mechanical energy

Mechanical energy is conserved as long as friction and radiation are not present. As with gravitational and elastic potential energy, electrical potential energy can be included in the expression for mechanical energy. If a gravitational force, an elastic force, and an electric force are all acting on an object, the mechanical energy can be written as follows:

$$ME = KE + PE_{grav} + PE_{elastic} + PE_{electric}$$

To account for the forces (except friction) that may also be present in a problem, the appropriate potential-energy terms associated with each force are added to the expression for mechanical energy.

Recall from your study of work and energy that any time a force is used to move an object, work is done on that object. This statement is also true for charges moved by an electric force. Whenever a charge moves—because of the electric field produced by another charge or group of charges—work is done on that charge.

For example, negative electric charges build up on the plate in the center of the device, called a *Tesla coil,* shown in **Figure 1.** The electrical potential energy associated with each charge decreases as the charge moves from the central plate to the walls (and through the walls to the ground).

Figure 1
As the charges in these sparks move, the electrical potential energy decreases, just as gravitational potential energy decreases as an object falls.

Electrical potential energy can be associated with a charge in a uniform field

Consider a positive charge in a uniform electric field. (A uniform field is a field that has the same value and direction at all points.) Assume the charge is displaced at a constant velocity *in the same direction as the electric field,* as shown in **Figure 2.**

There is a change in the electrical potential energy associated with the charge's new position in the electric field. The change in the electrical potential energy depends on the charge, q, as well as the strength of the electric field, E, and the displacement, d. It can be written as follows:

$$\Delta PE_{electric} = -qEd$$

The negative sign indicates that the electrical potential energy will increase if the charge is negative and decrease if the charge is positive.

As with other forms of potential energy, it is the *difference* in electrical potential energy that is physically important. If the displacement in the expression above is chosen so that it is the distance in the direction of the field from the reference point, or zero level, then the initial electrical potential energy is zero and the expression can be rewritten as shown below. As with other forms of energy, the SI unit for electrical potential energy is the joule (J).

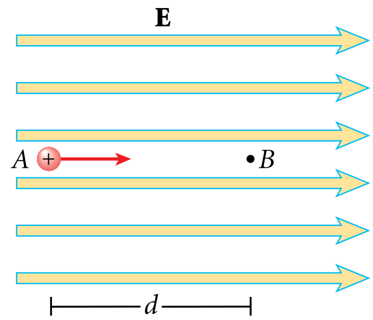

Figure 2
A positive charge moves from point *A* to point *B* in a uniform electric field, and the potential energy changes as a result.

ELECTRICAL POTENTIAL ENERGY IN A UNIFORM ELECTRIC FIELD

$$PE_{electric} = -qEd$$

electrical potential energy =
−(charge × electric field strength × displacement from the reference point in the direction of the field)

This equation is valid only for a uniform electric field, such as that between two oppositely charged parallel plates. In contrast, the electric field lines for a point charge are farther apart as the distance from the charge increases. Thus, the electric field of a point charge is an example of a nonuniform electric field.

Electrical potential energy is similar to gravitational potential energy

When electrical potential energy is calculated, d is the magnitude of the displacement's component *in the direction of the electric field.* The electric field does work on a positive charge by moving the charge in the direction of $\mathbf{E}$ (just as Earth's gravitational field does work on a mass by moving the mass toward Earth). After such a movement, the system's final potential energy is less than its initial potential energy. A negative charge behaves in the opposite manner, because a negative charge undergoes a force in the opposite direction. Moving a charge in a direction that is perpendicular to $\mathbf{E}$ is analogous to moving an object horizontally in a gravitational field: no work is done, and the potential energy of the system remains constant.

POTENTIAL DIFFERENCE

The concept of electrical potential energy is useful in solving problems, particularly those involving charged particles. But at any point in an electric field, as the magnitude of the charge increases, the magnitude of the associated electrical potential energy increases. It is more convenient to express the potential in a manner independent of the charge at that point, a concept called **electric potential.**

electric potential

the work that must be performed against electric forces to move a charge from a reference point to the point in question, divided by the charge

The electric potential at some point is defined as the electrical potential energy associated with a charged particle in an electric field divided by the charge of the particle.

$$V = \frac{PE_{electric}}{q}$$

The potential at a point is the result of the fields due to all *other* charges near enough and large enough to contribute force on a charge at that point. In other words, the electric potential at a point *is independent of the charge at that point.* The force that a test charge at the point in question experiences is proportional to the magnitude of the charge.

Potential difference is a change in electric potential

potential difference

the work that must be performed against electric forces to move a charge between the two points in question, divided by the charge

The **potential difference** between two points can be expressed as follows:

POTENTIAL DIFFERENCE

$$\Delta V = \frac{\Delta PE_{electric}}{q}$$

$$\text{potential difference} = \frac{\text{change in electrical potential energy}}{\text{electric charge}}$$

Figure 3
For a typical car battery, there is a potential difference of 13.2 V between the negative (black) and the positive (red) terminals.

Potential difference is a measure of the difference in the electrical potential energy between two positions in space divided by the charge. The SI unit for potential difference (and for electric potential) is the *volt,* V, and is equivalent to one joule per coulomb. As a 1 C charge moves through a potential difference of 1 V, the charge gains 1 J of energy. The potential difference between the two terminals of a battery can range from about 1.5 V for a small battery to about 13.2 V for a car battery like the one the student is looking at in **Figure 3.**

Because the reference point for measuring electrical potential energy is arbitrary, the reference point for measuring electric potential is also arbitrary. Thus, only changes in electric potential are significant.

Remember that electrical potential energy is a quantity of energy, with units in joules. However, electric potential and potential difference are both measures of energy per unit charge (measured in units of volts), and potential difference describes a change in energy per unit charge.

Did you know?

A unit of energy commonly used in atomic and nuclear physics that is convenient because of its small size is the *electron volt,* eV. It is defined as the energy that an electron (or proton) gains when accelerated through a potential difference of 1 V. One electron volt is equal to 1.60×10^{-19} J.

The potential difference in a uniform field varies with the displacement from a reference point

The expression for potential difference can be combined with the expressions for electrical potential energy. The resulting equations are often simpler to apply in certain situations. For example, consider the electrical potential energy of a charge in a uniform electric field.

$$PE_{electric} = -qEd$$

This expression can be substituted into the equation for potential difference.

$$\Delta V = \frac{\Delta(-qEd)}{q}$$

As the charge moves in a uniform electric field, the quantity in the parentheses does not change from the reference point. Thus, the potential difference in this case can be rewritten as follows:

POTENTIAL DIFFERENCE IN A UNIFORM ELECTRIC FIELD

$$\Delta V = -Ed$$

potential difference =
−(magnitude of the electric field × displacement)

Keep in mind that d is the displacement *parallel* to the field and that motion perpendicular to the field does not change the electrical potential energy.

The reference point for potential difference near a point charge is often at infinity

To determine the potential difference between two points in the field of a point charge, first calculate the electric potential associated with each point. Imagine a point charge q_2 at point A in the electric field of a point charge q_1 at point B some distance, r, away as shown in **Figure 4.** The electric potential at point A due to q_1 can be expressed as follows:

$$V_A = \frac{PE_{electric}}{q_2} = k_C\frac{q_1q_2}{rq_2} = k_C\frac{q_1}{r}$$

Do not confuse the two charges in this example. The charge q_1 is responsible for the electric potential at point A. Therefore, *an electric potential exists at some point in an electric field regardless of whether there is a charge at that point.* In this case, the electric potential at a point depends on only two quantities: the charge responsible for the electric potential (in this case q_1) and the distance r from this charge to the point in question.

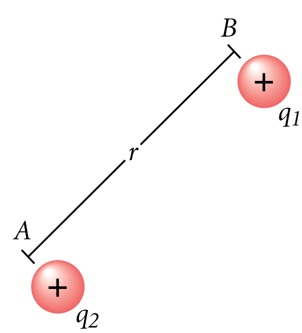

Figure 4
The electric potential at point *A* depends on the charge at point *B* and the distance *r*.

To determine the potential difference between any two points near the point charge q_1, first note that the electric potential at each point depends only on the distance from each point to the charge q_1. If the two distances are r_1 and r_2, then the potential difference between these two points can be written as follows:

$$\Delta V = k_C\frac{q_1}{r_2} - k_C\frac{q_1}{r_1} = k_C q_1\left(\frac{1}{r_2} - \frac{1}{r_1}\right)$$

If the distance r_1 between the point and q_1 is large enough, it is assumed to be infinitely far from the charge q_1. In that case, the quantity $1/r_1$ is zero. The expression then simplifies to the following (dropping the subscripts):

POTENTIAL DIFFERENCE BETWEEN A POINT AT INFINITY AND A POINT NEAR A POINT CHARGE

$$\Delta V = k_C\frac{q}{r}$$

$$\textbf{potential difference} = \textbf{Coulomb constant} \times \frac{\textbf{value of the point charge}}{\textbf{distance to the point charge}}$$

This result for the potential difference associated with a point charge appears identical to the electric potential associated with a point charge. The two expressions look the same only because we have chosen a special reference point from which to measure the potential difference.

One common application of the concept of potential difference is in the operation of electric circuits. Recall that the reference point for determining the electric potential at some point is arbitrary and must be defined. Earth is frequently designated to have an electric potential of zero and makes a convenient reference point. Thus, *grounding* an electrical device (connecting it to Earth) creates a possible reference point, which is commonly used to measure the electric potential in an electric circuit.

The superposition principle can be used to calculate the electric potential for a group of charges

The electric potential at a point near two or more charges is obtained by applying a rule called the *superposition principle.* This rule states that the total electric potential at some point near several point charges is the algebraic sum of the electric potentials resulting from each of the individual charges. While this is similar to the method used previously to find the resultant electric field at a point in space, here the summation is much easier to evaluate because the electric potentials are scalar quantities, not vector quantities. There are no vector components to consider.

To evaluate the electric potential at a point near a group of point charges, you simply take the algebraic sum of the potentials resulting from all charges. Remember, you must keep track of signs. The electric potential at some point near a positive charge is positive, and the potential near a negative charge is negative.

Did you know?

The volt is named after the Italian physicist Alessandro Volta (1745–1827), who developed the first practical electric battery, known as a voltaic pile. Because potential difference is measured in units of volts, it is sometimes referred to as *voltage*.

extension

Practice Problems

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SAMPLE PROBLEM A

Potential Energy and Potential Difference

PROBLEM

A charge moves a distance of 2.0 cm in the direction of a uniform electric field whose magnitude is 215 N/C. As the charge moves, its electrical potential energy decreases by 6.9 × 10^{-19} J. Find the charge on the moving particle. What is the potential difference between the two locations?

SOLUTION

Given: $\Delta PE_{electric} = -6.9 \times 10^{-19}$ J $d = 0.020$ m

$E = 215$ N/C

Unknown: $q = ?$ $\Delta V = ?$

Use the equation for the change in electrical potential energy.

$$\Delta PE_{electric} = -qEd$$

Rearrange to solve for q, and insert values.

$$q = -\frac{\Delta PE_{electric}}{Ed} = -\frac{(-6.9 \times 10^{-19}\ \text{J})}{(215\ \text{N/C})(0.020\ \text{m})}$$

$$\boxed{q = 1.6 \times 10^{-19}\ \text{C}}$$

The potential difference is the magnitude of E times the displacement.

$$\Delta V = -Ed = -(215\ \text{N/C})(0.020\ \text{m})$$

$$\boxed{\Delta V = -4.3\ \text{V}}$$

TIP *Remember that a newton·meter is equal to a joule and that a joule per coulomb is a volt. Thus, potential difference is expressed in volts.*

PRACTICE A

Potential Energy and Potential Difference

1. As a particle moves 10.0 m along an electric field of strength 75 N/C, its electrical potential energy decreases by 4.8 × 10^{-16} J. What is the particle's charge?

2. What is the potential difference between the initial and final locations of the particle in Problem 1?

3. An electron moves 4.5 m in the direction of an electric field of strength 325 N/C. Determine the change in electrical potential energy.

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Topic: Batteries
SciLinks Code: HF60139

A battery does work to move charges

A good illustration of the concepts of electric potential and potential difference is the way in which a battery powers an electrical apparatus, such as a flashlight, a motor, or a clock. A battery is an energy-storage device that provides a constant potential difference between two locations, called *terminals,* inside the battery.

Recall that the reference point for determining the electric potential at a location is arbitrary. For example, consider a typical 1.5 V alkaline battery. This type of battery maintains a potential difference across its terminals such that the positive terminal has an electric potential that is 1.5 V higher than the electric potential of the negative terminal. If we designate that the negative terminal of the battery is at zero potential, the positive terminal would have a potential of 1.5 V. We could just as correctly choose the potential of the negative terminal to be −0.75 V and the positive terminal to be +0.75 V.

Inside a battery, a chemical reaction produces electrons (negative charges) that collect on the negative terminal of the battery. Negative charges move inside the battery from the positive terminal to the negative terminal, through a potential difference of $\Delta V = -1.5$ V. The chemical reaction inside the battery does work on—that is, provides energy to—the charges when moving them from the positive terminal to the negative terminal. This transit increases the magnitude of the electrical potential energy associated with the charges. The result of this motion is that every coulomb of charge that leaves the positive terminal of the battery is associated with a total of 1.5 J of electrical potential energy.

