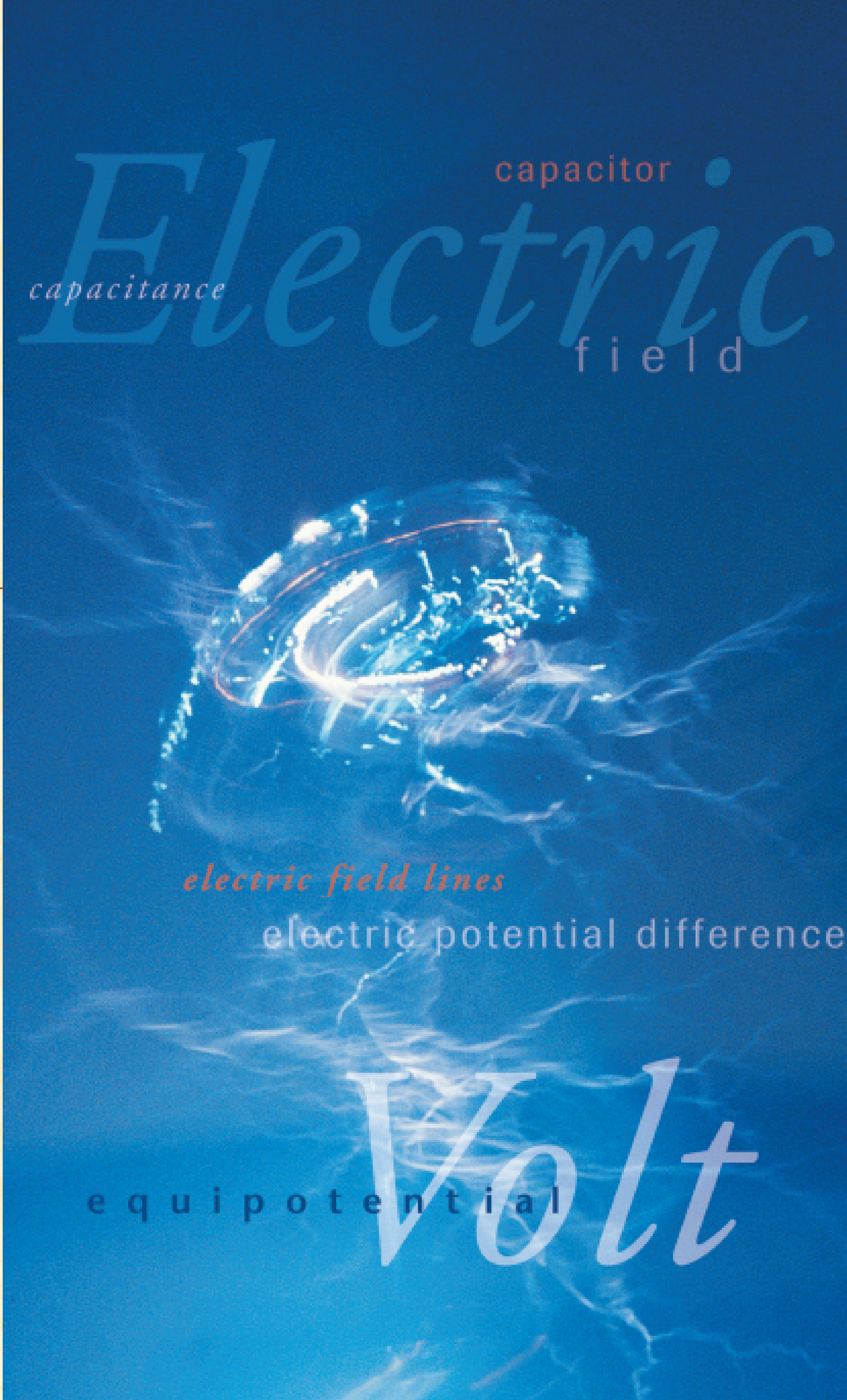
High-Energy Halo

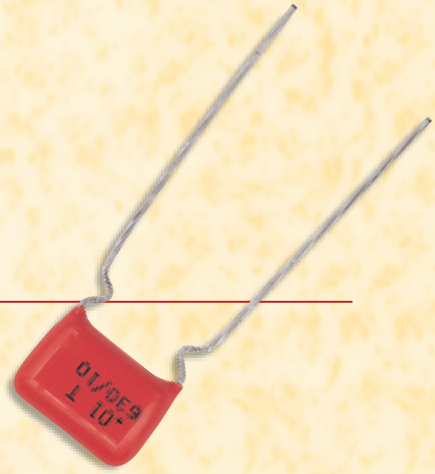
Research into the transmission of ultrahigh-voltage electricity measuring up to two million volts is essential for the development of future power technology. High-voltage air core resonant transformers can generate lightning-like discharges called coronas. Why can a corona be seen around a transformer or a power line when the effect is not seen in the electric wires in our homes?

