33 ELECTRIC FIELDS AND POTENTIAL

Objectives

- Describe how to measure the strength of an electric field at different points. (33.1)
- Describe how electric fields are represented by vectors and by electric field lines. (33.2)
- Describe how objects can be completely shielded from electric fields. (33.3)
- Explain why a charged object in an electric field is considered to have electrical potential energy. (33.4)
- Distinguish between electrical potential energy and electric potential. (33.5)
- Describe how electrical energy can be stored. (33.6)
- Describe the operation of a Van de Graaff generator. (33.7)

discover!

MATERIALS cell phone, aluminum foil

EXPECTED OUTCOME Students will find that they have to encase most, if not all, of the cell phone in foil in order to block an incoming call.

ANALYZE AND CONCLUDE

1. See Expected Outcome.
2. Answers may include metal containers or wire mesh.
3. Electric shielding involves blocking an object from outside electrical activity. Electric shielding works because when the charge on a conductor is not moving, the electric field inside the conductor is zero.

33 ELECTRIC FIELDS AND POTENTIAL

THE BIG IDEA *An electric field is a storehouse of energy.*

The space around a strong magnet is different from how it would be if the magnet were not there. Put a paper clip in the space and you'll see the paper clip move. The space around the sun is different from how it would be if the sun were not there. The sun's gravitational influence affects the motions of the planets around it. Similarly, the space around a concentration of electric charge is different from how it would be if the charge were not there. If you walk by the charged dome of an electrostatic machine—a Van de Graaff generator, for example—you can sense the charge. Hair on your body stands out—just a tiny bit if you're more than a meter away, and more if you're closer. The space that surrounds each of these things—the magnet, the sun, and the electric charge—is altered. The space is said to contain a *force field*.

discover!

What Is Electric Shielding?

1. Wrap a cellular phone completely in aluminum foil.
2. Make a call to the wrapped phone.
3. Unwrap the cell phone, and now cover only part of it with foil. Make a call to the partly wrapped cell phone.
4. Repeat Step 3 a few more times, covering different parts of the phone.

Analyze and Conclude

1. **Observing** What effect did completely wrapping the phone have on reception? Did wrapping only part of the phone block the incoming signal? If so, which part of the phone needed to be covered in order to block the signal?
2. **Predicting** What other materials do you think could be used to shield a cellular phone?
3. **Making Generalizations** What is electric shielding, and why does it work?

33.1 Electric Fields

The force field that surrounds a mass is a gravitational field. If you throw a ball into the air, it follows a curved path. Earlier chapters showed that it curves because there is an interaction between the ball and Earth—between their centers of gravity, to be exact. Their centers of gravity are quite far apart, so this is "action at a distance."

The idea that things not in contact could exert forces on one another bothered Isaac Newton and many others. The concept of a force field explains how Earth can exert a force on things without touching them, like a tossed ball. The ball is in contact with the field all the time. The ball curves because it interacts with Earth's gravitational field. You can think of distant space probes as interacting with gravitational fields rather than with the masses of Earth and other astronomical bodies that are responsible for the fields.

Just as the space around Earth and every other mass is filled with a gravitational field, the space around every electric charge is filled with an electric field. An **electric field** is a force field that surrounds an electric charge or group of charges. In Figure 33.2, a gravitational force holds a satellite in orbit about a planet, and an electrical force holds an electron in orbit about a proton. In both cases there is no contact between the objects, and the forces are "acting at a distance." In terms of the field concept, the satellite and electron interact with the force fields of the planet and the proton and are everywhere in contact with these fields. Just as in the gravitational case, the force that one electric charge exerts on another can be described as the interaction between one charge and the electric field set up by the other.

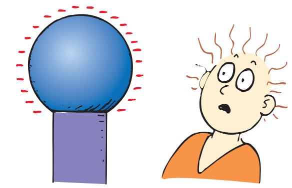
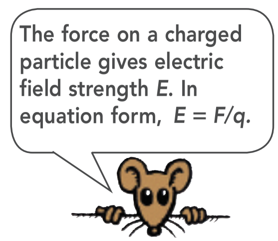
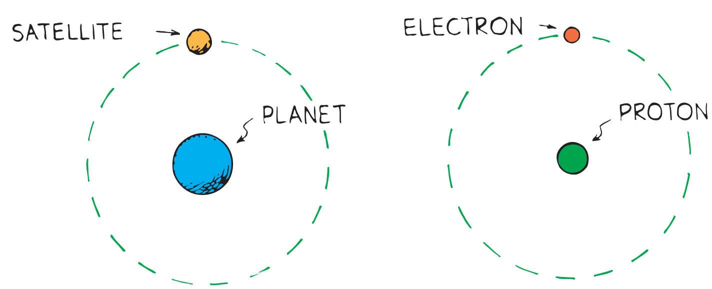


FIGURE 33.1 ▲
You can sense the force field that surrounds a charged Van de Graaff generator.





◀ **FIGURE 33.2**
The satellite and the electron both experience forces; they are both in force fields.

An electric field has both magnitude and direction. **The magnitude (strength) of an electric field can be measured by its effect on charges located in the field.** Imagine a small positive "test charge" that is placed in an electric field. Where the force is greatest on the test charge, the field is strongest. Where the force on the test charge is weak, the field is small.[33.1]

33.1 Electric Fields

Key Term
electric field

▶ **Teaching Tip** Introduce electric fields by mentioning (or showing) a Van de Graaff generator. Describe the altered space around it when it is charged. This space is an electric field.

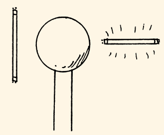
▶ **Teaching Tip** Compare gravitational and electric fields. Both are regions that are altered, by mass for the gravitational field, and by charge for the electric field.

▶ **Teaching Tip** The easiest fields for students to visualize are magnetic fields because of the familiar iron filing patterns (Figures 36.4 and 36.5.) Explain that fields are called "force fields" because forces are exerted on bodies in their vicinity, but a better term would be "energy field" because energy is stored in a field. In the case of an electric field, any charges in the vicinity are energized. We speak about the PE that electrically charged bodies have in a field—or more often, the PE compared to the amount of charge—electric potential. Explain that the field energy, and correspondingly the electric potential, is greater nearer the charged dome and weaker with increased distance, thus following the inverse-square law.

▶ **Teaching Tip** Point out that measuring instruments sometimes alter that which is being measured. A cold thermometer placed in a warm liquid absorbs heat from the liquid, thereby altering the temperature of the liquid. Similarly, placing a test charge in an electric field changes the nature of the field. The test charges used to measure electric fields are small so as to minimize such changes.

Demonstration

Hold a fluorescent lamp tube in the field of a charged Van de Graaff generator to show that it lights up when one end of the tube is closer to the dome than the other end.