Now, consider the movement of electrons in an electrical device that is connected to a battery. As 1 C of charge moves through the device toward the positive terminal of the battery, the charge gives up its 1.5 J of electrical energy to the device. When the charge reaches the positive terminal, the charge's electrical potential energy is again zero. Electrons must travel to the positive terminal for the chemical reaction in a battery to occur. For this reason, a battery can be unused for a period of time and still have power available.

Quick Lab

A Voltaic Pile

MATERIALS LIST

- salt
- water
- paper towel
- pennies
- nickels
- voltmeter (1 V range)

Dissolve as much salt as possible in the water. Soak the paper towel in the salt water and then tear it into small circles that are slightly bigger than a nickel. Make a stack alternating one penny, a piece of paper towel and then one nickel. Repeat this stack by placing the second penny on top of the first nickel. Measure the voltage between the first penny and the last nickel by placing the leads of the voltmeter at each end of the stack. Be sure to have your voltmeter on the lowest dc voltage setting. Try stacking additional layers of penny–paper towel–nickel, and measure the voltage again. What happens if you replace the nickels or pennies with dimes or quarters?

SECTION REVIEW

1. What is the difference between $\Delta PE_{electric}$ and $PE_{electric}$?
2. In a uniform electric field, what factors does the electrical potential energy depend on?
3. Describe the conditions that are necessary for mechanical energy to be a conserved quantity.
4. Is there a single correct reference point from which all electrical potential energy measurements must be taken?
5. A uniform electric field with a magnitude of 250 N/C is directed in the positive *x* direction. A 12 µC charge moves from the origin to the point (20.0 cm, 50.0 cm). What is the change in the electrical potential energy of the system as a result of the change in position of this charge?
6. What is the change in the electrical potential energy in a lightning bolt if 35 C of charge travel to the ground from a cloud 2.0 km above the ground in the direction of the field? Assume the electric field is uniform and has a magnitude of 1.0×10^6 N/C.
7. The gap between electrodes in a spark plug is 0.060 cm. Producing an electric spark in a gasoline-air mixture requires an electric field of 3.0×10^6 V/m. What minimum potential difference must be supplied by the ignition circuit to start a car?
8. A proton is released from rest in a uniform electric field with a magnitude of 8.0×10^4 V/m. The proton is displaced 0.50 m as a result.
   a. Find the potential difference between the proton's initial and final positions.
   b. Find the change in electrical potential energy of the proton as a result of this displacement.
9. In a thunderstorm, the air must be ionized by a high voltage before a conducting path for a lightning bolt can be created. An electric field of about 1.0×10^6 V/m is required to ionize dry air. What would the breakdown voltage in air be if a thundercloud were 1.60 km above ground? Assume that the electric field between the cloud and the ground is uniform.
10. Explain how electric potential and potential difference are related. What units are used for each one?
11. **Critical Thinking** Given the electrical potential energy, how do you calculate electric potential?
12. **Critical Thinking** Why is electric potential a more useful quantity for most calculations than electrical potential energy is?

SECTION 2

Capacitance

SECTION OBJECTIVES

- Relate capacitance to the storage of electrical potential energy in the form of separated charges.
- Calculate the capacitance of various devices.
- Calculate the energy stored in a capacitor.

CAPACITORS AND CHARGE STORAGE

A *capacitor* is a device that is used to store electrical potential energy. It has many uses, including tuning the frequency of radio receivers, eliminating sparking in automobile ignition systems, and storing energy in electronic flash units.

An *energized* (or charged) capacitor is useful because energy can be reclaimed from the capacitor when needed for a specific application. A typical design for a capacitor consists of two parallel metal plates separated by a small distance. This type of capacitor is called a *parallel-plate capacitor.* When we speak of *the charge on a capacitor,* we mean the magnitude of the charge on either plate.

The capacitor is energized by connecting the plates to the two terminals of a battery or other sources of potential difference, as **Figure 5** shows. When this connection is made, charges are removed from one of the plates, leaving the plate with a net charge. An equal and opposite amount of charge accumulates on the other plate. Charge transfer between the plates stops when the potential difference between the plates is equal to the potential difference between the terminals of the battery. This charging process is shown in **Figure 5(b).**

Capacitance is the ratio of charge to potential difference

The ability of a conductor to store energy in the form of electrically separated charges is measured by the **capacitance** of the conductor. Capacitance is defined as the ratio of the net charge on each plate to the potential difference created by the separated charges.

capacitance

the ability of a conductor to store energy in the form of electrically separated charges

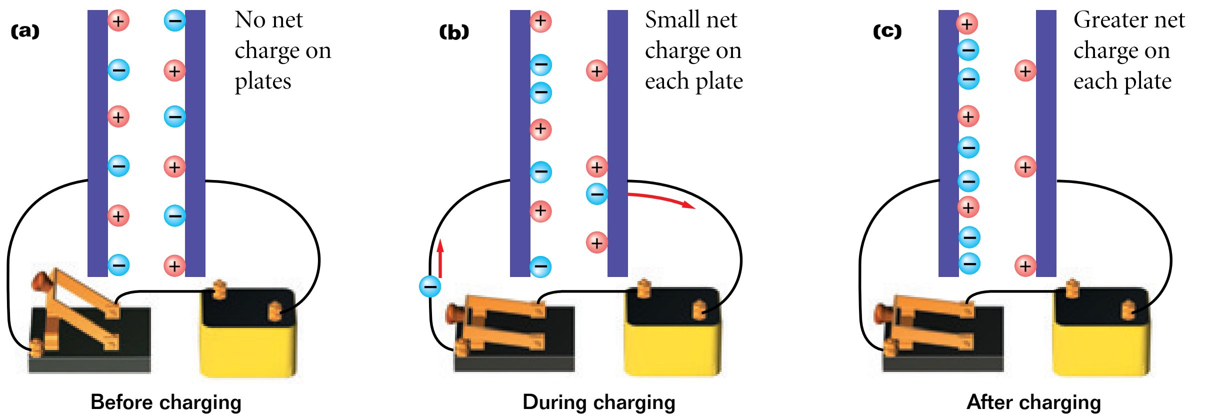

Figure 5
When connected to a battery, the plates of a parallel-plate capacitor become oppositely charged.

CAPACITANCE

$$C = \frac{Q}{\Delta V}$$

$$\text{capacitance} = \frac{\text{magnitude of charge on each plate}}{\text{potential difference}}$$

The SI unit for capacitance is the *farad,* F, which is equivalent to a coulomb per volt (C/V). In practice, most typical capacitors have capacitances ranging from microfarads ($1\ \mu F = 1 \times 10^{-6}$ F) to picofarads ($1\ pF = 1 \times 10^{-12}$ F).

Capacitance depends on the size and shape of the capacitor

The capacitance of a parallel-plate capacitor with no material between its plates is given by the following expression:

CAPACITANCE FOR A PARALLEL-PLATE CAPACITOR IN A VACUUM

$$C = \varepsilon_0 \frac{A}{d}$$

$$\text{capacitance} = \text{permittivity of a vacuum} \times \frac{\text{area of one of the plates}}{\text{distance between the plates}}$$

In this expression, the Greek letter ε (epsilon) represents a constant called the *permittivity* of the medium. When it is followed by a subscripted zero, it refers to a vacuum. It has a magnitude of $8.85 \times 10^{-12}\ C^2/N \bullet m^2$.

We can combine the two equations for capacitance to find an expression for the charge stored on a parallel-plate capacitor.

$$Q = \frac{\varepsilon_0 A}{d} \Delta V$$

This equation tells us that for a given potential difference, ΔV, the charge on a plate is proportional to the area of the plates and inversely proportional to the separation of the plates.

Suppose an isolated conducting sphere has a radius R and a charge Q. The potential difference between the surface of the sphere and infinity is the same as it would be for an equal point charge at the center of the sphere.

$$\Delta V = k_C \frac{Q}{R}$$

Substituting this expression into the definition of capacitance results in the following expression:

$$C_{sphere} = \frac{Q}{\Delta V} = \frac{R}{k_C}$$

Did you know?

The farad is named after Michael Faraday (1791–1867), a prominent nineteenth-century English chemist and physicist. Faraday made many contributions to our understanding of electromagnetic phenomena.

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Topic: Michael Faraday
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Topic: Capacitors
SciLinks Code: HF60211

This equation indicates that the capacitance of a sphere increases as the size of the sphere increases. Because Earth is so large, it has an extremely large capacitance. Thus, Earth can provide or accept a large amount of charge without its electric potential changing too much. This is the reason why Earth is often used as a reference point for measuring potential differences in electric circuits.

The material between a capacitor's plates can change its capacitance

So far, we have assumed that the space between the plates of a parallel-plate capacitor is a vacuum. However, in many parallel-plate capacitors, the space is filled with a material called a *dielectric.* A dielectric is an insulating material, such as air, rubber, glass, or waxed paper. When a dielectric is inserted between the plates of a capacitor, the capacitance increases. The capacitance increases because the molecules in a dielectric can align with the applied electric field, causing an excess negative charge near the surface of the dielectric at the positive plate and an excess positive charge near the surface of the dielectric at the negative plate. The surface charge on the dielectric effectively reduces the charge on the capacitor plates, as shown in **Figure 6.** Thus, the plates can store more charge for a given potential difference. According to the expression $Q = C\Delta V$, if the charge increases and the potential difference is constant, the capacitance must increase. A capacitor with a dielectric can store more charge and energy for a given potential difference than can the same capacitor without a dielectric. In this book, problems will assume that capacitors are in a vacuum, with no dielectrics.

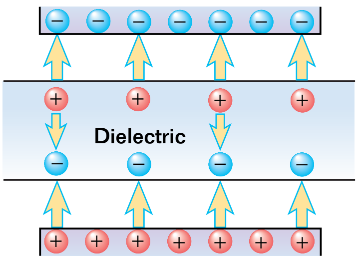


Figure 6
The effect of a dielectric is to reduce the strength of the electric field in a capacitor.

Discharging a capacitor releases its charge

Once a capacitor is charged, the battery or other source of potential difference that charged it can be removed from the circuit. The two plates of the capacitor will remain charged unless they are connected with a material that conducts. Once the plates are connected, the capacitor will *discharge.* This process

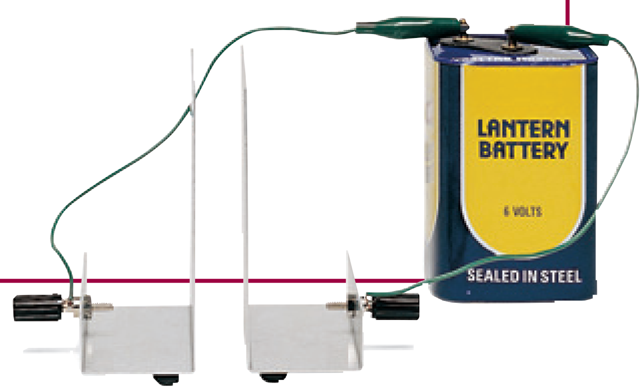
Conceptual Challenge

1. Charge on a Capacitor Plate

A certain capacitor is designed so that one plate is large and the other is small. Do the plates have the same magnitude of charge when connected to a battery?

2. Capacitor Storage

What does a capacitor store, given that the net charge in a parallel-plate capacitor is always zero?



is the opposite of charging. The charges move back from one plate to another until both plates are uncharged again because this is the state of lowest potential energy.

One device that uses a capacitor is the flash attachment of a camera. A battery is used to charge the capacitor, and this stored charge is then released when the shutter-release button is pressed to take a picture. One advantage of using a discharging capacitor instead of a battery to power a flash is that with a capacitor, the stored charge can be delivered to a flash tube much faster, illuminating the subject at the instant more light is needed.

Computers make use of capacitors in many ways. For example, one type of computer keyboard has capacitors at the base of its keys, as shown in **Figure 7.** Each key is connected to a movable plate, which represents one side of the capacitor. The fixed plate on the bottom of the keyboard represents the other side of the capacitor. When a key is pressed, the capacitor spacing decreases, causing an increase in capacitance. External electronic circuits recognize that a key has been pressed when its capacitance changes.

Because the area of the plates and the distance between the plates can be controlled, the capacitance, and thus the electric field strength, can also be easily controlled.

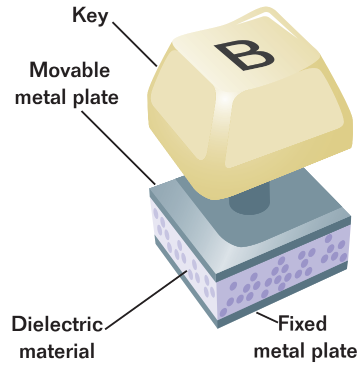


Figure 7
A parallel-plate capacitor is often used in keyboards.

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ENERGY AND CAPACITORS

A charged capacitor stores electrical potential energy because it requires work to move charges through a circuit to the opposite plates of a capacitor. The work done on these charges is a measure of the transfer of energy.