Look at the text on page 499 for the answer.



CHAPTER

21 Electric Fields



The blue glow in the photo is a modern version of St. Elmo's Fire. Sailors in the time of Columbus saw these ghostly streamers issuing from their ships' high masts. The faint glow from the top of a mast was visible in the dark. The ship's mast appeared to be on fire, but did not burn. Sailors recognized the glow as a warning sign of an approaching lightening storm.

Today, we can sometimes see the same glow around tall spires and steeples, or around the propellers of aircraft flying in stormy air or dry snow. The glow, like the bluish glow in the photo at the left, is a corona discharge. It is related to lightning, but in this case, the flow of electric charges is slow rather than extremely fast.

A corona discharge occurs because large electric forces exist around the pointed ends of charged objects. These fields result in forces that pull charged particles from the molecules in the air. The charged molecules that result collide with other molecules, producing light. If enough charged molecules are produced around a power line, for example, it can result in sparking from a wire to another electric conductor, thereby causing a short blackout. Designers of power lines work to reduce or completely eliminate corona discharges.

Electric fields exist around any object carrying a charge. When electric fields are not large enough to cause problems, the forces that they exert can transfer electrical energy from one object to another. This, in turn, provides the power you use on a daily basis–whether you plug an electric cord into an outlet or use a battery in a portable device. In this chapter, you will learn more about electric fields, forces, and electrical energy.

WHAT YOU'LL LEARN

- You will distinguish between electric force and electric fields.
- You will understand how grounding is related to charge sharing.
- You will recognize the relationship between conductor shape and electric field strength.

WHY IT'S IMPORTANT

- You use electric power every day. Almost every appliance and many of the tools you use run on electricity. As the demand for electricity increases, you need to understand this powerful source of energy.

PHYSICS Online

To find out more about electric fields, visit the Glencoe Science Web site at **science.glencoe.com**

CLICK HERE

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21.1 Creating and Measuring Electric Fields

OBJECTIVES

- **Define** and **measure** an electric field.
- **Solve** problems relating to charge, electric fields, and forces.
- **Diagram** electric field lines.

Charge and Field Conventions

- Positive charges are **red.**
- Negative charges are **blue.**
- Electric field lines are **indigo.**

Electric force, like the gravitational force you studied in Chapter 8, varies inversely as the square of the distance between two point objects. Both forces can act at a great distance. How can a force be exerted across what seems to be empty space? In trying to understand electric force, Michael Faraday developed the concept of an electric field. According to Faraday, a charge creates an electric field about it in all directions. If a second charge is placed at some point in the field, the second charge interacts with the field at that point. The resulting force is the result of a local interaction.

The Electric Field

The **electric field** is a vector quantity that relates the force exerted on a test charge to the size of the test charge. How does this work? An electric charge, q, produces an electric field that you can measure. This is shown in **Figure 21–1.** First, measure the field at a specific location. Call this point A. An electrical field can be observed only because it produces forces on other charges, so you must place a small positive test charge, q', at A. Then, measure the force exerted on the test charge, q', at this location.

According to Coulomb's law, the force is proportional to the test charge. If the size of the test charge is doubled, the force is doubled. Thus, the ratio of force to test charge is independent of the size of the test charge. If you divide the force, $\boldsymbol{F}$, on the test charge, measured at point A, by the size of the test charge, q', you obtain a vector quantity, $\boldsymbol{F}/q'$. This quantity does not depend on the test charge, only on the charge q and the location of point A. The electric field at point A, the location of q', is represented by the following equation.

Electric Field $$\boldsymbol{E} = \frac{\boldsymbol{F}_{\text{on } q'}}{q'}$$

The direction of the electric field is the direction of the force on the positive test charge. The magnitude of the electric field is measured in newtons per coulomb, N/C.