The electric field is stronger near the dome, and weaker farther away. Charges nearer the dome experience more force, which means more work is done when they are moved in the stronger parts of the field. Thus, each charge in the stronger field has more energy. The energy per charge is what we call potential. Show that when the two ends of the fluorescent tube are equidistant from the charged dome, light emission ceases.

CONCEPT CHECK The magnitude of an electric field can be measured by its effect on charges located in the field. The direction of the field at any point is the direction of the electrical force on a *positive* test charge placed at that point.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

The direction of an electric field at any point, by convention, is the direction of the electrical force on a small *positive* test charge placed at that point. Thus, if the charge that sets up the field is positive, the field points away from that charge. If the charge that sets up the field is negative, the field points toward that charge. (Be sure to distinguish between the hypothetical small test charge and the charge that sets up the field.)

CONCEPT CHECK How are the magnitude and direction of an electric field determined?

33.2 Electric Field Lines

Since an electric field has both magnitude and direction, it is a *vector quantity* and can be represented by vectors. The negatively charged particle in Figure 33.3a is surrounded by vectors that point toward the particle. (If the particle were positively charged, the vectors would point away from the particle. The vectors always point in the direction of the force that would act on a positive test charge.) The magnitude of the field is indicated by the length of the vectors. The electric field is greater where the vectors are long than it is where the vectors are short. To represent a complete electric field by vectors, you would have to show a vector at every point in the space around the charge. Such a diagram would be totally unreadable!

A more useful way to describe an electric field is shown in Figure 33.3b. **You can use electric field lines (also called lines of force) to represent an electric field. Where the lines are farther apart, the field is weaker.** For an isolated charge, the lines extend to infinity, while for two or more opposite charges, the lines emanate from a positive charge and terminate on a negative charge. Some electric field configurations are shown in Figure 33.4.

The photographs in Figure 33.5 show bits of thread that are suspended in an oil bath surrounding charged conductors. The ends of the bits of thread line up end-to-end with the electric field lines. In Figures 33.5a and 33.5b, we see the field lines are characteristic of a single pair of point charges.

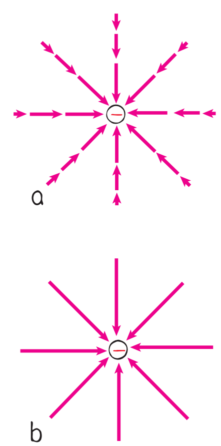


FIGURE 33.3
a. In a vector representation of an electric field, the length of the vectors indicates the magnitude of the field. **b.** In a lines-of-force representation, the distance between field lines indicates magnitudes.

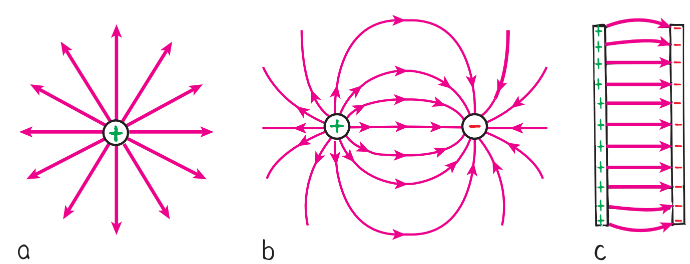
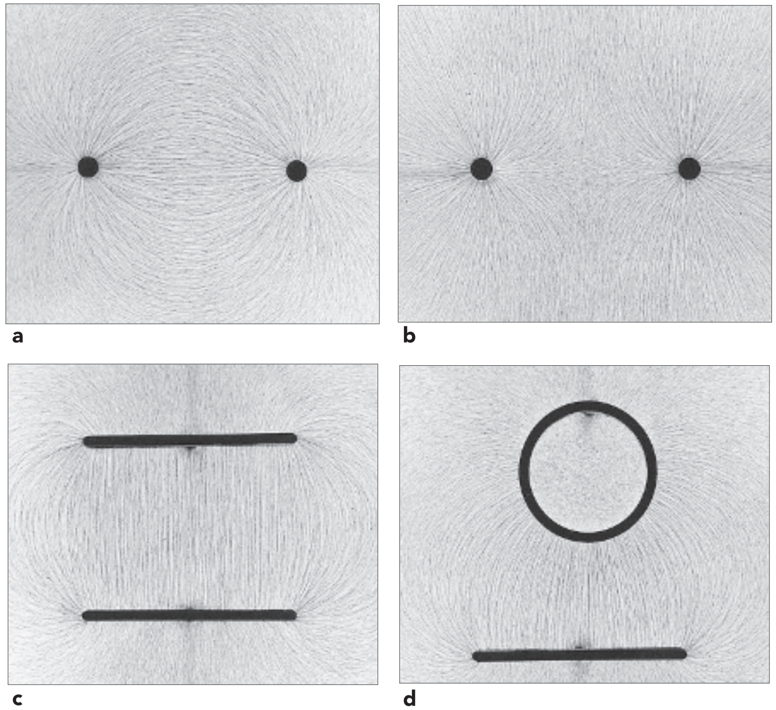


FIGURE 33.4
a. The field lines around a single positive charge extend to infinity. **b.** For a pair of equal but opposite charges, the field lines emanate from the positive charge and terminate on the negative charge. **c.** Field lines are evenly spaced between two oppositely charged capacitor plates.

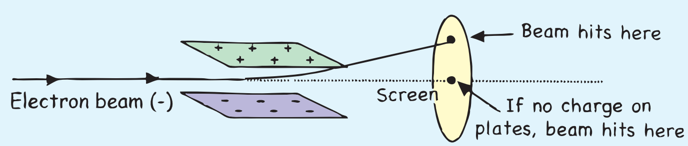


◀ **FIGURE 33.5**
Bits of fine thread suspended in an oil bath surrounding charged conductors line up end to end along the direction of the field. The photos illustrate field patterns for **a.** equal and opposite charges; **b.** equal like charges; **c.** oppositely charged plates; and **d.** oppositely charged cylinder and plate.

The oppositely charged parallel plates in Figure 33.5c produce nearly parallel field lines between the plates. Except near the ends, the field between the plates has a constant strength. Notice that in Figure 33.5d, there is no electric field inside the charged cylinder. The conductor shields the space from the field outside.

CONCEPT CHECK **How can you represent an electric field?**

think!



A beam of electrons is produced at one end of a glass tube and lights up a phosphor screen at the other end. When the beam is straight, it produces a spot in the middle of the screen. If the beam passes through the electric field of a pair of oppositely charged plates, it is deflected upward as shown. If the charges on the plates are reversed, in what direction will the beam deflect?
Answer: 33.2

33.2 Electric Field Lines

▶ **Teaching Tip** Describe the vector nature of a force field and describe the lines of force as shown in Figure 33.5.