For example, if a capacitor is initially uncharged so that the plates are at the same electric potential, that is, if both plates are neutral, then almost no work is required to transfer a small amount of charge from one plate to the other. However, once a charge has been transferred, a small potential difference appears between the plates. As additional charge is transferred through this potential difference, the electrical potential energy of the system increases. This increase in energy is the result of work done on the charge. The electrical potential energy stored in a capacitor that is charged from zero to some charge, Q, is given by the following expression:

ELECTRICAL POTENTIAL ENERGY STORED IN A CHARGED CAPACITOR

$$PE_{electric} = \frac{1}{2}Q\Delta V$$

electrical potential energy =
$\frac{1}{2}$(charge on one plate)(final potential difference)

Note that this equation is also an expression for the work required to charge the capacitor.

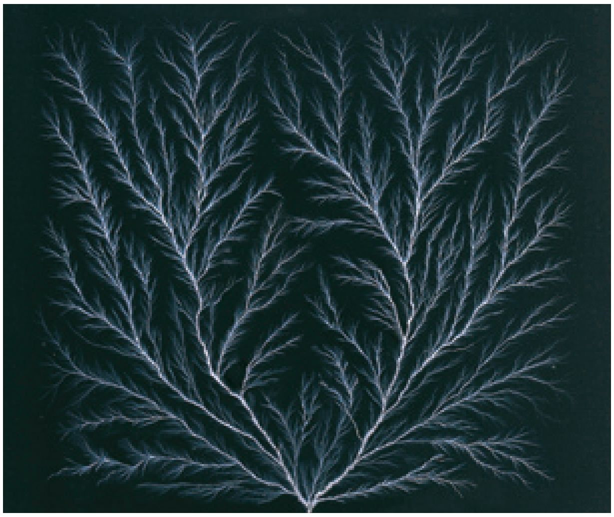


Figure 8
The markings caused by electrical breakdown in this material look similar to the lightning bolts produced when air undergoes electrical breakdown.

By substituting the definition of capacitance ($C = Q/\Delta V$), we can see that these alternative forms are also valid:

$$PE_{electric} = \frac{1}{2}C(\Delta V)^2$$

$$PE_{electric} = \frac{Q^2}{2C}$$

These results apply to any capacitor. In practice, there is a limit to the maximum energy (or charge) that can be stored because electrical breakdown ultimately occurs between the plates of the capacitor for a sufficiently large potential difference. So, capacitors are usually labeled with a maximum operating potential difference. Electrical breakdown in a capacitor is like a lightning discharge in the atmosphere. **Figure 8** shows a pattern created in a block of plastic resin that has undergone electrical breakdown. This book's problems assume that all potential differences are below the maximum.

SAMPLE PROBLEM B

Capacitance

PROBLEM

A capacitor, connected to a 12 V battery, holds 36 µC of charge on each plate. What is the capacitance of the capacitor? How much electrical potential energy is stored in the capacitor?

SOLUTION

Given: $Q = 36\ \mu C = 3.6 \times 10^{-5}\ C$ $\quad \Delta V = 12\ V$

Unknown: $C = ?$ $\quad PE_{electric} = ?$

To determine the capacitance, use the definition of capacitance.

$$C = \frac{Q}{\Delta V} = \frac{3.6 \times 10^{-5}\ C}{12\ V}$$

$$\boxed{C = 3.0 \times 10^{-6}\ F = 3.0\ \mu F}$$

To determine the potential energy, use the alternative form of the equation for the potential energy of a charged capacitor shown on this page:

$$PE_{electric} = \frac{1}{2}C(\Delta V)^2$$

$$PE_{electric} = (0.5)(3.0 \times 10^{-6}\ F)(12\ V)^2$$

$$\boxed{PE_{electric} = 2.2 \times 10^{-4}\ J}$$

PRACTICE B

Capacitance

1. A 4.00 μF capacitor is connected to a 12.0 V battery.

a. What is the charge on each plate of the capacitor?

b. If this same capacitor is connected to a 1.50 V battery, how much electrical potential energy is stored?

2. A parallel-plate capacitor has a charge of 6.0 μC when charged by a potential difference of 1.25 V.

a. Find its capacitance.

b. How much electrical potential energy is stored when this capacitor is connected to a 1.50 V battery?

3. A capacitor has a capacitance of 2.00 pF.

a. What potential difference would be required to store 18.0 pC?

b. How much charge is stored when the potential difference is 2.5 V?

4. You are asked to design a parallel-plate capacitor having a capacitance of 1.00 F and a plate separation of 1.00 mm. Calculate the required surface area of each plate. Is this a realistic size for a capacitor?

SECTION REVIEW

1. Assume Earth and a cloud layer 800.0 m above the Earth can be treated as plates of a parallel-plate capacitor.

a. If the cloud layer has an area of 1.00×10^6 m^2, what is the capacitance?

b. If an electric field strength of 2.0×10^6 N/C causes the air to conduct charge (lightning), what charge can the cloud hold?

2. A parallel-plate capacitor has an area of 2.0 cm^2, and the plates are separated by 2.0 mm.

a. What is the capacitance?

b. How much charge does this capacitor store when connected to a 6.0 V battery?

3. A parallel-plate capacitor has a capacitance of 1.35 pF. If a 12.0 V battery is connected to this capacitor, how much electrical potential energy would it store?

4. **Critical Thinking** Explain why two metal plates near each other will not become charged unless they are connected to a source of potential difference.

SECTION 3

Current and Resistance

SECTION OBJECTIVES

- **Describe the basic properties of electric current, and solve problems relating current, charge, and time.**
- **Distinguish between the drift speed of a charge carrier and the average speed of the charge carrier between collisions.**
- **Calculate resistance, current, and potential difference by using the definition of *resistance*.**
- **Distinguish between ohmic and non-ohmic materials, and learn what factors affect resistance.**

CURRENT AND CHARGE MOVEMENT

Although many practical applications and devices are based on the principles of static electricity, electricity did not become an integral part of our daily lives until scientists learned to control the movement of electric charge, known as *current*. Electric currents power our lights, radios, television sets, air conditioners, and refrigerators. Currents are also used in automobile engines, travel through miniature components that make up the chips of computers, and perform countless other invaluable tasks.

Electric currents are even part of the human body. This connection between physics and biology was discovered by Luigi Galvani (1737–1798). While conducting electrical experiments near a frog he had recently dissected, Galvani noticed that electrical sparks caused the frog's legs to twitch and even convulse. After further research, Galvani concluded that electricity was present in the frog. Today, we know that electric currents are responsible for transmitting messages between body muscles and the brain. In fact, every function involving the nervous system is initiated by electrical activity.

Current is the rate of charge movement

A current exists whenever there is a net movement of electric charge through a medium. To define *current* more precisely, suppose electrons are moving through a wire, as shown in **Figure 9.** The **electric current** is the rate at which these charges move through the cross section of the wire. If ΔQ is the amount of charge that passes through this area in a time interval, Δt, then the current, I, is the ratio of the amount of charge to the time interval. Note that the direction of current is *opposite* the movement of the negative charges. We will further discuss this detail later in this section.

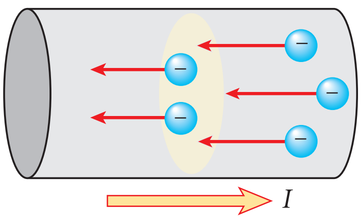


Figure 9
The current in this wire is defined as the rate at which electric charges pass through a cross-sectional area of the wire.

electric current

the rate at which electric charges pass through a given area

ELECTRIC CURRENT

$$I = \frac{\Delta Q}{\Delta t}$$

$$\text{electric current} = \frac{\text{charge passing through a given area}}{\text{time interval}}$$

The SI unit for current is the *ampere*, A. One ampere is equivalent to one coulomb of charge passing through a cross-sectional area in a time interval of one second (1 A = 1 C/s).

SAMPLE PROBLEM C

Current

PROBLEM

The current in a light bulb is 0.835 A. How long does it take for a total charge of 1.67 C to pass through the filament of the bulb?

SOLUTION

Given: $\Delta Q = 1.67\ \mathrm{C}$ $\quad I = 0.835\ \mathrm{A}$

Unknown: $\Delta t = ?$

Use the definition of electric current. Rearrange to solve for the time interval.

$$I = \frac{\Delta Q}{\Delta t}$$

$$\Delta t = \frac{\Delta Q}{I}$$

$$\boxed{\Delta t = \frac{1.67\ \mathrm{C}}{0.835\ \mathrm{A}} = 2.00\ \mathrm{s}}$$

PRACTICE C

Current

1. If the current in a wire of a CD player is 5.00 mA, how long would it take for 2.00 C of charge to pass through a cross-sectional area of this wire?

2. In a particular television tube, the beam current is 60.0 µA. How long does it take for 3.75×10^{14} electrons to strike the screen? (Hint: Recall that an electron has a charge of -1.60×10^{-19} C.)

3. If a metal wire carries a current of 80.0 mA, how long does it take for 3.00×10^{20} electrons to pass a given cross-sectional area of the wire?

4. The compressor on an air conditioner draws 40.0 A when it starts up. If the start-up time is 0.50 s, how much charge passes a cross-sectional area of the circuit in this time?

5. A total charge of 9.0 mC passes through a cross-sectional area of a nichrome wire in 3.5 s.

a. What is the current in the wire?

b. How many electrons pass through the cross-sectional area in 10.0 s?

c. If the number of charges that pass through the cross-sectional area during the given time interval doubles, what is the resulting current?

Conventional current is defined in terms of positive charge movement

The moving charges that make up a current can be positive, negative, or a combination of the two. In a common conductor, such as copper, current is due to the motion of negatively charged electrons, because the atomic structure of solid conductors allows the electrons to be transferred easily from one atom to the next. In contrast, the protons are relatively fixed inside the nucleus of the atom. In certain particle accelerators, a current exists when positively charged protons are set in motion. In some cases—in gases and dissolved salts, for example—current is the result of positive charges moving in one direction and negative charges moving in the opposite direction.

Positive and negative charges in motion are sometimes called *charge carriers. Conventional current* is defined in terms of the flow of positive charges. Thus, negative charge carriers, such as electrons, would have a conventional current in the direction opposite their physical motion. The three possible cases of charge flow are shown in **Table 1.** We will use conventional current in this book unless stated otherwise.

Table 1 **Conventional Current**

	First case	Second case	Third case
Motion of charge carriers	← −	+ →	+ → ← −
Equivalent conventional current	+ →	+ →	+ → + →

As you learned in Section 1, an electric field in a material sets charges in motion. For a material to be a good conductor, charge carriers in the material must be able to move easily through the material. Many metals are good conductors because metals usually contain a large number of free electrons. Body fluids and salt water are able to conduct electric charge because they contain charged atoms called *ions.* Because dissolved ions can move through a solution easily, they can be charge carriers. A solute that dissolves in water to give a solution that conducts electric current is called an *electrolyte.*

DRIFT VELOCITY

When you turn on a light switch, the light comes on almost immediately. For this reason, many people think that electrons flow very rapidly from the socket to the light bulb. However, this is not the case. When you turn on the switch, electron motion near the switch changes the electric field there, and the change propagates throughout the wire very quickly. Such changes travel through the wire at nearly the speed of light. The charges themselves, however, travel much more slowly.

Quick Lab

A Lemon Battery

MATERIALS LIST

- lemon
- copper wire
- paper clip

Straighten the paper clip, and insert it and the copper wire into the lemon to construct a chemical cell. Touch the ends of both wires with your tongue. Because a potential difference exists across the two metals and because your saliva provides an electrolytic solution that conducts electric current, you should feel a slight tingling sensation on your tongue. CAUTION: Do not share battery set-ups with other students. Dispose of your materials according to your teacher's instructions.

Drift velocity is the net velocity of charge carriers

To see how the electrons move, consider a solid conductor in which the charge carriers are free electrons. When the conductor is in electrostatic equilibrium, the electrons move randomly, similar to the movement of molecules in a gas. When a potential difference is applied across the conductor, an electric field is set up inside the conductor. The force due to that field sets the electrons in motion, thereby creating a current.

These electrons do not move in straight lines along the conductor in a direction opposite the electric field. Instead, they undergo repeated collisions with the vibrating metal atoms of the conductor. If these collisions were charted, the result would be a complicated zigzag pattern like the one shown in **Figure 10.** The energy transferred from the electrons to the metal atoms during the collisions increases the vibrational energy of the atoms, and the conductor's temperature increases.

The electrons gain kinetic energy as they are accelerated by the electric field in the conductor. They also lose kinetic energy because of the collisions described above. However, despite the internal collisions, the individual electrons move slowly along the conductor in a direction opposite the electric field, **E,** with a velocity known as the **drift velocity,** $\mathbf{v}_{drift}$.

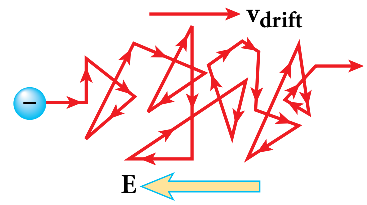


Figure 10
When an electron moves through a conductor, collisions with the vibrating metal atoms of the conductor force the electron to change its direction constantly.

drift velocity

the net velocity of a charge carrier moving in an electric field

Drift speeds are relatively small

The magnitudes of drift velocities, or drift speeds, are typically very small. In fact, the drift speed is much less than the average speed between collisions. For example, in a copper wire that has a current of 10.0 A, the drift speed of electrons is only 2.46×10^{-4} m/s. These electrons would take about 68 min to travel 1 m! The electric field, on the other hand, reaches electrons throughout the wire at a speed approximately equal to the speed of light.