A picture of an electric field can be made by using arrows to represent the field vectors at various locations, as shown in **Figure 21–1.** The length of the arrow will be used to show the strength of the field. The direction of the arrow shows the field direction. To find the field from two charges, the fields from the individual charges are added vectorially. A test charge can be used to map out the field resulting from any collection of charges. Typical electric fields produced by charge collections are shown in **Table 21-1.**

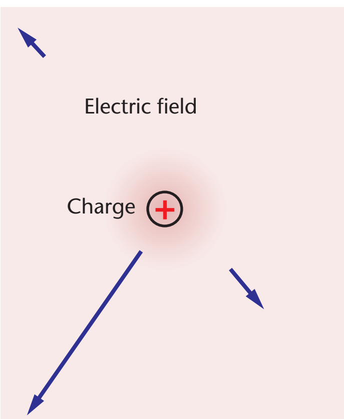

FIGURE 21–1 Arrows can be used to represent the magnitude and direction of the electric field about an electric charge at various locations.

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TABLE 21–1	
Approximate Values of Typical Electric Fields	
Field	**Value (N/C)**
Nearby a charged hard rubber rod	1×10^3
In a television picture tube	1×10^5
Needed to create a spark in air	3×10^6
At an electron orbit in hydrogen atom	5×10^{11}

An electric field should be measured only by a small test charge. Why? The test charge also exerts a force on q. It is important that the force exerted by the test charge doesn't move q to another location, and thus change the force on q' and the electric field being measured. A small test charge cannot move q.

F.Y.I.

Robert Van de Graaff devised the high-voltage electrostatic generator in the 1930s. These generators can build up giant potentials that can accelerate particles to high energy levels.

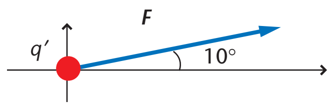
Example Problem

Calculating an Electric Field

An electric field is to be measured using a positive test charge of 4.0×10^{-5} C. This test charge experiences a force of 0.60 N acting at an angle of 10°. What is the magnitude and direction of the electric field at the location of the test charge?

Sketch the Problem

- Draw the force vector on the test charge, q', on a two-dimensional grid at an angle of 10°.



Calculate Your Answer

Known:

$q' = +4.0 \times 10^{-5}$ C

$\boldsymbol{F} = 0.60$ N at 10°

Unknown:

$\boldsymbol{E}$ = ? at 10°

Strategy:

Use the relationship $E = \dfrac{F}{q'}$

Calculations:

$$E = \frac{F}{q'} = \frac{0.60\ \text{N}}{4.0 \times 10^{-5}\ \text{C}}$$

$$\boldsymbol{E} = 1.5 \times 10^4\ \text{N/C at } 10^\circ$$

Check Your Answer

- Are the units correct? The electric field is correctly measured in newtons per coulomb.
- Are the signs correct? The field direction is in the direction of the force because the test charge is positive, so $\boldsymbol{E}$ is positive.
- Is the magnitude correct? Electric fields can have values around 10^5 N/C as shown in **Table 21-1.**

Practice Problems

1. A negative charge of 2.0×10^{-8} C experiences a force of 0.060 N to the right in an electric field. What are the field magnitude and direction?

2. A positive test charge of 5.0×10^{-4} C is in an electric field that exerts a force of 2.5×10^{-4} N on it. What is the magnitude of the electric field at the location of the test charge?

3. Suppose the electric field in problem 2 was caused by a point charge. The test charge is moved to a distance twice as far from the charge. What is the magnitude of the force that the field exerts on the test charge now?

4. You are probing the field of a charge of unknown magnitude and sign. You first map the field with a 1.0×10^{-6} C test charge, then repeat your work with a 2.0×10^{-6} C test charge.

a. Would you measure the same forces with the two test charges? Explain.

b. Would you find the same fields? Explain.

So far you have measured the field at a single point. Now, imagine moving the test charge to another location. Measure the force on it again and calculate the electric field. Repeat this process again and again until you assign every location in space a measurement of the vector quantity of the electric field associated with it. The field is present even if there is no test charge to measure it. Any charge placed in an electric field experiences a force on it resulting from the electric field at that location. The strength of the force depends on the magnitude of the field, $\mathbf{E}$, and the size of the charge, q. Thus, $\mathbf{F} = \mathbf{E}q$. The direction of the force depends on the direction of the field and the sign of the charge.