Ask **If a tiny test charge were dropped in the oil bath shown in Figure 33.5, in what direction would it move?** *Along the same directions as the bits of thread—away from the conductor of same sign of charge and toward the conductor of opposite sign of charge.*

▶ **Teaching Tidbit** Sharks and related species of fish are equipped with specialized receptors in their snouts that sense extremely weak electric fields generated by other creatures in seawater.

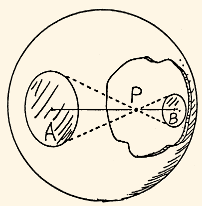
CONCEPT CHECK You can use electric field lines (also called lines of force) to represent an electric field. Where the lines are farther apart, the field is weaker.

Teaching Resources
- **Reading and Study Workbook**
- **Concept-Development Practice Book** *33-1*
- **Problem-Solving Exercises in Physics** *16-2*
- **Transparencies** *78, 79*
- **Presentation*EXPRESS***
- **Interactive Textbook**

33.3 Electric Shielding

▶ **Teaching Tip** Call attention to Figure 33.5d showing that the threads have no directional properties inside the charged cylinder. This shows that the electric field is shielded by the metal. The dramatic photo of the car being struck by lightning (Figure 33.6) also illustrates that the electric field inside a conductor is normally zero, regardless of what is happening outside.

▶ **Teaching Tip** After discussing Figure 33.7, go a step further and consider the test charge off center, twice as far from region A as region B, as shown.



The dotted lines represent a sample cone of action, subtending both A and B. Region A has twice the diameter, four times the area, and four times the charge of region B. Four times the charge at twice the distance will have one fourth the effect. The greater charge is balanced by the correspondingly greater distance. This will be the case for all points inside the conductor. And the conductor need not be a sphere, as shown by the shapes in Figure 33.8.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

FIGURE 33.6 ▲
Electrons from the lightning bolt mutually repel and spread over the outer metal surface. The overall electric field inside the car practically cancels to zero.

33.3 Electric Shielding

The dramatic photo in Figure 33.6 shows a car being struck by lightning. Yet, the occupant inside the car is completely safe. This is because the electrons that shower down upon the car are mutually repelled and spread over the outer metal surface, finally discharging when additional sparks jump from the car's body to the ground. The configuration of electrons on the car's surface at any moment is such that the electric fields inside the car practically cancel to zero. This is true of any charged conductor. ✓ **If the charge on a conductor is not moving, the electric field inside the conductor is exactly zero.**

Charged Conductors The absence of electric field within a conductor holding static charge does not arise from the inability of an electric field to penetrate metals. It comes about because free electrons within the conductor can "settle down" and stop moving only when the electric field is zero. So the charges arrange themselves to ensure a zero field with the material.

Consider the charged metal sphere shown in Figure 33.7. Because of mutual repulsion, the electrons spread as far apart from one another as possible. They distribute themselves uniformly over the surface of the sphere. A positive test charge located exactly in the middle of the sphere would feel no force. The electrons on the left side of the sphere would tend to pull the test charge to the left, but the electrons on the right side of the sphere would tend to pull the test charge to the right equally hard. The net force on the test charge would be zero. Thus, the electric field is also zero. Interestingly enough, complete cancellation will occur *anywhere* inside the sphere.

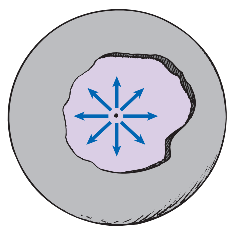
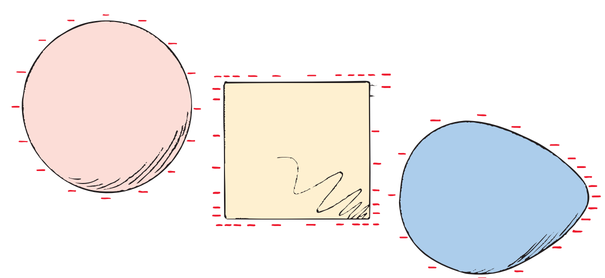


FIGURE 33.7 ▲
The forces on a test charge located inside a charged hollow sphere cancel to zero.

If the conductor is not spherical, then the charge distribution will not be uniform. The remarkable thing is this: The exact charge distribution over the surface is such that the electric field everywhere inside the conductor is zero. Look at it this way: If there were an electric field inside a conductor, then free electrons inside the conductor would be set in motion. How far would they move? Until equilibrium is established, which is to say, when the positions of all the electrons produce a zero field inside the conductor.

FIGURE 33.8 ▶
Static charges are distributed on the surface of all conductors in such a way that the electric field inside the conductors is zero.



How to Shield an Electric Field There is no way to shield gravity, because gravity only attracts. There are no repelling parts of gravity to offset attracting parts. Shielding electric fields, however, is quite simple. Surround yourself or whatever you wish to shield with a conducting surface. Put this surface in an electric field of whatever field strength. The free charges in the conducting surface will arrange themselves on the surface of the conductor in a way such that all field contributions inside cancel one another. That's why certain electronic components are encased in metal boxes, and why certain cables have a metal covering—to shield them from all outside electrical activity.

CONCEPT CHECK **How can you describe the electric field within a conductor holding static charge?**

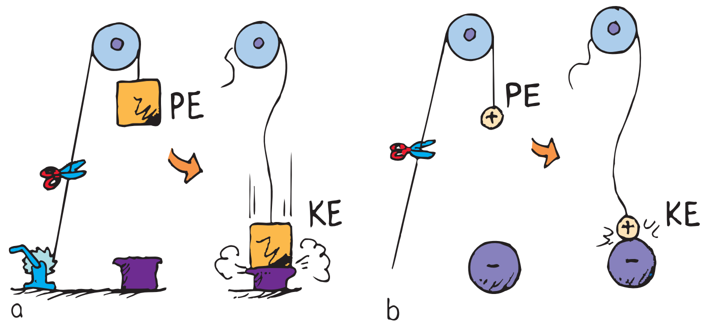
FIGURE 33.9 ▲
The metal-lined cover shields the internal electrical components from external electric fields. Similarly, a metal cover shields the coaxial cable.

think!

It is said that a gravitational field, unlike an electric field, cannot be shielded. But the gravitational field at the center of Earth cancels to zero. Isn't this evidence that a gravitational field *can* be shielded?
Answer: 33.3

33.4 Electrical Potential Energy

Recall the relationship between work and potential energy. Work is done when a force moves something in the direction of the force. An object has potential energy by virtue of its location, say in a force field. For example, if you lift an object, you apply a force equal to its weight. When you raise it through some distance, you are doing work on the object. You are also increasing its gravitational potential energy. The greater the distance it is raised, the greater is the increase in its gravitational potential energy. Doing work increases its gravitational potential energy, as shown in Figure 33.10a.