Conceptual Challenge

1. Electric Field Inside a Conductor

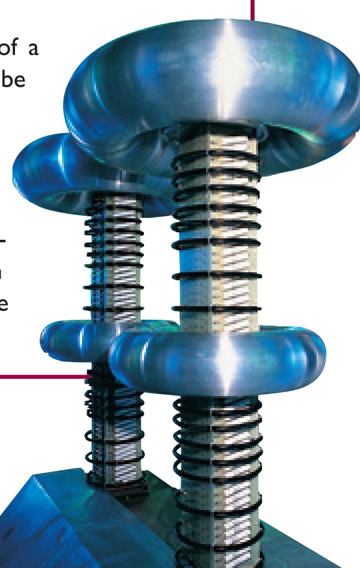
We concluded in our study of electrostatics that the field inside a conductor is zero, yet we have seen that an electric field exists inside a conductor that carries a current. How is this zero electric field possible?

2. Turning on a Light

If charges travel very slowly through a metal (approximately 10^{-4} m/s), why doesn't it take several hours for a light to come on after you flip a switch?

3. Particle Accelerator

The positively charged dome of a Van de Graaff generator can be used to accelerate positively charged protons. A current exists due to the motion of these protons. In this case, how does the direction of conventional current compare with the direction in which the charge carriers move?



RESISTANCE TO CURRENT

When a light bulb is connected to a battery, the current in the bulb depends on the potential difference across the battery. For example, a 9.0 V battery connected to a light bulb generates a greater current than a 6.0 V battery connected to the same bulb. But potential difference is not the only factor that determines the current in the light bulb. The materials that make up the connecting wires and the bulb's filament also affect the current in the bulb. Even though most materials can be classified as conductors or insulators, some conductors allow charges to move through them more easily than others. The opposition to the motion of charge through a conductor is the conductor's **resistance.** Quantitatively, resistance is defined as the ratio of potential difference to current, as follows:

resistance

the opposition presented to electric current by a material or device

RESISTANCE

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

$$\text{resistance} = \frac{\text{potential difference}}{\text{current}}$$

The SI unit for resistance, the *ohm*, is equal to one volt per ampere and is represented by the Greek letter Ω (*omega*).

Resistance is constant over a range of potential differences

For many materials, including most metals, experiments show that *the resistance is constant over a wide range of applied potential differences.* This statement, known as Ohm's law, is named for Georg Simon Ohm (1789–1854), who was the first to conduct a systematic study of electrical resistance. Mathematically, Ohm's law is stated as follows:

$$\frac{\Delta V}{I} = \text{constant}$$

As can be seen by comparing the definition of resistance with Ohm's law, the constant of proportionality in the Ohm's law equation is resistance. It is common practice to express Ohm's law as $\Delta V = IR$.

Ohm's law does not hold for all materials

Ohm's law is not a fundamental law of nature like the conservation of energy or the universal law of gravitation. Instead, it is a behavior that is valid only for certain materials. Materials that have a constant resistance over a wide range of potential differences are said to be *ohmic.* A graph of current versus potential difference for an ohmic material is linear, as shown in **Figure 11(a).** This is because the slope of such a graph ($I/\Delta V$) is inversely proportional to resistance. When resistance is constant, the current is proportional to the potential difference and the resulting graph is a straight line.

Materials that do not function according to Ohm's law are said to be *non-ohmic.* **Figure 11(b)** shows a graph of current versus potential difference for a non-ohmic material. In this case, the slope is not constant because resistance varies. Hence, the resulting graph is nonlinear. One common semiconducting device that is non-ohmic is the *diode.* Its resistance is small for currents in one direction and large for currents in the reverse direction. Diodes are used in circuits to control the direction of current. This book assumes that all resistors function according to Ohm's law unless stated otherwise.

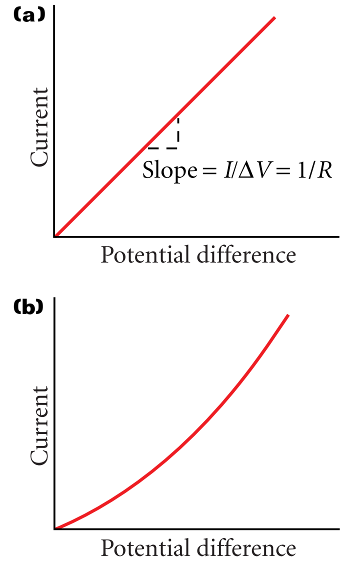


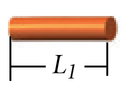
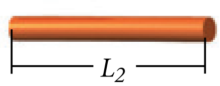
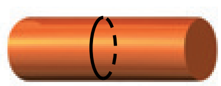
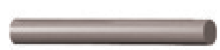
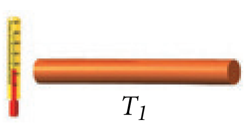
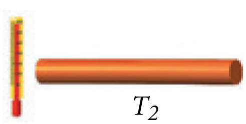
Figure 11
(a) The current–potential difference curve of an ohmic material is linear, and the slope is the inverse of the material's resistance. **(b)** The current–potential difference curve of a non-ohmic material is nonlinear.

Resistance depends on length, area, material, and temperature

Earlier in this section, you learned that electrons do not move in straight-line paths through a conductor. Instead, they undergo repeated collisions with the metal atoms. These collisions affect the motion of charges somewhat as a force of internal friction would. This is the origin of a material's resistance. Thus, any factors that affect the number of collisions will also affect a material's resistance. Some of these factors are shown in **Table 2.**

Two of these factors—length and cross-sectional area—are purely geometrical. It is intuitive that a longer length of wire provides more resistance than a shorter length of wire does. Similarly, a wider wire allows charges to flow more easily than a thinner wire does, much as a larger pipe allows water to flow more easily than a smaller pipe does. The material effects have to do with the structure of the atoms making up the material. Finally, for most materials, resistance increases as the temperature of the metal increases. When a material is hot, its atoms vibrate fast, and it is more difficult for an electron to flow through the material.

Table 2 Factors That Affect Resistance

Factor	Less resistance	Greater resistance
Length	 L_1	 L_2
Cross-sectional area	 A_1	 A_2
Material	 Copper	 Iron
Temperature	 T_1	 T_2

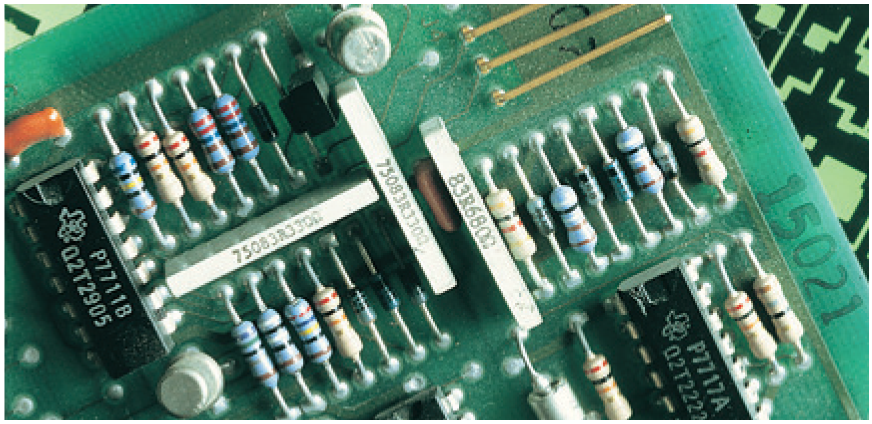


Figure 12
Resistors, such as those shown here, are used to control current. The colors of the bands represent a code for the values of the resistances.

Resistors can be used to control the amount of current in a conductor

One way to change the current in a conductor is to change the potential difference across the ends of the conductor. But in many cases, such as in household circuits, the potential difference does not change. How can the current in a certain wire be changed if the potential difference remains constant?

According to the definition of resistance, if ΔV remains constant, current decreases when resistance increases. Thus, the current in a wire can be decreased by replacing the wire with one of higher resistance. The same effect can be accomplished by making the wire longer or by connecting a *resistor* to the wire. A resistor is a simple electrical element that provides a specified resistance. **Figure 12** shows a group of resistors in a circuit board. Resistors are sometimes used to control the current in an attached conductor because this is often more practical than changing the potential difference or the properties of the conductor.

SAMPLE PROBLEM D

Resistance

PROBLEM

The resistance of a steam iron is 19.0 Ω. What is the current in the iron when it is connected across a potential difference of 120 V?

SOLUTION

Given: $R = 19.0\ \Omega \qquad \Delta V = 120\ \text{V}$

Unknown: $I = ?$

Use Ohm's law to relate resistance to potential difference and current.

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

$$\boxed{I = \frac{\Delta V}{R} = \frac{120\ \text{V}}{19.0\ \Omega} = 6.32\ \text{A}}$$

PRACTICE D

Resistance

1. A 1.5 V battery is connected to a small light bulb with a resistance of 3.5 Ω. What is the current in the bulb?
2. A stereo with a resistance of 65 Ω is connected across a potential difference of 120 V. What is the current in this device?
3. Find the current in the following devices when they are connected across a potential difference of 120 V.
   a. a hot plate with a resistance of 48 Ω
   b. a microwave oven with a resistance of 20 Ω
4. The current in a microwave oven is 6.25 A. If the resistance of the oven's circuitry is 17.6 Ω, what is the potential difference across the oven?
5. A typical color television draws 2.5 A of current when connected across a potential difference of 115 V. What is the effective resistance of the television set?
6. The current in a certain resistor is 0.50 A when it is connected to a potential difference of 110 V. What is the current in this same resistor if
   a. the operating potential difference is 90.0 V?
   b. the operating potential difference is 130 V?

Salt water and perspiration lower the body's resistance

The human body's resistance to current is on the order of 500 000 Ω when the skin is dry. However, the body's resistance decreases when the skin is wet. If the body is soaked with salt water, its resistance can be as low as 100 Ω. This is because ions in salt water readily conduct electric charge. Such low resistances can be dangerous if a large potential difference is applied between parts of the body because current increases as resistance decreases. Currents in the body that are less than 0.01 A either are imperceptible or generate a slight tingling feeling. Greater currents are painful and can disturb breathing, and currents above 0.15 A disrupt the electrical activity of the heart and can be fatal.

Perspiration also contains ions that conduct electric charge. In a *galvanic skin response* (GSR) test, commonly used as a stress test and as part of some so-called lie detectors, a very small potential difference is set up across the body. Perspiration increases when a person is nervous or stressed, thereby decreasing the resistance of the body. In GSR tests, a state of low stress and high resistance, or "normal" state, is used as a control, and a state of higher stress is reflected as a decreased resistance compared with the normal state.

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ADVANCED TOPICS

See "Superconductors and BCS Theory" in **Appendix J: Advanced Topics** to learn more about superconducting materials.

Potentiometers have variable resistance

A *potentiometer* is a special type of resistor that has a fixed contact on one end and an adjustable, sliding contact that allows the user to tap off different potential differences. The sliding contact is frequently mounted on a rotating shaft, and the resistance is adjusted by rotating a knob. Potentiometers (frequently called *pots* for short) have many applications. In fact, most of the knobs on everyday items, such as volume controller on a stereo, are potentiometers. Potentiometers may also be mounted linearly. One example is a dimmer switch to control the light output of a light fixture. The joystick on your video game controller uses two potentiometers, one for motion in the x direction and one for motion in the y direction, to tell the computer the movements that you make when playing a game.

SECTION REVIEW

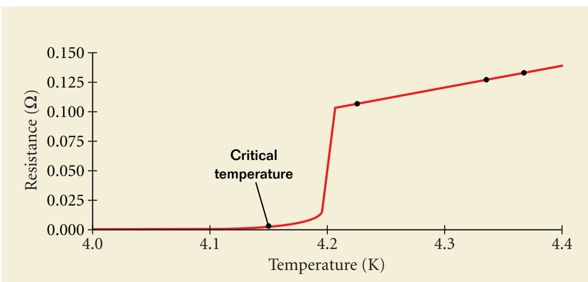
1. Can the direction of conventional current ever be opposite the direction of charge movement? If so, when?
2. The charge that passes through the filament of a certain light bulb in 5.00 s is 3.0 C.
   a. What is the current in the light bulb?
   b. How many electrons pass through the filament of the light bulb in a time interval of 1.0 min?
3. How much current would a 10.2 Ω toaster oven draw when connected to a 120 V outlet?
4. An ammeter registers 2.5 A of current in a wire that is connected to a 9.0 V battery. What is the wire's resistance?
5. In a particular diode, the current triples when the applied potential difference is doubled. What can you conclude about the diode?
6. What is the function of resistors in a circuit board? What is the function of diodes in a circuit board?
7. Calculate the current in a 75 Ω resistor when a potential difference of 115 V is placed across it. What will the current be if the resistor is replaced with a 47 Ω resistor?
8. **Critical Thinking** In a conductor that carries a current, which is less, the drift speed of an electron or the average speed of the electron between collisions? Explain your answer.
9. **Critical Thinking** You have only one type of wire. If you are connecting a battery to a light bulb with this wire, how could you decrease the current in the wire?