Picturing the Electric Field

An alternative picture of an electric field is shown in **Figure 21–2.** The lines are called **electric field lines.** The direction of the field at any point is the tangent drawn to the field line at that point. The strength of the electric field is indicated by the spacing between the lines. The field is strong where the lines are close together. It is weaker where the lines are spaced farther apart. Although only two-dimensional models can be shown here, remember that electric fields exist in three dimensions.

The direction of the force on a positive test charge near another positive charge is away from the other charge. Thus, the field lines extend radially outward like the spokes of a wheel, as shown in **Figure 21–2a.** Near a negative charge, the direction of the force on the positive test charge is toward the negative charge, so the field lines point radially inward, as shown in **Figure 21–2b.** When there are two or more charges,

Pocket Lab

Electric Fields

How does the electric field around a charged piece of plastic foam vary in strength and direction? Try this activity to find out. Tie a pith ball on the end of a 20-cm nylon thread and tie the other end to a plastic straw. When you hold the straw horizontally, notice that the ball hangs straight down on the thread. Now rub a piece of wool on a 30 cm × 30 cm square of plastic foam to charge both objects. Stand the foam in a vertical orientation. Hold the straw and touch the pith ball to the wool, then slowly bring the hanging ball towards the charged plastic foam. Move the pith ball to different regions and notice the angle of the thread.

Analyze and Conclude Why did the ball swing toward the charged plastic? Explain in terms of the electric field. Did the angle of the thread change? Why? Does the angle of the thread indicate the direction of the electric field? Explain.

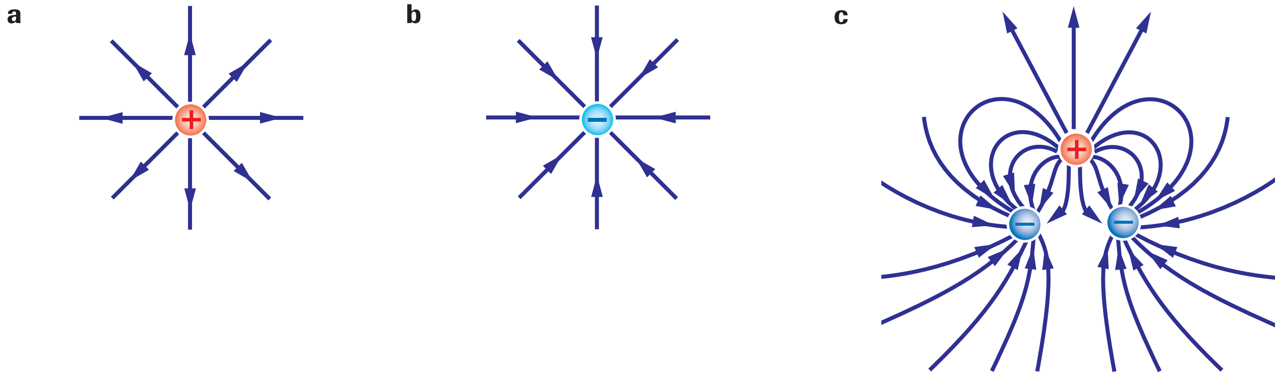


FIGURE 21–2 Lines of force are drawn perpendicularly away from the positively-charged object **(a)** and perpendicularly into the negatively-charged object **(b)**. Electric field lines between like charged and oppositely charged objects are shown in **(c).**

the field is the vector sum of the fields resulting from the individual charges. The field lines become curved and the pattern is more complex, as shown in **Figure 21–2c.** Note that field lines always leave a positive charge and enter a negative charge.

The Van de Graaff machine is a device that transfers large amounts of charge from one part of the machine to the top metal terminal, as shown in **Figure 21–3a.** A person touching the terminal is charged electrically. The charges on the person's hairs repel each other, causing the hairs to follow the field lines. This transfer of charge is diagrammed in **Figure 21–3b.** Charge is transferred onto a moving belt at the base of the generator, Position A, and is transferred off the belt at the metal dome at the top, Position B. An electric motor does the work needed to increase the electric potential energy. Another method of visualizing field lines is to use grass seed in an insulating liquid such as mineral oil. The electric forces cause a separation of charge in each long, thin grass seed. The seeds then turn so that they line up along the direction of the electric field. The seeds thus form a pattern of the electric field lines. The patterns in **Figure 21–4** were made this way.