◀ FIGURE 33.10
a. Work is done to lift the mass against the gravitational field of Earth. In an elevated position, the mass has gravitational potential energy. When released, this energy is transferred to the piling below.
b. Similar energy transfer occurs for electric charges.

▶ **Teaching Tip** Another point to consider: If the field inside a conductor were not zero, then free charges inside would move, but the movement would not continue forever. The charges would finally move to positions of equilibrium. In these positions their effects on one another would be mutually balanced. There would be complete cancellation of fields everywhere inside the conductor. This is what happens—not gradually, but suddenly.

▶ **Teaching Tip** Revisit the Discover! activity at the beginning of the chapter, but with a twist: Use a small portable radio instead of a cell phone, and a metal screen enclosure instead of aluminum foil. Using a metal screen or meshwork demonstrates that shielding still may occur even with small gaps in the conductor. The foil and screen are examples of *Faraday cages.* Named after physicist Michael Faraday, a Faraday cage is an enclosure or mesh made from conducting material.

CONCEPT CHECK If the charge on a conductor is not moving, the electric field inside the conductor is exactly zero.

33.4 Electrical Potential Energy

Key Term
electrical potential energy

▶ **Teaching Tip** Briefly review the relationship between work and potential energy (Chapter 9). Explain that, just as doing work on an object increases the object's gravitational potential energy, the work required to push a charged particle against the electric field of a charged object increases the particle's electrical potential energy.

CONCEPT CHECK The electrical potential energy of a charged particle is increased when work is done to push it against the electric field of something else that is charged.

33.5 Electric Potential

Key Terms
electric potential, volt, voltage

Common Misconceptions
Electrical potential energy and electric potential are the same.

FACT Electric potential is electrical potential energy per charge.

The voltage produced by rubbing a balloon on one's hair is low compared to the voltage of electric circuits in the household.

FACT The voltage resulting from rubbing a balloon on hair could be several thousand volts.

Teaching Tip Use a Van de Graaff generator to illustrate the difference between electrical potential energy and electric potential. Although the generator is normally charged to thousands of volts, the amount of charge is relatively small, so the electrical potential energy is relatively small. A person is not normally harmed when the charge discharges through his or her body because very little energy flows through the person. In contrast, it would be unadvisable to intentionally become the short-circuit for the household 110 V because, although the voltage is much lower, the transfer of energy is appreciable. Less energy per charge, but many many more charges!

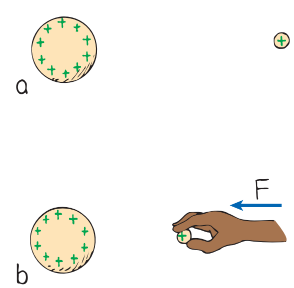
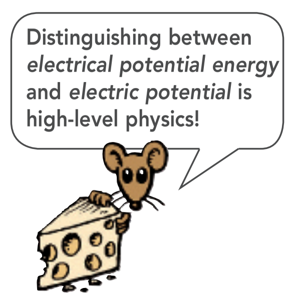


FIGURE 33.11 The small positive charge has more potential energy when it is closer to the positively charged sphere because work is required to move it to the closer location.



In a similar way, a charged object can have potential energy by virtue of its location in an electric field. Just as work is required to lift an object against the gravitational field of Earth, work is required to push a charged particle against the electric field of a charged body. (It may be more difficult to visualize, but the physics of both the gravitational case and the electrical case is the same.) **The electrical potential energy of a charged particle is increased when work is done to push it against the electric field of something else that is charged.**

Figure 33.11a shows a small positive charge located at some distance from a positively charged sphere. If we push the small charge closer to the sphere (Figure 33.11b), we will expend energy to overcome electrical repulsion. Just as work is done in compressing a spring, work is done in pushing the charge against the electric field of the sphere. This work is equal to the energy gained by the charge. The energy a charge has due to its location in an electric field is called **electrical potential energy.** If the charge is released, it will accelerate in a direction away from the sphere, and its electrical potential energy will transform into kinetic energy.

CONCEPT CHECK **How can you increase the electrical potential energy of a charged particle?**

33.5 Electric Potential

If in the preceding discussion we push two charges instead, we do twice as much work. The two charges in the same location will have twice the electrical potential energy as one; a group of ten charges will have ten times the potential energy; and so on.

Rather than deal with the total potential energy of a group of charges, it is convenient when working with electricity to consider the *electrical potential energy per charge.* The electrical potential energy per charge is the total electrical potential energy divided by the amount of charge. At any location the potential energy *per charge*—whatever the amount of charge—will be the same. For example, an object with ten units of charge at a specific location has ten times as much potential energy as an object with a single unit of charge. But it also has ten times as much charge, so the potential energy per charge is the same. The concept of electrical potential energy per charge has a special name, **electric potential.**

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

Electric potential is *not* the same as electrical potential energy. Electric potential is electrical potential energy per charge.

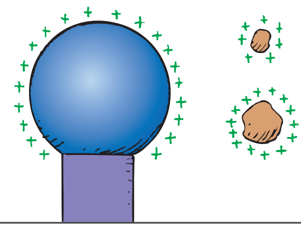


FIGURE 33.12
An object of greater charge has more electrical potential energy in the field of the charged dome than an object of less charge, but the *electric potential* of any amount of charge at the same location is the same.

The SI unit of measurement for electric potential is the **volt,** named after the Italian physicist Allesandro Volta (1745–1827). The symbol for volt is V. Since potential energy is measured in joules and charge is measured in coulombs,

$$1 \text{ volt} = 1 \frac{\text{joule}}{\text{coulomb}}$$

Thus, a potential of 1 volt equals 1 joule of energy per coulomb of charge; 1000 volts equals 1000 joules of energy per coulomb of charge. If a conductor has a potential of 1000 volts, it would take 1000 joules of energy per coulomb to bring a small charge from very far away and add it to the charge on the conductor.[33.5] (Since the small charge would be much less than one coulomb, the energy required would be much less than 1000 joules. For example, to add the charge of one proton to the conductor, 1.6×10^{-19} C, it would take only 1.6×10^{-16} J of energy.)

Since electric potential is measured in volts, it is commonly called **voltage.** In this book the names will be used interchangeably. The significance of voltage is that once the location of zero voltage has been specified, a definite value for it can be assigned to a location whether or not a charge exists at that location. We can speak about the voltages at different locations in an electric field whether or not any charges occupy those locations.