THE INSIDE STORY ON SUPERCONDUCTORS

Take a moment to imagine the many things that could be created with materials that conduct electricity with *zero* resistance. There would be no heating or reduction in the current when conducting electricity with such a material. These materials exist and are called *superconductors*.

Superconductors have zero resistance below a certain temperature, called the *critical temperature*. The graph of resistance as a function of temperature for a superconductor resembles that of a normal metal at temperatures well above the critical temperature. But when the temperature is near or below the critical temperature, the resistance suddenly drops to zero, as the graph below shows. This graph shows the resistance of mercury just above and below its critical temperature of 4.15 K.

This express train in Tokyo, Japan, which utilizes the Meissner effect, levitates above the track and can reach speeds exceeding 225 km/h.



Today, there are thousands of known superconductors, including common metals such as aluminum, tin, lead, and zinc. However, for common metals that exhibit superconductivity, the critical temperature is extremely low—near absolute zero. For example, aluminum reaches superconductivity at 1.19 K, just a little more than one degree above absolute zero. Temperatures near absolute zero are difficult to achieve and maintain. Interestingly, copper, silver, and gold, which are excellent conductors at room temperature, do not exhibit superconductivity.

An important recent development in physics is the discovery of high-temperature superconductors. The excitement began with a 1986 publication by scientists at the IBM Zurich Research Laboratory in Switzerland. In this publication, scientists reported evidence for superconductivity at a temperature near 30 K. More recently, scientists have found superconductivity at temperatures as high as 150 K. However, 150 K is still –123°C, which is much colder than room temperature. The search continues for a material that has superconducting qualities at room temperature. This important search has both scientific and practical applications.

One of the truly remarkable features of superconductors is that once a current is established in them, the current continues even if the applied potential difference is removed. In fact, steady currents have been observed to persist for many years in superconducting loops with no apparent decay. This feature makes superconducting materials attractive for a wide variety of applications.

Because electric currents produce magnetic effects, current in a superconductor can be used to float a magnet in the air over a superconductor. This effect, known as the Meissner effect, is used with high-speed express trains, such as the one shown in the figure above. This type of train levitates a few inches above the track.

One useful application of superconductivity is superconducting magnets. Such magnets are being considered for storing energy. The idea of using superconducting power lines to transmit power more efficiently is also being researched. Modern superconducting electronic devices that consist of two thin-film superconductors separated by a thin insulator have been constructed. They include magnetometers (magnetic-field measuring devices) and various microwave devices.

SECTION 4

Electric Power

SECTION OBJECTIVES

- **Differentiate between direct current and alternating current.**
- **Relate electric power to the rate at which electrical energy is converted to other forms of energy.**
- **Calculate electric power and the cost of running electrical appliances.**

SOURCES AND TYPES OF CURRENT

When you drop a ball, it falls to the ground, moving from a place of higher gravitational potential energy to one of lower gravitational potential energy. As discussed in Section 1, charges behave in similar ways. For example, free electrons in a conductor move randomly when all points in the conductor are at the same potential. But when a potential difference is applied across the conductor, they will move from a position of higher electric potential to a position of lower electric potential. Thus, a potential difference maintains current in a circuit.

Figure 13
Batteries maintain electric current by converting chemical energy into electrical energy.

Batteries and generators supply energy to charge carriers

Batteries maintain a potential difference across their terminals by converting *chemical* energy to electrical potential energy. **Figure 13** shows students measuring the potential difference of a battery created using a lemon, copper, and tin.

As charge carriers move from higher to lower electrical potential energy, this energy is converted into kinetic energy. This motion allows collisions to occur between the moving charges and the remaining material in the circuit elements. These collisions transfer energy (in the form of heat) back to the circuit.

A battery stores energy in the form of chemical energy, and its energy is released through a chemical reaction that occurs inside the battery. The battery continues to supply electrical energy to the charge carriers until its chemical energy is depleted. At this point, the battery must be replaced or recharged.

Because batteries must often be replaced or recharged, generators are sometimes preferable. Generators convert *mechanical* energy into electrical energy. For example, a hydroelectric power plant converts the kinetic energy of falling water into electrical potential energy. Generators are the source of the current to a wall outlet in your home and supply the electrical energy to operate your appliances. When you plug an appliance into an outlet, an effective potential difference of 120 V is applied to the device.

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Current can be direct or alternating

There are two different types of current: *direct current* (dc) and *alternating current* (ac). In direct current, charges move in only one direction with negative charges moving from a lower to higher electric potential. Hence, the conventional current is directed from the positive terminal to the negative terminal of a battery. Note, however, that the electrons actually move in the opposite direction.

Consider a light bulb connected to a battery. The potential difference between the terminals of a battery is fixed, so batteries always generate a direct current.

In alternating current, the terminals of the source of potential difference are constantly changing sign. Hence, there is no net motion of the charge carriers in alternating current; they simply vibrate back and forth. If this vibration were slow enough, you would notice flickering in lights and similar effects in other appliances. To eliminate this problem, alternating current is made to change direction rapidly. In the United States, alternating current oscillates 60 times every second. Thus, its frequency is 60 Hz. The graphs in **Figure 14** compare direct and alternating current. Alternating current has advantages that make it more practical for use in transferring electrical energy. For this reason, the current supplied to your home by power companies is alternating current rather than direct current.

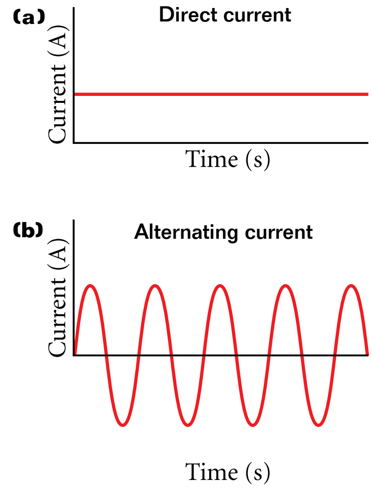


Figure 14
(a) The direction of direct current does not change, while **(b)** the direction of alternating current continually changes.

ENERGY TRANSFER

When a battery is used to maintain an electric current in a conductor, chemical energy stored in the battery is continuously converted to the electrical energy of the charge carriers. As the charge carriers move through the conductor, this electrical energy is converted to internal energy due to collisions between the charge carriers and other particles in the conductor.

For example, consider a light bulb connected to a battery, as shown in **Figure 15(a).** Imagine a charge Q moving from the battery's terminal to the light bulb and then back to the other terminal. The changes in electrical potential energy are shown in **Figure 15(b).** If we disregard the resistance of the connecting wire, no loss in energy occurs as the charge moves through the wire (A to B). But when the charge moves through the filament of the light bulb (B to C), which has a higher resistance than the wire has, it loses electrical potential energy due to collisions. This electrical energy is converted into internal energy, and the filament warms up and glows.

When the charge first returns to the battery's terminal (D), its potential energy is, by convention, zero, and the battery must do work on the charge. As the charge moves between the terminals of the battery (D to A), its electrical potential energy increases by $Q\Delta V$ (where ΔV is the potential difference across the two terminals). The battery's chemical energy must decrease by the same amount.

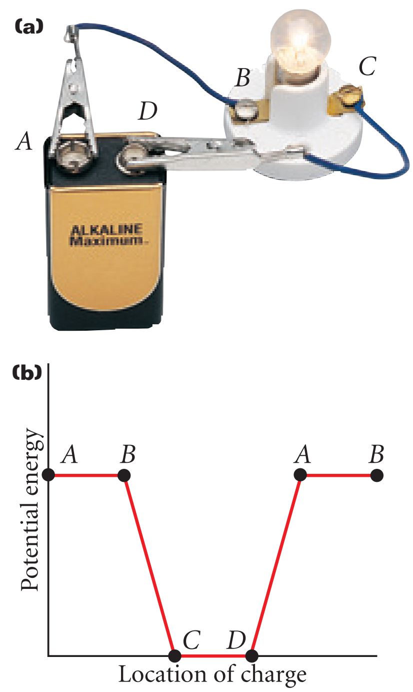


Figure 15
A charge leaves the battery at *A* with a certain amount of electrical potential energy. The charge loses this energy while moving from *B* to *C*, and then regains the energy as it moves through the battery from *D* to *A*.

Quick Lab

Energy Use in Home Appliances

MATERIALS LIST

- three small household appliances, such as a toaster, television, lamp, or stereo
- household electric-company bill (optional)

SAFETY CAUTION

Unplug appliances before examination. Use extreme caution when handling electrical equipment.

Look for a label on the back or bottom of each appliance. Record the power rating, which is given in units of watts (W). Use the billing statement to find the cost of energy per kilowatt-hour. (If you don't have a bill, choose a value between $0.05 and $0.20 per kilowatt-hour to use for your calculations.) Calculate the cost of running each appliance for 1 h. Estimate how many hours a day each appliance is used. Then calculate the monthly cost of using each appliance based on your daily estimate.

Electric power is the rate of conversion of electrical energy

Earlier in the text, power was described as the rate at which work is done. *Electric power,* then, is the rate at which charge carriers do work. Put another way, electric power is the rate at which charge carriers convert electrical potential energy to nonelectrical forms of energy.

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

Potential difference is the change in potential energy per unit of charge.

$$\Delta V = \frac{\Delta PE}{q}$$

This equation can be rewritten in terms of potential energy.

$$\Delta PE = q\Delta V$$

We can then substitute this expression for potential energy into the equation for power.

$$P = \frac{\Delta PE}{\Delta t} = \frac{q\Delta V}{\Delta t}$$

Because current, I, is defined as the rate of charge movement ($q/\Delta t$), we can express electric power as current multiplied by potential difference.

ELECTRIC POWER

$$P = I\Delta V$$

electric power = current × potential difference

This equation describes the rate at which charge carriers lose electrical potential energy. In other words, power is the rate of conversion of electrical energy. Recall that the SI unit of power is the *watt,* W. In terms of the dissipation of electrical energy, 1 W is equivalent to 1 J of electrical energy being converted to other forms of energy per second.

Most light bulbs are labeled with their power ratings. The amount of heat and light given off by a bulb is related to the power rating, also known as *wattage,* of the bulb.

Because $\Delta V = IR$ for ohmic resistors, we can express the power dissipated by a resistor in the following alternative forms:

$$P = I\Delta V = I(IR) = I^2R$$

$$P = I\Delta V = \left(\frac{\Delta V}{R}\right)\Delta V = \frac{(\Delta V)^2}{R}$$

The conversion of electrical energy to internal energy in a resistant material is called *joule heating,* also often referred to as an I^2R loss.

extension

Practice Problems

Visit go.hrw.com to find a sample and practice problems on the cost of electrical energy.

Keyword HF6ELCX

SAMPLE PROBLEM E

Electric Power

PROBLEM

An electric space heater is connected across a 120 V outlet. The heater dissipates 1320 W of power in the form of electromagnetic radiation and heat. Calculate the resistance of the heater.

SOLUTION

Given: $\Delta V = 120 \text{ V} \qquad P = 1320 \text{ W}$

Unknown: $R = ?$

Because power and potential difference are given but resistance is unknown, use the form of the power equation that relates power to the other two variables.

$$P = \frac{(\Delta V)^2}{R}$$

Rearrange the equation to solve for resistance.

$$R = \frac{(\Delta V)^2}{P} = \frac{(120 \text{ V})^2}{1320 \text{ W}} = \frac{(120)^2 \text{ J}^2/\text{C}^2}{1320 \text{ J/s}}$$

$$R = \frac{(120)^2 \text{ J/C}}{1320 \text{ C/s}} = 10.9 \text{ V/A}$$

$$\boxed{R = 10.9\ \Omega}$$

PRACTICE E

Electric Power

1. A 1050 W electric toaster operates on a household circuit of 120 V. What is the resistance of the wire that makes up the heating element of the toaster?
2. A small electronic device is rated at 0.25 W when connected to 120 V. What is the resistance of this device?
3. A calculator is rated at 0.10 W and has an internal resistance of 22 Ω. What battery potential difference is required for this device?
4. An electric heater is operated by applying a potential difference of 50.0 V across a wire of total resistance 8.00 Ω. Find the current in the wire and the power rating of the heater.
5. What would the current in the heater in Problem 4 be if the wire developed a short and the resistance was reduced to 0.100 Ω?

ADVANCED TOPICS

See "Electron Tunneling" in **Appendix J: Advanced Topics** to learn about the wave characteristics of electrons.