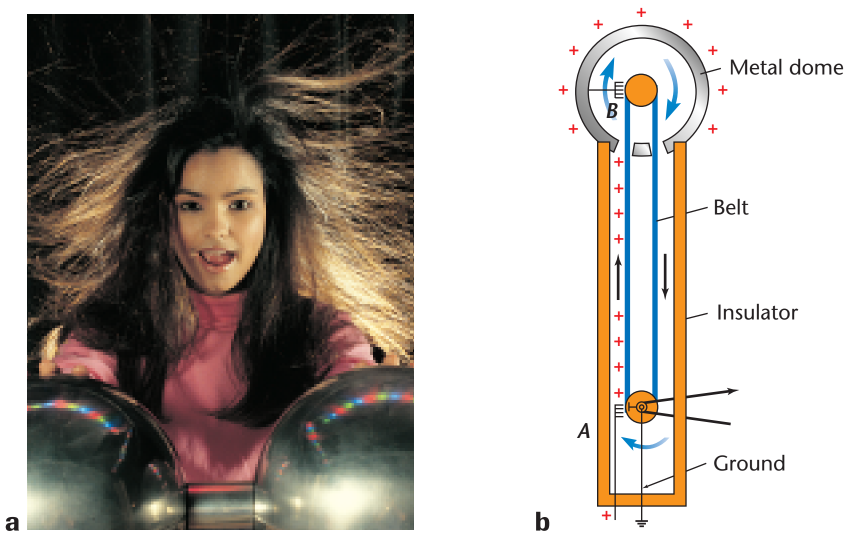


FIGURE 21–3 When a person touches a Van de Graaff generator, the results can be dramatic **(a).** In the Van de Graaff generator, charge is transferred onto a moving belt at A, and from the belt to the metal dome at B. An electric motor does the work needed to increase the electric potential energy **(b).**

Physics & Society

Computers for People with Disabilities

Studying physics, math, and other sciences can be difficult enough without the additional challenges presented by physical disabilities. People with impaired vision, hearing, or mobility require assistance that can be provided through the use of computers.

Computer technology that translates written text into Braille or speech provides people who are blind with ready access to textbooks and scientific journals without the need for another person to read the material to them. Speech also can be turned into written text by voice recognition software. Electronic readouts from laboratory instruments can be fed into computers programmed to produce Braille or speech. Also, devices have been developed to create textured charts and graphs meant to be felt with the fingers rather than viewed with the eyes.

People with hearing loss depend heavily on printed materials and on computerized translations and informational sources, including the Internet. Speech synthesis software enables those who cannot speak to participate in verbal discussions. Computer programs that teach sign language help facilitate communication between those who can hear and those who cannot.

Both speech synthesis and voice recognition software are valuable for people with mobility impairment, as are devices that replace or augment the conventional keyboard and mouse. Those who do not have use of their hands and arms can use mouth sticks or head sticks to press keys and to move the cursor around the screen by manipulating track balls or glide pads.

Another aid for people with mobility limitations is the sip-and-puff switch which is placed in the mouth. The user's inhalations (sips) and exhalations (puffs) create the dots and dashes of letters in Morse code, which are then translated into text or speech by a computer. Word-prediction software that completes words based on the first few letters helps to reduce the number of keystrokes required by a typist who is disabled.

Investigating the Issue

1. **Researching Information** Research and describe the life and career of Stephen Hawking to find out more about his scientific contributions, his physical challenges, and the technologies that have helped him overcome some of those challenges.
2. **Debating the Issue** Computer aids for people with disabilities are expensive, and they often have to be paid for by the schools or employers who train or employ these people. Find out what kinds of tools are used by students and working adults with disabilities in your community, and how those tools are made available to them. Who decides how much money should be spent on these items? How do you think such decisions should be handled?
3. **Evaluating** Evaluate the impact of computer technology research on society.