Rub a balloon on your hair and the balloon becomes negatively charged, perhaps to several thousand volts! If the charge on the balloon were one coulomb, it would take several thousand joules of energy to give the balloon that voltage. However, one coulomb is a very large amount of charge; the charge on a balloon rubbed on hair is typically much less than a millionth of a coulomb. Therefore, the amount of energy associated with the charged balloon is very, very small—about a thousandth of a joule. A high voltage requires great energy only if a great amount of charge is involved. This example highlights the difference between electrical potential energy and electric potential.

CONCEPT CHECK What is the difference between electric potential and electrical potential energy?

think!

If there were twice as much charge on one of the charged objects near the charged sphere in Figure 33.12, would the electrical potential energy of the object in the field of the charged sphere be the same or would it be twice as great? Would the electrical potential of the object be the same or would it be twice as great? *Answer: 33.5*

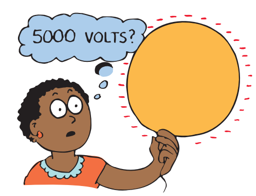


FIGURE 33.13
Although the voltage of the charged balloon is high, the electrical potential energy is low because of the small amount of charge.

Teaching Tip Ask students how much energy is needed to put positive charges on a spherical conductor until it has a total potential V. Tell them to think of bringing positive charges up to the conductor one by one. It takes no energy to put the first charge on the conductor because there are no electric forces acting on the charge. Now that the conductor has a positive charge, it takes a little energy to bring a second positive charge up to it. It takes more energy to bring the third charge because it is acted on by twice the force that acted on the second charge. It takes more and more energy to add each successive charge. The total amount of energy needed to put all the charges on the sphere is $0.5QV$, where V is the final potential on the surface of the sphere and Q is the total charge on it. It also turns out that the charge needed to produce a certain potential on the surface of a charged sphere depends on the radius R. The charge is $Q = RV/k$, where k is the Coulomb constant. As a numerical example, suppose a conducting sphere of radius 10 cm has a potential of 45,000 V. The charge on the sphere is then $Q = RV/k = 5.0 \times 10^{-7}$ C. The total energy needed to assemble this charge is $0.5QV = 0.011$ J. As this example shows, even high potentials involve very little energy!

CONCEPT CHECK Electric potential is electrical potential energy per charge.

Teaching Resources

- **Concept-Development Practice Book** *33-2*
- **Problem-Solving Exercises in Physics** *16-3*

33.6 Electrical Energy Storage

Key Term
capacitor

Common Misconception
A capacitor is a source of electrical energy.

FACT Energy from a capacitor comes from the work done in charging the capacitor.

▶ **Teaching Tip** Show some common capacitors to your class.

▶ **Teaching Tip** The capacitance of a capacitor, the ratio of net change on each plate to the potential difference created by the separated charges, is measured in units of *farads* (F). The farad is named after Michael Faraday.

33.6 Electrical Energy Storage

Electrical energy can be stored in a common device called a **capacitor.** Capacitors are found in nearly all electronic circuits. Computer memories use very tiny capacitors to store the 1's and 0's of the binary code. Some keyboards have them beneath each key. Capacitors in photoflash units store larger amounts of energy slowly and release it rapidly during the short duration of the flash. Similarly, but on a grander scale, enormous amounts of energy are stored in banks of capacitors that power giant lasers in national laboratories.

The simplest capacitor is a pair of conducting plates separated by a small distance, but not touching each other. When the plates are connected to a charging device such as the battery shown in Figure 33.14, charge is transferred from one plate to the other. This occurs as the positive battery terminal pulls electrons from the plate connected to it. These electrons in effect are pumped through the battery and through the negative terminal to the opposite plate. The capacitor plates then have equal and opposite charges—the positive plate is connected to the positive battery terminal, and the negative plate is connected to the negative battery terminal. The charging process is complete when the potential difference between the plates equals the potential difference between the battery terminals—the battery voltage. The greater the battery voltage and the larger and closer the plates, the greater the charge that is stored.

In practice, the plates may be thin metallic foils separated by a thin sheet of paper. This "paper sandwich" is then rolled up to save space and may be inserted into a cylinder. Such a practical capacitor is shown with others in Figure 33.15. (We will consider the role of capacitors in circuits in the next chapter.)

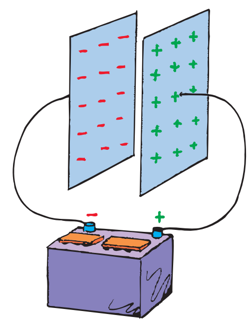


FIGURE 33.14 ▲
A simple capacitor consists of two closely spaced metal parallel plates. When connected to a battery, the plates become equally and oppositely charged.

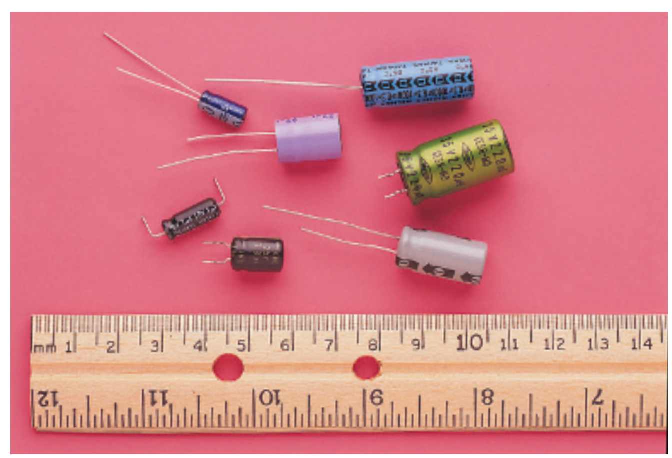


FIGURE 33.15 ▶
In these capacitors, the plates consist of thin metallic foils that have been rolled up into a cylinder.

Capacitors store and hold electric charges until discharged. A charged capacitor is discharged when a conducting path is provided between the plates. Note that a capacitor might store charge even after the electricity to a device has been turned off—for seconds, minutes, or even longer. Discharging a capacitor can be a shocking experience if you happen to be the conducting path. The energy transfer can be fatal where high voltages are present. That's the main reason for the warning labels on devices such as TV sets.

The energy stored in a capacitor comes from the work done to charge it. The energy is in the form of the electric field between its plates. Between parallel plates the electric field is uniform, as indicated in Figures 33.4c and 33.5c on previous pages. So the energy stored in a capacitor is energy stored in the electric field.

Electric fields are storehouses of energy. We will see in the next chapter that energy can be transported over long distances by electric fields, which can be directed through and guided by metal wires or directed through empty space. In Chapter 37 we will see how energy from the sun is radiated in the form of electric and magnetic fields. The fact that energy is contained in electric fields is truly far-reaching.