Electric companies measure energy consumed in kilowatt-hours

Electric power, as discussed previously, is the rate of energy transfer. Power companies charge for energy, not power. However, the unit of energy used by electric companies to calculate consumption, the *kilowatt-hour,* is defined in terms of power. One kilowatt-hour (kW•h) is the energy delivered in 1 h at the constant rate of 1 kW. The following equation shows the relationship between the kilowatt-hour and the SI unit of energy, the joule:

$$1\ \mathrm{kW \bullet h} \times \frac{10^3\ \mathrm{W}}{1\ \mathrm{kW}} \times \frac{60\ \mathrm{min}}{1\ \mathrm{h}} \times \frac{60\ \mathrm{s}}{1\ \mathrm{min}} = 3.6 \times 10^6\ \mathrm{W \bullet s} = 3.6 \times 10^6\ \mathrm{J}$$

On an electric bill, the electrical energy used in a given period is usually stated in multiples of kilowatt-hours. An electric meter, such as the one outside your home, is used by the electric company to determine how much energy is consumed over some period of time. *So, the electric company does not charge how much power is delivered to your house but instead charges for the amount of energy used.*

The Inside Story on Household Appliance Power Usage

Hair dryers contain a resistive coil that becomes hot when there is an electric current in the coil.

The electrical energy supplied by power companies is used to generate electric currents. These currents are used to operate household appliances. When the charge carriers that make up an electric current encounter resistance, some of the electrical energy is converted to internal energy by collisions and the conductor warms up. This effect is used in many appliances, such as hair dryers, electric heaters, electric clothes dryers, steam irons, and toasters.

Hair dryers contain a long, thin heating coil that becomes very hot when there is an electric current in the coil. This coil is commonly made of an alloy of the two metals nickel and chromium. This nickel chromium alloy conducts electricity poorly.

In a hair dryer, a fan behind the heating coil blows air through the hot coils. The air is then heated and blown out of the hair dryer. The same principle is also used in clothes dryers and electric heaters.

In a steam iron, a heating coil warms the bottom of the iron and also turns water into steam. An electric toaster has heating elements around the edges and in the center. When bread is loaded into the toaster, the heating coils turn on and a timer controls how long the elements remain on before the bread is popped out of the toaster.

Appliances that use resistive heater coils consume a relatively large amount of electric energy. This energy consumption occurs because a large amount of current is required to heat the coils to a useful level. Because power is proportional to the current squared times the resistance, energy consumption is high.

Electrical energy is transferred at high potential differences to minimize energy loss

When transporting electrical energy by power lines, such as those shown in **Figure 16,** power companies want to minimize the I^2R loss and maximize the energy delivered to a consumer. This can be done by decreasing either current or resistance. Although wires have little resistance, recall that resistance is proportional to length. Hence, resistance becomes a factor when power is transported over long distances. Even though power lines are designed to minimize resistance, some energy will be lost due to the length of the power lines.

As expressed by the equation $P = I^2R$, energy loss is proportional to the *square* of the current in the wire. For this reason, decreasing current is even more important than decreasing resistance. Because $P = I\Delta V$, the same amount of power can be transported either at high currents and low potential differences or at low currents and high potential differences. Thus, transferring electrical energy at low currents, thereby minimizing the I^2R loss, requires that electrical energy be transported at very high potential differences. Power plants transport electrical energy at potential differences of up to 765 000 V. Locally, this potential difference is reduced by a transformer to about 4000 V. At your home, this potential difference is reduced again to about 120 V by another transformer.

Figure 16
Power companies transfer electrical energy at high potential differences in order to minimize the I^2R loss.

SECTION REVIEW

1. What does the power rating on a light bulb describe?
2. If the resistance of a light bulb is increased, how will the electrical energy used by the light bulb over the same time period change?
3. The potential difference across a resting neuron in the human body is about 70 mV, and the current in it is approximately 200 µA. How much power does the neuron release?
4. How much does it cost to watch an entire World Series (21 h) on a 90.0 W black-and-white television set? Assume that electrical energy costs \$0.070/kW•h.
5. Explain why it is more efficient to transport electrical energy at high potential differences and low currents rather than at low potential differences and high currents.

PHYSICS CAREERS

Electrician

Electricity enables us to see at night, to cook, to have heat and hot water, to communicate, to be entertained, and to do many other things. Without electricity, our lives would be unimaginably different. To learn more about being an electrician, read the interview with master electrician David Ellison.

David Ellison teaches electrician skills to students at a local community college.

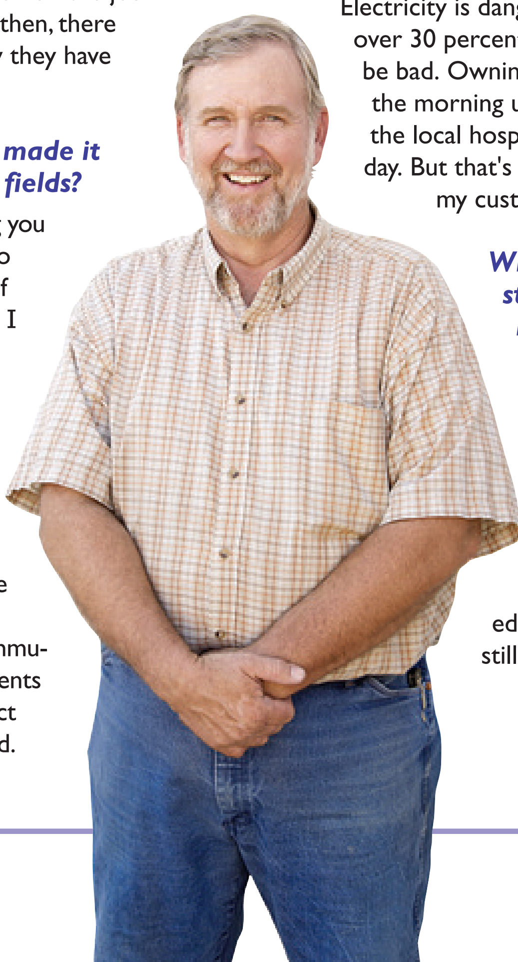
How did you become an electrician?

I went to junior college to learn electronics—everything from TVs and radios to radio towers and television stations. But I didn't particularly like that sort of work. While working in a furniture factory, I got to know the master electrician for the factory, and I began working with him. Eventually he got me a job with a master electrician in town.

Most of my experience has been on the job—very little schooling. But back then, there wasn't a lot of schooling. Now they have some good classes.

What about electrical work made it more interesting than other fields?

I enjoy working with something you can't see or smell—but if you do touch it, it'll let you know. And if you flip a light switch, there it is. I also enjoy wiring up the switches and safeties, and solving problems when they don't work.



Where do you currently work?

I have been self-employed since 1989. About three years ago, I was invited to teach at the community college. I enjoy it. My students seem to relate better to the fact that I'm still working in the field. When I explain something to them, I can talk from recent experience. Teaching helps me stay on top of the field, too.

Are there any drawbacks to your work?

Electricity is dangerous. I've been burned twice over 30 percent of my body. Also, the hours can be bad. Owning my own business, I go from 6 in the morning until 9 or 10 at night. I am on call at the local hospital—I was there on Thanksgiving day. But that's the nature of my relationship with my customers.

What advice do you have for a student who is interested in becoming an electrician?

If you know a local electrical contractor, go talk or visit for the day. Or take a class at the local community college to see if it interests you. Some companies have their own classes, usually one night a week. Going to school gives you some technical knowledge, but getting out and doing it is still the best way to learn.

CHAPTER 17 *Highlights*

KEY IDEAS

Section 1 Electric Potential

- Electrical potential energy is energy that a charged object has because of its shape and its position in an electric field.
- Electric potential is electrical potential energy divided by charge.
- Only differences in electric potential (potential differences) from one position to another are useful in calculations.

Section 2 Capacitance

- The capacitance, C, of an object is the magnitude of the charge, Q, on each of a capacitor's plates divided by the potential difference, ΔV, between the plates.
- A capacitor is a device that is used to store electrical potential energy. The potential energy stored in a charged capacitor depends on the charge and the potential difference between the capacitor's two plates.

Section 3 Current and Resistance

- Current is the rate of charge movement.
- Resistance equals potential difference divided by current.
- Resistance depends on length, cross-sectional area, temperature, and material.

Section 4 Electric Power

- In direct current, charges move in a single direction; in alternating current, the direction of charge movement continually alternates.
- Electric power is the rate of conversion of electrical energy.
- The power dissipated by a resistor equals current squared times resistance.
- Electric companies measure energy consumed in kilowatt-hours.

Variable Symbols

Quantities		Units		Conversions
$PE_{electric}$	electrical potential energy	J	joule	$= N\bullet m = kg\bullet m^2/s^2$
ΔV	potential difference	V	volt	$= J/C$
C	capacitance	F	farad	$= C/V$
I	current	A	ampere	$= C/s$
R	resistance	Ω	ohm	$= V/A$
P	electric power	W	watt	$= J/s$

KEY TERMS

electrical potential energy (p. 594)

electric potential (p. 596)

potential difference (p. 596)

capacitance (p. 602)

electric current (p. 608)

drift velocity (p. 611)

resistance (p. 612)

PROBLEM SOLVING

See **Appendix D: Equations** for a summary of the equations introduced in this chapter. If you need more problem-solving practice, see **Appendix I: Additional Problems.**

Diagram Symbols

Electric field	→ **E**
Current	→ I
Positive charge	+
Negative charge	−

CHAPTER 17 Review

ELECTRICAL POTENTIAL ENERGY AND POTENTIAL DIFFERENCE

Review Questions

1. Describe the motion and explain the energy conversions that are involved when a positive charge is placed in a uniform electric field. Be sure your discussion includes the following terms: *electrical potential energy, work,* and *kinetic energy.*

2. If a point charge is displaced perpendicular to a uniform electric field, which of the following expressions is likely to be equal to the change in electrical potential energy?

a. $-qEd$
b. 0
c. $-k_c\left(\frac{q^2}{r^2}\right)$

3. Differentiate between electrical potential energy and electric potential.

4. Differentiate between electric potential and potential difference.

5. At what location in relationship to a point charge is the electric potential considered by convention to be zero?

Conceptual Questions

6. If the electric field in some region is zero, must the electric potential in that same region also be zero? Explain your answer.

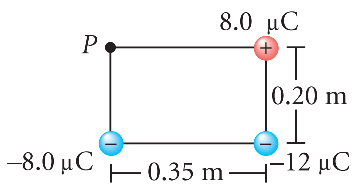
7. If a proton is released from rest in a uniform electric field, does the corresponding electric potential at the proton's changing locations increase or decrease? What about the electrical potential energy?

Practice Problems

For problems 8–9, see Sample Problem A.

8. The magnitude of a uniform electric field between two plates is about 1.7×10^6 N/C. If the distance between these plates is 1.5 cm, find the potential difference between the plates.

9. In the figure below, find the electric potential at point *P* due to the grouping of charges at the other corners of the rectangle.



CAPACITANCE

Review Questions

10. What happens to the charge on a parallel-plate capacitor if the potential difference doubles?

11. You want to increase the maximum potential difference of a parallel-plate capacitor. Describe how you can do this for a fixed plate separation.

12. Why is the Earth considered a "ground" in electric terms? Can any other object act as a ground?

Conceptual Questions

13. If the potential difference across a capacitor is doubled, by what factor is the electrical potential energy stored in the capacitor multiplied?

14. Two parallel plates are uncharged. Does the set of plates have a capacitance? Explain.

15. If you were asked to design a small capacitor with high capacitance, what factors would be important in your design?

16. A parallel-plate capacitor is charged and then disconnected from a battery. How much does the stored energy change when the plate separation is doubled?

17. Why is it dangerous to touch the terminals of a high-voltage capacitor even after the potential difference has been removed? What can be done to make the capacitor safe to handle?

Practice Problems

For problems 18–19, see Sample Problem B.

18. A 12.0 V battery is connected to a 6.0 pF parallel-plate capacitor. What is the charge on each plate?

19. Two devices with capacitances of 25 μF and 5.0 μF are each charged with separate 120 V power supplies. Calculate the total energy stored in the two capacitors.

ELECTRIC CURRENT

Review Questions

20. What is electric current? What is the SI unit for electric current?

21. In a metal conductor, current is the result of moving electrons. Can charge carriers ever be positive?

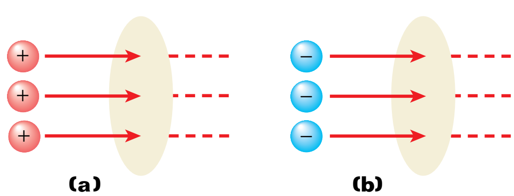
22. What is meant by the term *conventional current*?

23. What is the difference between the drift speed of an electron in a metal wire and the average speed of the electron between collisions with the atoms of the metal wire?

24. There is a current in a metal wire due to the motion of electrons. Sketch a possible path for the motion of a single electron in this wire, the direction of the electric field vector, and the direction of conventional current.

25. What is an electrolyte?

26. What is the direction of conventional current in each case shown below?



Conceptual Questions

27. In an analogy between traffic flow and electric current, what would correspond to the charge, *Q*? What would correspond to the current, *I*?

28. Is current ever "used up"? Explain your answer.

29. Why do wires usually warm up when an electric current is in them?

30. When a light bulb is connected to a battery, charges begin moving almost immediately, although each electron travels very slowly across the wire. Explain why the bulb lights up so quickly.