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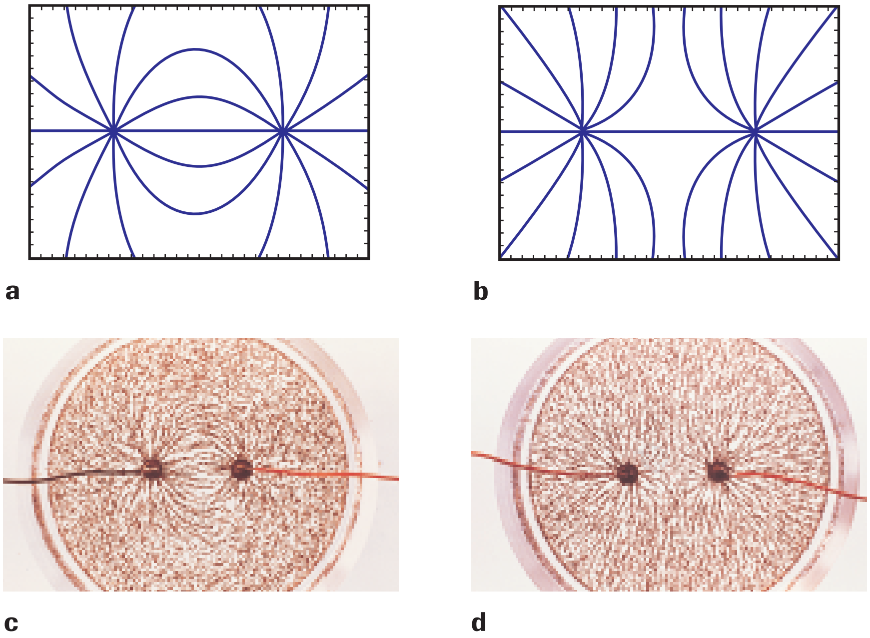

FIGURE 21–4 Lines of force between unlike charges **(a, c)** and between like charges **(b, d)** describe the behavior of a positively charged object in a field. The top photographs are computer tracings of electric field lines.

Field lines do not really exist. They are simply a means of providing a model of an electric field. Electric fields, on the other hand, do exist. They provide a method of calculating the force on a charged body, but do not explain, however, why charged bodies exert forces on each other.

21.1 Section Review

1. Suppose you are asked to measure the electric field in space. Answer the following questions about this step-by-step procedure.
   - **a.** How do you detect the field at a point?
   - **b.** How do you determine the magnitude of the field?
   - **c.** How do you choose the size of the test charge?
   - **d.** What do you do next?
2. Suppose you are given an electric field, but the charges that produce the field are hidden. If all the field lines point into the hidden region, what can you say about the sign of the charge in that region?
3. How does the electric field, ***E,*** differ from the force, ***F,*** on the test charge?
4. **Critical Thinking** **Figure 21–4b** shows the field from two like charges. The top positive charge in **Figure 21–2c** could be considered a test charge measuring the field resulting from the two negative charges. Is this positive charge small enough to produce an accurate measure of the field? Explain.

21.2 Applications of Electric Fields

OBJECTIVES

- **Define** and **calculate** electric potential difference.
- **Explain** how Millikan used electric fields to find the charge of the electron.
- **Determine** where charges reside on solid and hollow conductors.
- **Describe** capacitance and **solve** capacitor problems.

As you have learned, the concept of energy is extremely useful in mechanics. The law of conservation of energy allows us to solve motion problems without knowing the forces in detail. The same is true in the study of electrical interactions. The work performed moving a charged particle in an electric field can result in the particle gaining either potential or kinetic energy, or both. Because this chapter investigates charges at rest, only changes in potential energy will be discussed.

Energy and the Electric Potential

Recall the change in gravitational potential energy of a ball when it is lifted, as shown in **Figure 21–5.** Both the gravitational force, $\boldsymbol{F}$, and the gravitational field, $\boldsymbol{g} = \boldsymbol{F}/m$, point toward Earth. If you lift a ball against the force of gravity, you do work on it, increasing its potential energy.

The situation is similar with two unlike charges: they attract each other, and so you must do work to pull one charge away from the other. When you do the work, you store it as potential energy. The larger the test charge, the greater the increase in its potential energy, ΔU_e.

The force on the test charge depends on its magnitude, but it is convenient to define a quantity, the electric field, that does not depend on the magnitude of the test charge. Recall from Section 21.1 that $\boldsymbol{E} = \boldsymbol{F}/q'$, where q' is the magnitude of the test charge. The electric field is then the force per unit charge. In a similar way, the **electric potential difference,** ΔV, is defined as the work done moving a test charge in an electric field divided by the magnitude of the test charge.