FIGURE 33.16 ▲
Mona El Tawil-Nassar adjusts demonstration capacitor plates.

CONCEPT CHECK Where does the energy stored in a capacitor come from?

Link to TECHNOLOGY

Ink-Jet Printers The printhead of an ink-jet printer typically ejects a thin, steady stream of thousands of tiny ink droplets each second as it shuttles back and forth across the paper. As the stream flows between electrodes that are controlled by the computer, selective droplets are charged. The uncharged droplets then pass undeflected in the electric field of a parallel plate capacitor and form the image on the page; the charged droplets are deflected and do not reach the page. Thus, the image produced on the paper is made from ink droplets that are *not* charged. The blank spaces correspond to deflected ink that never made it to the paper.

33.7 The Van de Graaff Generator

A common laboratory device for building up high voltages is the *Van de Graaff generator.* This is the lightning machine often used by "evil scientists" in old science fiction movies. A simple model of the Van de Graaff generator is shown in Figure 33.17.

CONCEPT CHECK The energy stored in a capacitor comes from the work done to charge it.

Teaching Resources
- Reading and Study Workbook
- Laboratory Manual *92*
- Probeware Lab Manual *15*
- Presentation*EXPRESS*
- Interactive Textbook
- Next-Time Question *33-1*

33.7 The Van de Graaff Generator

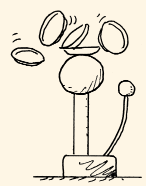
Common Misconception
High voltage is dangerous under any conditions.

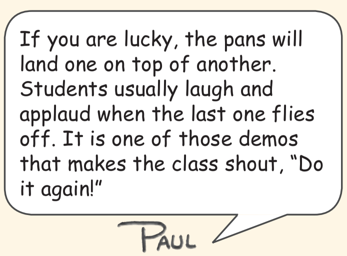
FACT A high voltage is not dangerous if only a small amount of charge is involved.

▶ **Teaching Tip** End your lecture on this chapter with a return to the Van de Graaff demo and discussion of the lack of current in the lamp when there was no potential difference across its ends. This is the lead-in to the next chapter.

Demonstration

If you did not do so in Chapter 32, now is a good time to use the Van de Graaff generator to show the repulsion of like charges. Crank up the generator with a dozen 10-in. aluminum pie pans resting on top of the sphere. The weight of the pans above each pan is greater than the force of repulsion between the pans and so they remain on the sphere—all except the pan on top, which has no pans on top of it. The top pan "floats" off and the second pan becomes the top pan. It too floats off. This continues until all the pans have floated off one by one.





CONCEPT CHECK: The voltage of a Van de Graaff generator can be increased by increasing the radius of the sphere or by placing the entire system in a container filled with high-pressure gas.

Teaching Resources

- **Reading and Study Workbook**
- **Next-Time Question** *33-2*

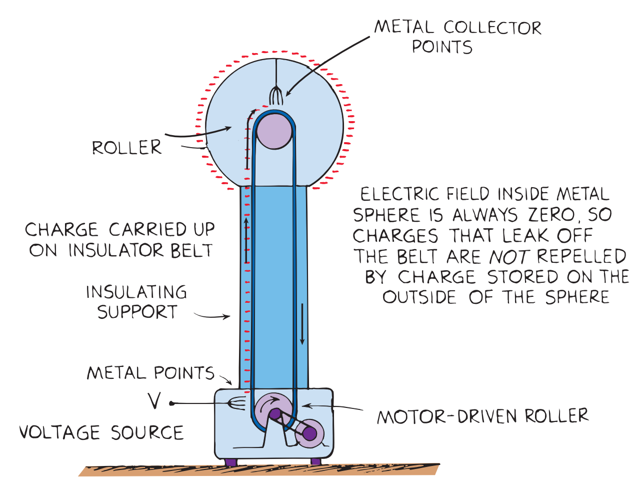
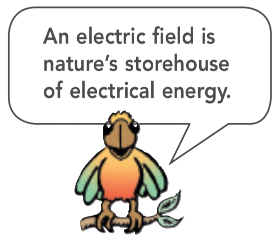


FIGURE 33.17 ▶
In a Van de Graaff generator, a moving rubber belt carries electrons from the voltage source to a conducting sphere.



A large hollow metal sphere is supported by a cylindrical insulating stand. A motor-driven rubber belt inside the support stand moves past a comblike set of metal needles that are maintained at a high electric potential. A continuous supply of electrons is deposited on the belt through electric discharge by the points of the needles and is carried up into the hollow metal sphere. The electrons leak onto metal points (which act like tiny lightning rods) attached to the inner surface of the sphere. Because of mutual repulsion, the electrons move to the outer surface of the conducting sphere. (Remember, static charge on any conductor is on the outside surface.) This leaves the inside surface uncharged and able to receive more electrons as they are brought up the belt. The process is continuous, and the charge builds up to a very high electric potential—on the order of millions of volts. Touching a Van de Graaff generator can be a hair-raising experience, as shown in Figure 33.18.

A sphere with a radius of 1 m can be raised to a potential of 3 million volts before electric discharge occurs through the air (because breakdown occurs in air when the electric field strength is about 3×10^6 V/m).[33.7] **The voltage of a Van de Graaff generator can be increased by increasing the radius of the sphere or by placing the entire system in a container filled with high-pressure gas.** Van de Graaff generators in pressurized gas can produce voltages as high as 20 million volts. These devices accelerate charged particles used as projectiles for penetrating the nuclei of atoms.

FIGURE 33.18 ▲
The physics enthusiast and the dome of the Van de Graaff generator are charged to a high voltage.

CONCEPT CHECK: How can the voltage of a Van de Graaff generator be increased?

33 REVIEW

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Concept Summary

- The magnitude (strength) of an electric field can be measured by its effect on charges located in the field. The direction of an electric field at any point is the direction of the electrical force on a small *positive* test charge.
- You can use electric field lines (also called lines of force) to represent an electric field. Where the lines are farther apart, the field is weaker.
- If the charge on a conductor is not moving, the electric field inside the conductor is exactly zero.
- The electrical potential energy of a charged particle is increased when work is done to push it against the electric field of something else that is charged.
- Electric potential is not the same as electrical potential energy. Electric potential is electrical potential energy per charge.
- The energy stored in a capacitor comes from the work done to charge it.
- The voltage of a Van de Graaff generator can be increased by increasing the radius of the sphere or by placing the system in a container filled with high-pressure gas.