31. What is the net drift velocity of an electron in a wire that has alternating current in it?

Practice Problems

For problems 32–33, see Sample Problem C.

32. How long does it take a total charge of 10.0 C to pass through a cross-sectional area of a copper wire that carries a current of 5.0 A?

33. A hair dryer draws a current of 9.1 A.

a. How long does it take for 1.9×10^3 C of charge to pass through the hair dryer?

b. How many electrons does this amount of charge represent?

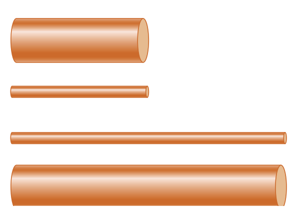
RESISTANCE

Review Questions

34 What factors affect the resistance of a conductor?

35. Each of the wires shown below is made of copper. Assuming each piece of wire is at the same temperature, which has the greatest resistance? Which has the least resistance?

(a)
(b)
(c)
(d)



36. Why are resistors used in circuit boards?

Conceptual Questions

37. For a constant resistance, how are potential difference and current related?

38. If the potential difference across a conductor is constant, how is current dependent on resistance?

39. Using the atomic theory of matter, explain why the resistance of a material should increase as its temperature increases.

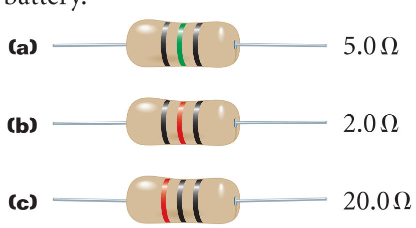
Practice Problems

For problems 40–42, see Sample Problem D.

40. A nichrome wire with a resistance of 15 Ω is connected across the terminals of a 3.0 V flashlight battery. How much current is in the wire?

41. How much current is drawn by a television with a resistance of 35 Ω that is connected across a potential difference of 120 V?

42. Calculate the current that each resistor shown below would draw when connected to a 9.0 V battery.



ELECTRIC POWER

Review Questions

43. Why must energy be continuously pumped into a circuit by a battery or a generator to maintain an electric current?

44. Name at least two differences between batteries and generators.

45. What is the difference between direct current and alternating current? Which type of current is supplied to the appliances in your home?

46. Compare and contrast mechanical power with electric power.

47. What quantity is measured in kilowatt-hours? What quantity is measured in kilowatts?

48. If electrical energy is transmitted over long distances, the resistance of the wires becomes significant. Why?

49. How many joules are in a kilowatt-hour?

Conceptual Questions

50. A student in your class claims that batteries work by supplying the charges that move in a conductor, generating a current. What is wrong with this reasoning?

51. A 60 W light bulb and a 75 W light bulb operate from 120 V. Which bulb has a greater current in it?

52. Two conductors of the same length and radius are connected across the same potential difference. One conductor has twice as much resistance as the other. Which conductor dissipates more power?

53. It is estimated that in the United States (population 250 million) there is one electric clock per person, with each clock using energy at a rate of 2.5 W. Using this estimate, how much energy is consumed by all of the electric clocks in the United States in a year?

54. When a small lamp is connected to a battery, the filament becomes hot enough to emit electromagnetic radiation in the form of visible light, while the wires do not. What does this tell you about their relative resistances of the filament and the wires?

Practice Problems

For problems 55–56, see Sample Problem E.

55. A computer is connected across a 110 V power supply. The computer dissipates 130 W of power in the form of electromagnetic radiation and heat. Calculate the resistance of the computer.

56. The operating potential difference of a light bulb is 120 V. The power rating of the bulb is 75 W. Find the current in the bulb and the bulb's resistance.

MIXED REVIEW

57. At some distance from a point charge, the electric potential is 600.0 V and the magnitude of the electric field is 200.0 N/C. Determine the distance from the charge and the charge.

58. A circular parallel-plate capacitor with a spacing of 3.0 mm is charged to produce a uniform electric field with a strength of 3.0×10^6 N/C. What plate radius is required if the stored charge is -1.0 μC?

59. A 12 V battery is connected across two parallel metal plates separated by 0.30 cm. Find the magnitude of the electric field.

60. A parallel-plate capacitor has an area of 5.00 cm^2, and the plates are separated by 1.00 mm. The capacitor stores a charge of 400.0 pC.

a. What is the potential difference across the plates of the capacitor?

b. What is the magnitude of the uniform electric field in the region that is located between the plates?

61. A proton is accelerated from rest through a potential difference of 25 700 V.

a. What is the kinetic energy of this proton in joules after this acceleration?

b. What is the speed of the proton after this acceleration?

62. A proton is accelerated from rest through a potential difference of 120 V. Calculate the final speed of this proton.

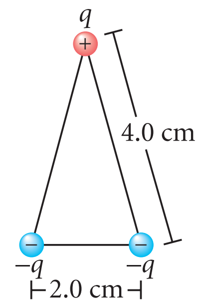
63. A pair of oppositely charged parallel plates are separated by 5.33 mm. A potential difference of 600.0 V exists between the plates.

a. What is the magnitude of the electric field strength in the region that is located between the plates?

b. What is the magnitude of the force on an electron that is in the region between the plates at a point that is exactly 2.90 mm from the positive plate?

c. The electron is moved to the negative plate from an initial position 2.90 mm from the positive plate. What is the change in electrical potential energy due to the movement of this electron?

64. The three charges shown at right are located at the vertices of an isosceles triangle. Calculate the electric potential at the midpoint of the base if each one of the charges at the corners has a magnitude of 5.0×10^{-9} C.



65. A charge of -3.00×10^{-9} C is at the origin of a coordinate system, and a charge of 8.00×10^{-9} C is on the x-axis at 2.00 m. At what two locations on the x-axis is the electric potential zero?
(Hint: One location is between the charges, and the other is to the left of the y-axis.)

66. An ion is displaced through a potential difference of 60.0 V and experiences an increase of electrical potential energy of 1.92×10^{-17} J. Calculate the charge on the ion.

67. A proton is accelerated through a potential difference of 4.5×10^6 V.

a. How much kinetic energy has the proton acquired?

b. If the proton started at rest, how fast is it moving?

68. Each plate on a 3750 pF capacitor carries a charge with a magnitude of 1.75×10^{-8} C.

a. What is the potential difference across the plates when the capacitor has been fully charged?

b. If the plates are 6.50×10^{-4} m apart, what is the magnitude of the electric field between the two plates?

69. A net charge of 45 mC passes through the cross-sectional area of a wire in 15 s.

a. What is the current in the wire?

b. How many electrons pass the cross-sectional area in 1.0 min?

70. The current in a lightning bolt is 2.0×10^5 A. How many coulombs of charge pass through a cross-sectional area of the lightning bolt in 0.50 s?

71. A person notices a mild shock if the current along a path through the thumb and index finger exceeds 80.0 μA. Determine the maximum allowable potential difference without shock across the thumb and index finger for the following:

a. a dry-skin resistance of $4.0 \times 10^5\ \Omega$

b. a wet-skin resistance of $2.0 \times 10^3\ \Omega$

72. A color television has a power rating of 325 W. How much current does this set draw from a potential difference of 120 V?

73. An X-ray tube used for cancer therapy operates at 4.0 MV with a beam current of 25 mA striking a metal target. Calculate the power of this beam.

74. The mass of a gold atom is 3.27×10^{-25} kg. If 1.25 kg of gold is deposited on the negative electrode of an electrolytic cell in a period of 2.78 h, what is the current in the cell in this period? Assume that each gold ion carries one elementary unit of positive charge.

75. The power supplied to a typical black-and-white television is 90.0 W when the set is connected across a potential difference of 120 V. How much electrical energy does this set consume in 1.0 h?

Graphing Calculator Practice

Resistance and Current

When you install a 100 W light bulb, what is the resistance of and current passing through this light bulb? The answer to this question and similar questions is found in two equations that you learned earlier in this chapter:

$$P = \frac{(\Delta V)^2}{R} \text{ and } P = I\Delta V$$

These equations describe the power dissipated by a resistor. In these equations, P is the power in watts, ΔV is the potential difference in volts, R is the resistance in ohms, and I is the current in amperes.

In this graphing calculator activity, you will calculate a series of tables of resistance and current versus potential difference for various values of dissipated power. By analyzing these tables, you will better understand the relationships between power, potential difference, resistance, and current. (You will also be able to answer the question about the 100 W light bulb.)

Visit go.hrw.com and type in the keyword **HF6ELCX** to find this graphing calculator activity. Refer to **Appendix B** for instructions on downloading the program for this activity.

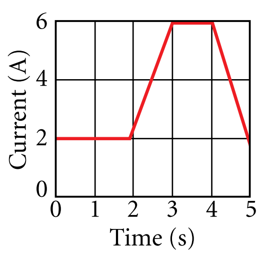
76. A color television set draws about 2.5 A of current when connected to a potential difference of 120 V. How much time is required for it to consume the same energy that the black-and-white model described in item 75 consumes in 1.0 h?

77. The headlights on a car are rated at 80.0 W. If they are connected to a fully charged 90.0 A•h, 12.0 V battery, how long does it take the battery to completely discharge?

78. The current in a conductor varies over time as shown in the graph below.

a. How many coulombs of charge pass through a cross section of the conductor in the time interval $t = 0$ to $t = 5.0$ s?

b. What constant current would transport the same total charge during the 5.0 s interval as does the actual current?



79. Birds resting on high-voltage power lines are a common sight. A certain copper power line carries a current of 50.0 A, and its resistance per unit length is 1.12×10^{-5} Ω/m. If a bird is standing on this line with its feet 4.0 cm apart, what is the potential difference across the bird's feet?

80. An electric car is designed to run on a bank of batteries with a total potential difference of 12 V and a total energy storage of 2.0×10^{7} J.

a. If the electric motor draws 8.0 kW, what is the current delivered to the motor?

b. If the electric motor draws 8.0 kW as the car moves at a steady speed of 20.0 m/s, how far will the car travel before it is "out of juice"?

Alternative Assessment

1. Imagine that you are assisting nuclear scientists who need to accelerate electrons between electrically charged plates. Design and sketch a piece of equipment that could accelerate electrons to 10^{7} m/s. What should the potential difference be between the plates? How would protons move inside this device? What would you change in order to accelerate the electrons to 100 m/s?

2. Tantalum is an element widely used in electrolytic capacitors. Research tantulum and its properties. Where on Earth is it found? In what form is it found? How expensive is it? Present your findings to the class in the form of a report, poster, or computer presentation.

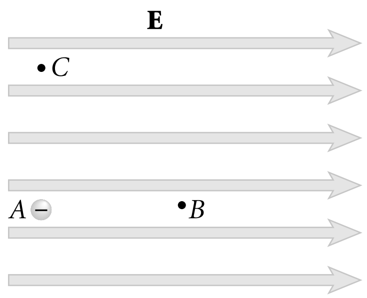
3. Visit an electric parts or electronic parts store or consult a print or on-line catalog to learn about different kinds of resistors. Find out what the different resistors look like, what they are made of, what their resistance is, how they are labeled, and what they are used for. Summarize your findings in a poster or a brochure entitled *A Consumer's Guide to Resistors.*

4. The units of measurement you learned about in this chapter were named after four famous scientists: Andre-Marie Ampere, Michael Faraday, Georg Simon Ohm, and Alessandro Volta. Research their lives, works, discoveries, and contributions. Create a presentation about one of these scientists. The presentation can be in the form of a report, poster, short video, or computer presentation.

Standardized Test Prep

MULTIPLE CHOICE

Use the diagram below to answer questions 1–2.



1. What changes would take place if the electron moved from point A to point B in the uniform electric field?
   A. The electron's electrical potential energy would increase; its electric potential would increase.
   B. The electron's electrical potential energy would increase; its electric potential would decrease.
   C. The electron's electrical potential energy would decrease; its electric potential would decrease.
   D. Neither the electron's electrical potential energy nor its electric potential would change.

2. What changes would take place if the electron moved from point A to point C in the uniform electric field?
   F. The electron's electrical potential energy would increase; its electric potential would increase.
   G. The electron's electrical potential energy would increase; its electric potential would decrease.
   H. The electron's electrical potential energy would decrease; its electric potential would decrease.
   J. Neither the electron's electrical potential energy nor its electric potential would change.

Use the following passage to answer questions 3–4.

A proton ($q = 1.6 \times 10^{-19}$ C) moves 2.0×10^{-6} m in the direction of an electric field that has a magnitude of 2.0 N/C.

3. What is the change in the electrical potential energy associated with the proton?
   A. -6.4×10^{-25} J
   B. -4.0×10^{-6} V
   C. $+6.4 \times 10^{-25}$ J
   D. $+4.0 \times 10^{-6}$ V

4. What is the potential difference between the proton's starting point and ending point?
   F. -6.4×10^{-25} J
   G. -4.0×10^{-6} V
   H. $+6.4 \times 10^{-25}$ J
   J. $+4.0 \times 10^{-6}$ V

5. If the negative terminal of a 12 V battery is grounded, what is the potential of the positive terminal?
   A. -12 V
   B. $+0$ V
   C. $+6$ V
   D. $+12$ V

6. If the area of the plates of a parallel-plate capacitor is doubled while the spacing between the plates is halved, how is the capacitance affected?
   F. C is doubled
   G. C is increased by four times
   H. C is decreased by 1/4
   J. C does not change

Use the following passage to answer questions 7–8.