Electric Potential Difference $$\Delta V = \frac{W_{\text{on } q'}}{q'}$$

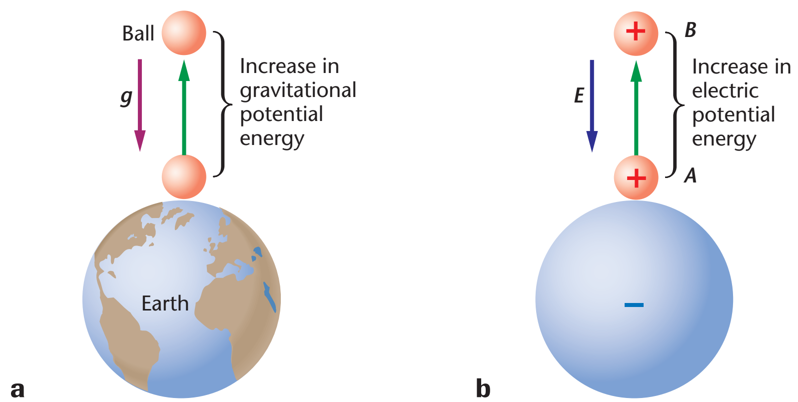

FIGURE 21–5 Work is needed to move an object against the force of gravity **(a)** and against the electric force **(b).** In both cases, the potential energy of the object is increased.

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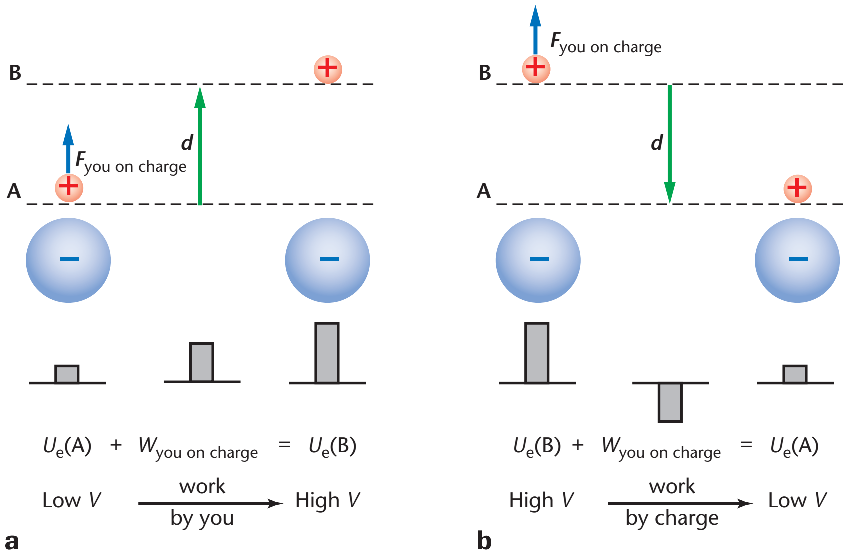

FIGURE 21–6 Electric potential difference is determined by measuring the force per unit charge. If you move the charges apart, you increase the electric potential difference **(a).** If you move the charges closer together, you reduce the electric potential difference **(b).**

Electric potential difference is measured in joules per coulomb. One joule per coulomb is called a **volt** (J/C = V).

Consider the situation shown in **Figure 21–6.** The negative charge creates an electric field, ***E,*** around itself. Suppose you placed a small positive test charge, q', in the field at position A. It will experience a force in the direction of the field. If you now move the test charge away from the negative charge to position B, you will have to exert a force, $\boldsymbol{F}_{\text{by you}}$, on the charge. Because the force you exert is in the same direction as the displacement, the work you do on the test charge is positive. Therefore there will also be a positive change in the electric potential difference. **Figure 21–6a** shows that the potential energy is raised by the amount of work done so, $U_e(A) + W_{\text{by you}} = U_e(B)$. The change does not depend on the size of the test charge. It only depends on the field and the displacement.

Suppose you now move the test charge back to position A from position B. The force you exert is now in the direction opposite the displacement, so the work you do is negative. The electric potential difference is also negative. In fact, it is equal and opposite to the potential difference for the move from position A to position B. **Figure 21–6b** shows that the potential energy is changed again by the amount of work you did, so $U_e(B) + W_{\text{by you}} = U_e(A)$. The electric potential difference does not depend on the path used to go from one position to another. It does depend on the two positions.