Key Terms

electric field *(p. 665)*
electrical potential energy *(p. 670)*
electric potential *(p. 670)*
volt *(p. 671)*
voltage *(p. 671)*
capacitor *(p. 672)*

think! Answers

33.2 When the charge on the plates is reversed, the electric field will be in the opposite direction, so the electron beam will be deflected upward. If the field is made to oscillate, the beam will be swept up and down. With a second set of plates and further refinements it could sweep a picture onto the screen! (Think television!)

33.3 No. Gravity can be canceled inside a planet or between planets, but it cannot be shielded by a planet or by any arrangement of masses. During a lunar eclipse, for example, when Earth is directly between the sun and the moon, there is no shielding of the sun's field to affect the moon's orbit. Even a very slight shielding would accumulate over a period of years and show itself in the timing of subsequent eclipses. Shielding requires a combination of repelling and attracting forces, and gravity only attracts.

33.5 Twice as much charge would cause the object to have twice as much electrical potential energy, because it would have taken twice as much work to bring the object to that location. But the electric potential would be the same, because the electric potential is total electrical potential energy divided by total charge. In this case, twice the energy divided by twice the charge gives the same value as the original energy divided by the original charge.

33 REVIEW

Teaching Resources

- Teacher*EXPRESS*
- Virtual Physics Lab *30*

33 ASSESS

Check Concepts

1. Interaction between things that are physically apart
2. There is actual contact between a field and an object.
3. Both exert forces.
4. It has magnitude and direction.
5. a. Lines depicting an electric field
   b. They are the same.
6. The closer the lines, the stronger the field
7. Parallel, equally spaced lines
8. The charges on the outside are mutually repelled and the electric fields inside cancel to zero.
9. a. No, it is only attractive in nature.
   b. Yes, it consists of both attractive and repulsive forces.
10. Field cancels to zero.
11. Work = ΔPE + possible changes in other energy forms
12. It transforms to KE.
13. Electrical potential is electrical potential energy per charge.
14. More joules per more coulombs equals same electric potential.
15. volt
16. No, electric potential = PE per charge *as if* a test charge were present.
17. Ratio can be high when charge is small.

33 ASSESS

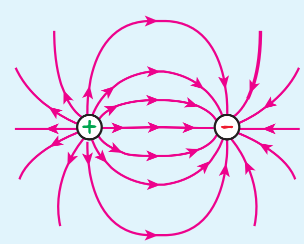
Check Concepts

Section 33.1

1. What is meant by the expression *action at a distance?*
2. How does the concept of a field eliminate the idea of action at a distance?
3. How are a gravitational field and an electric field similar?

Section 33.2

4. Why is an electric field considered a vector quantity?
5. **a.** What are electric field lines?
   b. How do their directions compare with the direction of the force that acts on a positive test charge in the same region?
6. How is the strength of an electric field indicated with field lines?



7. Describe the electric field lines in the space between a pair of parallel plates with equal and opposite charges.

Section 33.3

8. Why are occupants safe inside a car struck by lightning?
9. **a.** Can gravity be shielded?
   b. Can electric fields be shielded?
10. What happens to the electric field inside a conductor when free charges arrange themselves on its surface?

Section 33.4

11. What is the relationship between the amount of work you do on an object and its potential energy?
12. What will happen to the electrical potential energy of a charged particle in an electric field when the particle is released and free to move?

Section 33.5

13. Clearly distinguish between *electrical potential energy* and *electric potential.*
14. If you do more work to move more charge a certain distance against an electric field, and increase the electrical potential energy as a result, why do you not also increase the electric potential?
15. The SI unit for electrical potential energy is the joule. What is the SI unit for electric potential?
16. Charge must be present at a location in order for there to be electrical potential energy. Must charge also be present at a location for there to be electric potential?
17. How can electric potential be high when electrical potential energy is relatively low?

Section 33.6

18. How does the amount of charge on the plate of a charged capacitor compare with the amount of charge on the opposite plate?

Section 33.7

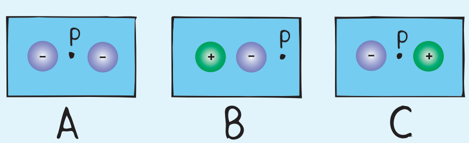
19. How does the amount of charge on the inside surface of the sphere of a charged Van de Graaff generator compare with the amount on the outside?

20. How much voltage can be built up on a Van de Graaff generator of 1 m radius before electric discharge occurs through the air?

Think and Rank

Rank each of the following sets of scenarios in order of the quantity of property involved. List them from left and right. If scenarios have equal rankings, separate them with an equal sign. (e.g., A = B)

21. The diagrams A, B, and C represent pairs of charges in three different arrangements. The distance from point P to the nearest charge is the same in each arrangement. Rank the arrangements A, B, and C from strongest to weakest electric field at point P.



22. Rank from greatest to least the force on the following particles in the following electric fields.

(A) $6q$ in field E

(B) $4q$ in field $2E$

(C) q in field $3E$

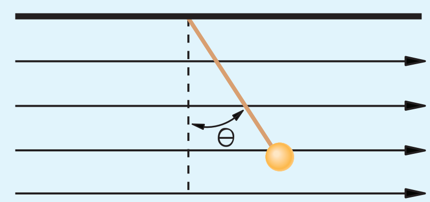
23. Three charged particles are in an electric field E. Rank their accelerations from greatest to least:

(A) charge q, mass m

(B) charge $3q$, mass $2m$

(C) charge $2q$, mass m

24. A charged ball is suspended by a string in a uniform electric field pointing to the right. The string makes an angle θ with the vertical, as two forces act on the ball—one gravitational and the other electric.



Consider the following three scenarios for the ball's mass and charge.

(A) mass = 3 g; charge = 2 nC

(B) mass = 6 g; charge = 8 nC

(C) mass = 9 g; charge = 4 nC

Rank, from greatest to least, the angle the string makes with the vertical.

18. equal

19. None on the inside; all charges repel to the outside.

20. About 3 million volts

Think and Rank

21. C, B, A

22. B, A, C

23. C, B, A

24. B, A, C

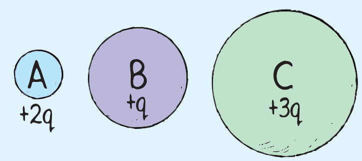
25. **a.** C, A, B
b. A = B = C = 0
c. C, A, B
d. A = B = C

Think and Explain

26. An electric field interacts with charge (instead of mass). It can exert repulsive forces as well as attractive forces, and can therefore be shielded.
27. By convention, direction is that of the force on a positive test charge.
28. The acceleration of the electron would be greater (same *F*, smaller *m*), and the directions of acceleration would be opposite (because directions of forces are opposite); electron first.
29. 1/4 as much; inverse-square law
30. Mutual repulsion
31. Greater at the corners; see Figure 33.8.
32. Only if it has the same charge; $V = PE/q$, so $PE = Vq$
33. Yes, both are amounts of energy per some quantity. With the balloon, it's energy/charge; with the sparkler, it's energy/molecule. The ratios may be high, but if the quantity in the denominator is small, the amount of energy is small.
34. Strands of hair are charged with the same sign of charge and are mutually repelled.