A potential difference of 10.0 V exists across the plates of a capacitor when the charge on each plate is 40.0 µC.

7. What is the capacitance of the capacitor?
   A. 2.00×10^{-4} F
   B. 4.00×10^{-4} F
   C. 2.00×10^{-6} F
   D. 4.00×10^{-6} F

8. How much electrical potential energy is stored in the capacitor?
   F. 2.00×10^{-4} J
   G. 4.00×10^{-4} J
   H. 2.00×10^{-6} J
   J. 4.00×10^{-6} J

9. How long does it take 5.0 C of charge to pass through a given cross section of a copper wire if $I = 5.0$ A?
   A. 0.20 s
   B. 1.0 s
   C. 5.0 s
   D. 25 s

10. A potential difference of 12 V produces a current of 0.40 A in a piece of copper wire. What is the resistance of the wire?
    F. 4.8 Ω
    G. 12 Ω
    H. 30 Ω
    J. 36 Ω

11. How many joules of energy are dissipated by a 50.0 W light bulb in 2.00 s?
    A. 25.0 J
    B. 50.0 J
    C. 100 J
    D. 200 J

12. How much power is needed to operate a radio that draws 7.0 A of current when a potential difference of 115 V is applied across it?
    F. 6.1×10^{-2} W
    G. 2.3×10^{0} W
    H. 1.6×10^{1} W
    J. 8.0×10^{2} W

SHORT RESPONSE

13. Electrons are moving from left to right in a wire. No other charged particles are moving in the wire. In what direction is the conventional current?

14. What is drift velocity, and how does it compare with the speed at which an electric field travels through a wire?

15. List four factors that can affect the resistance of a wire.

EXTENDED RESPONSE

16. A parallel-plate capacitor is made of two circular plates, each of which has a diameter of 2.50×10^{-3} m. The plates of the capacitor are separated by a space of 1.40×10^{-4} m.
    a. Assuming that the capacitor is operating in a vacuum and that the permittivity of a vacuum ($\varepsilon_0 = 8.85 \times 10^{-12}$ $C^2/N \bullet m^2$) can be used, determine the capacitance of the capacitor.
    b. How much charge will be stored on each plate of the capacitor when the capacitor's plates are connected across a potential difference of 0.12 V?
    c. What is the electrical potential energy stored in the capacitor when fully charged by the potential difference of 0.12 V?
    d. What is the potential difference between a point midway between the plates and a point that is 1.10×10^{-4} m from one of the plates?
    e. If the potential difference of 0.12 V is removed from the circuit and the circuit is allowed to discharge until the charge on the plates has decreased to 70.7 percent of its fully charged value, what will the potential difference across the capacitor be?

Test TIP If at any point while taking a test you do not clearly understand the directions or the wording of a question, raise your hand and ask for help.

CHAPTER 17

Skills Practice Lab

Current and Resistance

OBJECTIVES

- **Determine** the resistance of conductors, using the definition of resistance.
- **Explore** the relationships between length, diameter, material, and the resistance of a conductor.

MATERIALS LIST

- 2 multimeters or 1 dc ammeter and 1 voltmeter
- insulated connecting wire
- momentary contact switch
- mounted resistance coils
- power supply

In this experiment, you will study the effects of length, cross-sectional area, and material on the resistance of conductors. You will use a set of mounted resistance coils, which will provide wire coils of different lengths, diameters, and metals. You will measure the potential difference across the resistance coil, and you will find the current in the conductor. Then you will use these values to calculate the resistance of each resistance coil using the definition of resistance.

SAFETY

- **Never close a circuit until it has been approved by your teacher. Never rewire or adjust any element of a closed circuit. Never work with electricity near water; be sure the floor and all work surfaces are dry.**
- **If the pointer on any kind of meter moves off scale, open the circuit immediately by opening the switch.**
- **Do not attempt this exercise with any batteries or electrical devices other than those provided by your teacher for this purpose.**
- **Use a hot mitt to handle resistors, light sources, and other equipment that may be hot. Allow all equipment to cool before storing it.**

PROCEDURE

Preparation

1. Read the entire lab, and plan what steps you will take.
2. If you are not using a datasheet provided by your teacher, prepare a data table in your lab notebook with seven columns and six rows. Label the first through seventh columns *Trial, Metal, Gauge Number, Length (cm), Cross-sectional Area* (cm^2), ΔV_x *(V)*, and *I (A)*. In the first column, label the second through sixth rows *1, 2, 3, 4,* and *5*.

Current at Varied Resistances

3. Set up the apparatus as shown in **Figure 1.** Construct a circuit that includes a power supply, a switch, a current meter, a voltmeter, and the mounted resistance coils. ***Do not turn on the power supply. Do not close the switch until your teacher has approved your circuit.***

4. With the switch open, connect the current meter in a straight line in series with the mounted resistance coils. Make sure the black lead on the meter is connected to the black pin on the power supply. Connect the black lead on the voltmeter to the side of the first resistance coil that is connected to the black pin on the power supply, and connect the red lead to the other side of the coil in parallel. ***Do not close the switch until your teacher approves your circuit.***

5. When your teacher has approved your circuit, make sure the power supply dial is turned completely counterclockwise. Turn on the power supply, and slowly turn the dial clockwise. Periodically close the switch briefly and read the current value on the current meter. Adjust the dial until the current is approximately 0.15 A.

6. Close the switch. Quickly record the current in and the potential difference across the resistance coil in your data table. Open the switch immediately. Turn off the power supply by turning the dial completely counterclockwise. Your teacher will tell you the length and cross-sectional area of the wire on the coil. Record these values in your data table.

7. Repeat steps 3–6 with different coils until five coils have been studied.

8. Clean up your work area. Put equipment away safely.

ANALYSIS

1. **Organizing Data** Use the measurements for current and potential difference to calculate the resistance, R_C, for each resistance coil you tested. Use the definition of resistance, $R = \frac{\Delta V}{I}$.

CONCLUSIONS

2. **Drawing Conclusions** Rate the coils from lowest to highest resistance. Record your ratings.

   a. According to your results for this experiment, how does the length of the wire affect the resistance of the coil?

   b. According to your results for this experiment, how does the cross-sectional area affect the resistance of the coil?

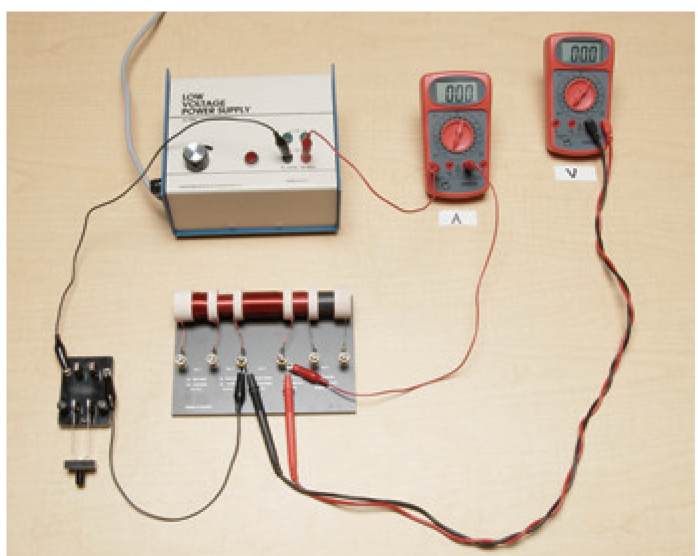
3. **Drawing Conclusions** Based on your results for the metals used in this experiment, which metal has the greatest resistance? Which metal has the least resistance? Explain how you arrived at these conclusions.

Figure 1

Step 3: The set of mounted resistance coils shown includes five different resistance coils. In this lab, you will measure the current and potential difference for each coil in turn.

Step 4: Use your finger to trace the circuit from the black pin on the power supply through the circuit to the red pin on the power supply to check for proper connections.

Step 6: Close the switch only long enough to take readings. Open the switch as soon as you have taken the readings.



Hybrid Electric Vehicles

At the start of the 20th century, electric-powered vehicles and gasoline-powered vehicles were competing for dominance in the emerging automobile industry. Electric cars were considered more reliable, and certainly quieter and less polluting, than gasoline-powered cars. However, they could go only a few miles before they needed recharging, so they were only suitable for use over short distances. A few inventors developed hybrid cars that used both electricity and gasoline engines for power, but these never caught on. As more roads were paved and as more people wanted to travel farther, electric cars were abandoned in favor of cars that burned gasoline in *internal combustion engines* (ICEs).

Problems in the Gasoline Era

As the 20th century progressed, industry spread and the number of cars on the road increased. The air in North America became more polluted, and people searched for ways to reduce the pollution and its harmful effects on human health. ICEs emit nitrogen oxides, carbon monoxide, and unburned hydrocarbons—all of which, along with ozone, make up a major part of urban air pollution. In addition, ICEs give off large quantities of carbon dioxide, which contributes to Earth's greenhouse effect and increases the threat of global warming.

In recent decades, federal and state laws have required industries and businesses—from steelmakers to dry cleaners—to limit polluting emissions. Regulations and incentives have also been put in place to increase the fuel-efficiency and reduce the emissions of passenger cars. Although overall air quality has improved as a result of these efforts, air pollution still remains a serious problem, largely due to emissions from vehicles with ICEs.

In the 1970s, a global energy crisis emerged as several oil-exporting countries cut off their oil exports for political and economic reasons. Oil and gas prices rose dramatically, and many people suddenly had no access to gasoline or could no longer afford it. Although the crisis subsided, worldwide economic and political instability, and a growing awareness that global oil supplies are finite, has kept oil and gas prices uncertain ever since. Now in the early 21st century, the United States imports more than half of the oil it uses. As a result, access to oil resources plays a key role in U.S. foreign policy.

A Return to Electric Cars?

As the problems with air pollution and rising oil prices have become more apparent, people have started to reexamine alternatives to gasoline-powered ICEs. In the 1990s, several *electric vehicles* (EVs), which run solely on electricity, were developed for passenger use. While the performance of these EVs was comparable to gasoline-powered cars, they typically had driving ranges of only 80–240 km (50–150 miles), and were more expensive than gasoline-powered models.

In the mid to late 1990's, several automakers started research and development of *hybrid electric vehicles*

(HEVs), which use electricity in combination with a gasoline engine. HEVs have been more commercially successful than pure EVs. Today, several HEV models are available to consumers, and more are appearing on the road every day.

Advantages of Hybrid Electric Vehicles

All HEVs combine the power of a battery-driven electric motor with the power of an ICE. However, different models do this in different ways. In a *series design,* the electric motor powers the car directly, while the ICE serves only to power a generator that recharges the battery for the electric motor. With this design, the ICE is used very efficiently because it is always actively recharging the battery. However, series-design HEVs have less power-on-demand for acceleration.

In a *parallel design,* both the electric motor and the ICE attach directly to the drive train to power the wheels. With this design, the electric motor provides the primary power when driving in stop-and-go traffic, while the ICE kicks in at higher speeds, when the ICE is more efficient. Unlike conventional gasoline-powered vehicles, parallel-design HEVs get better gas mileage and produce fewer emissions in town than they do on the highway.

Both series and parallel HEVs have longer driving ranges than their pure EV counterparts. Some HEVs can go as much as 700 miles before they need refueling. Furthermore, because the ICE charges the battery, an HEV never needs to be plugged in. In addition to maximizing the efficiency of the electric motor and the engine, many HEVs also have *regenerative braking* systems that recapture some of the power lost during braking and use it to recharge the battery. The result is a more efficient car that produces fewer emissions and gets better gas mileage than a comparable car powered solely by gasoline. HEVs are still more expensive than conventional gasoline-powered cars, but the cost savings over time due to increased fuel economy is usually enough to compensate for the greater initial price.

HEVs are a step toward solving the problems with air pollution and the politics of oil. As research continues, HEVs will likely become even more efficient. New technologies, such as hydrogen fuel cells, may replace the ICE component in HEVs, resulting in an even better car for the future.

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For a variety of links related to this chapter, go to www.scilinks.org

Topic: Electric Vehicles
SciLinks Code: HF60474

Researching the Issue

1. Go to a local car dealer and ask about hybrid electric vehicles. Do they have any HEV models available? Are they going to offer any new HEV models in the future? Do these models use a series design, a parallel design, or another type of design?

2. Unlike pure electric vehicles, HEVs still burn gasoline in combustion engines. Do you think the increase in fuel economy and the reduced emissions of HEVs go far enough to address the problems at hand? What alternative or additional solutions can you recommend?

3. The federal government and some states offer tax deductions and other incentives for people who own HEVs or other alternative-fuel vehicles. Hold a discussion or debate on the question, "Should the government spend taxpayers' money to subsidize the purchase of alternative-fuel vehicles that people might otherwise not buy?"

4. Research hydrogen fuel cell technology. How do fuel cells work? Do they produce any harmful emissions? In what form is the hydrogen stored? What are some possible sources of hydrogen fuel? What problems must be solved before hydrogen fuel cells are ready for widespread use?