33 ASSESS *(continued)*

25. Shown below are three hollow copper spheres. Sphere A has a radius *R*, Sphere B has a radius of 2*R*, and Sphere C has a radius 3*R*. On each sphere is a charge, as indicated, which is evenly distributed over the spheres surface. (Each sphere is independent of the others; they don't influence one another.)



a. Rank from greatest to least the magnitude of the electric fields at a distance 4*R* from the center of the spheres.
b. Rank the field strengths at the center of the spheres.
c. Rank the potentials at distance 4*R* (assuming the potential at infinity is zero).
d. Suppose the charge is redistributed so that all three spheres have identical charges. Rank the fields at distance 4*R* from greatest to least.

Think and Explain

26. How is an electric field different from a gravitational field?

27. The vectors for the gravitational field of Earth point *toward* Earth; the vectors for the electric field of a proton point *away* from the proton. Explain.

28. Imagine an electron and a proton held midway between the plates of a charged parallel plate capacitor. If they are released, how do their accelerations and directions of travel compare? (Ignore their attraction to each other.) Which reaches a capacitor plate first?

29. Suppose that the strength of the electric field about an isolated point charge has a certain value at a distance of 1 m. How will the electric field strength compare at a distance of 2 m from the point charge? What law guides your answer?

30. When a conductor is charged, the charge moves to the outer surface of the conductor. What property of charge accounts for this spreading?

31. Suppose that a metal file cabinet is charged. How will the charge concentration at the corners of the cabinet compare with the charge concentration on the flat parts of the cabinet? Defend your answer.

32. Does an object with twice the electric potential of another have twice the electrical potential energy? Explain.

33. You are not harmed by contact with a charged balloon, even though its voltage is very high. Is the reason for this similar to why you are not harmed by the greater-than-1000°C sparks from a Fourth of July-type sparkler (like the one shown on page 404)?

34. Why does your hair stand out when you are charged by a device such as a Van de Graaff generator?

Think and Solve

35. If you put in 10 joules of work to push 1 coulomb of charge against an electric field, what will be its voltage with respect to its starting position? When released, what will be its kinetic energy if it flies past its starting position?

36. At a particular point near a second charge, a 50-μC charge experiences a force of 2.0 N. What is the electric field strength at that point? (1 μC = 10^{-6} coulomb.)

37. When placed near another charge, a 20-μC charge experiences an attractive force of 0.080 N. Show that the electric field strength at the location of the 20-μC charge is 4000 N/C.

38. A 12-μC charge is located in a 350-N/C electric field. Show that the charge experiences a force of 0.0042 N.

39. **a.** If you do 12 J of work to push 0.001 C of charge from point A to point B in an electric field, what is the voltage difference between points A and B?
    b. When the charge is released, what will be its kinetic energy as it flies back past its starting point A? What principle guides your answer?

40. What is the voltage at the location of a 0.0001-C charge that has an electrical potential energy of 0.5 J? Both voltage and potential energy are measured relative to the same reference point.

41. **a.** Suppose that you start with a charge of 0.002 C in an electric field and find that it takes 24 J of work to move the charge from point A to point B. What is the voltage difference between points A and B?
    b. If the charge is released, what is its kinetic energy as it flies back past point A?

42. Point A is at +10 V, point B is at +7 V, and point C is at 0 V. Show that it takes
    a. 6 J of work to move 2 C of charge from point B to point A.
    b. 14 J of work to move 2 C of charge from point C to point B.
    c. 20 J of work to move 2 C of charge from point C to point A.

43. In a hydrogen atom, the proton and the electron ($q = 1.6 \times 10^{-19}$ C) are separated by an average distance of 5×10^{-11} m.
    a. Calculate the force that the proton exerts on the electron at this distance.
    b. Show that the electric field strength at the average location of the electron is an enormous 6×10^{11} N/C.

44. The potential difference between a storm cloud and the ground is 5.0×10^{7} volts. During a lightning flash, 3.0 coulombs of charge are transferred to the ground.
    a. How much energy is transferred to the ground in this lightning flash?
    b. If this much energy were used to accelerate a 3500-kg truck from rest, how fast would the truck end up going?

More Problem-Solving Practice
Appendix F

Think and Solve

35. 10 V; 10 J

36. $E = F/q = (2.0 \text{ N})/(50 \times 10^{-6} \text{ C}) = 40{,}000$ N/C

37. $E = F/q = (0.080 \text{ N})/(20 \times 10^{-6} \text{ C}) = 4000$ N/C

38. From $E = F/q$, $F = qE = (12 \times 10^{-6} \text{ C})(350 \text{ N/C}) = 0.0042$ N

39. **a.** $\Delta V = W/q = (12 \text{ J})/(0.001 \text{ C}) = 12{,}000$ V
b. 12 J; conservation of energy

40. (0.5 J)/(0.0001 C) = 5000 V

41. **a.** $\Delta V = W/q = (24 \text{ J})/(0.002 \text{ C}) = 12{,}000$ V
b. 24 J (same as the work done on it)

42. **a.** From $V = W/q$, $W = qV = (2 \text{ C})(10 \text{ V} - 7 \text{ V}) = 6$ J
b. $W = qV = (2 \text{ C})(7 \text{ V} - 0 \text{ V}) = 14$ J
c. $W = qV = (2 \text{ C})(10 \text{ V} - 0 \text{ V}) = 20$ J

43. **a.** $F = kq_1q_2/d^2 = (9.0 \times 10^9 \text{ N·m}^2/\text{C}^2) \times (1.6 \times 10^{-19} \text{ C}) \times (1.6 \times 10^{-19} \text{ C})/(5 \times 10^{-11} \text{ m})^2 = 9 \times 10^{-8}$ N
b. $E = F/q = (9 \times 10^{-8} \text{ N})/(1.6 \times 10^{-19} \text{ C}) = 6 \times 10^{11}$ N/C

44. **a.** From $V = W/q$, $W = qV = (3.0 \text{ C})(5 \times 10^7 \text{ V}) = 1.5 \times 10^8$ J
b. From $W = 1/2mv^2$, $v = \sqrt{2W/m} = \sqrt{2(1.5 \times 10^8 \text{ J})/(3500 \text{ kg})} = 290$ m/s

Teaching Resources
- Computer Test Bank
- Chapter and Unit Tests