Is there always an electric potential difference between the two positions? Suppose you moved the test charge in a circle around the negative charge. The force the electric field exerts on the test charge is always perpendicular to the direction you moved it, so you do no work. Therefore, the electric potential difference is zero. Whenever the electric potential difference between two or more positions is zero, those positions are said to be at **equipotential.**

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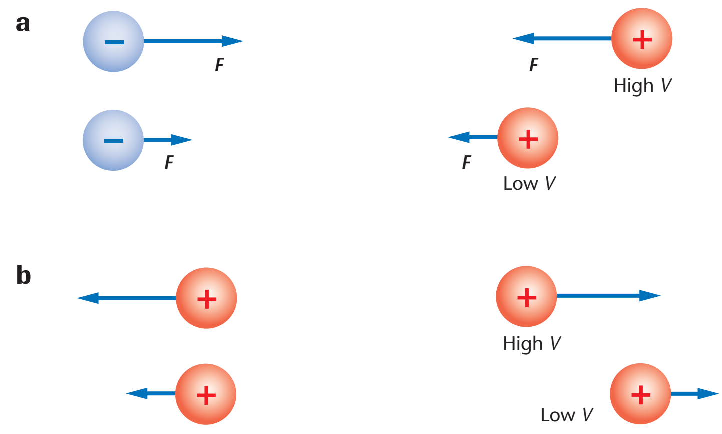
20 North Wacker Drive
Chicago, IL 60606

FIGURE 21–7 Electric potential is smaller when two unlike charges are closer together **(a)** and larger when two like charges are closer together **(b).**



F.Y.I.

Some manufacturers of computers recommend that you keep computers plugged in to maintain the ground even when they are not in use. It is also a good idea to never remove the grounding pin on electrical equipment.

Only differences in potential energy can be measured. The same is true of electric potential. Thus, only differences in electric potential are important. The electric potential difference from point A to point B is defined as $\Delta V = V_B - V_A$. Electric potential differences are measured with a voltmeter. Sometimes the electric potential difference is simply called the voltage. Do not confuse the electric potential difference, ΔV, with the volts, V.

As you learned in Chapter 11, the potential energy of a system can be defined as zero at any reference point. In the same way, the electric potential of any point can be defined as zero. Choose a point and label it point A. If $V_A = 0$, then $\Delta V = V_B$. If instead, $V_B = 0$, then $\Delta V = -V_A$. No matter what reference point is chosen, the value of the electric potential difference from point A to point B will always be the same.

You have seen that electric potential difference increases as a positive test charge is separated from a negative charge. What happens when a positive test charge is separated from a positive charge? There is a repulsive force between these two charges. Potential energy decreases as the two charges are moved farther apart. Therefore, the electric potential is smaller at points farther from the positive charge, as shown in **Figure 21–7.**

The Electric Potential in a Uniform Field

A uniform electric force and field can be made by placing two large, flat conducting plates parallel to each other. One is charged positively and the other negatively. The electric field between the plates is constant except at the edges of the plates. Its direction is from the positive to the negative plate. The grass seeds pictured in **Figure 21–8** represent the electric field between parallel plates.

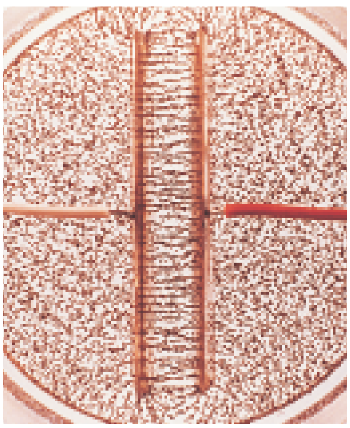


FIGURE 21–8 A representation of an electric field between parallel plates is shown.

If a positive test charge, q', is moved a distance d, in the direction opposite the electric field direction, the work done is found by the relationship $W_{\text{on } q'} = Fd$. Thus, the electric potential difference, the work done per unit charge, is $\Delta V = Fd/q' = (F/q')d$. Now, the electric field intensity is the force per unit charge, $E = F/q'$. Therefore, the electric

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potential difference, ΔV, between two points a distance d apart in a uniform field, $\boldsymbol{E}$, is represented by the following equation.

Electric Potential Difference in a Uniform Field $\Delta V = Ed$

The electric potential increases in the direction opposite the electric field direction. That is, the electric potential is higher near the positively charged plate. By dimensional analysis, the product of the units of E and d is (N/C)·(m). This is equivalent to one J/C, the definition of one volt.

Math Handbook

To review **dimensional analysis,** see the Math Handbook, Appendix A, page 740.

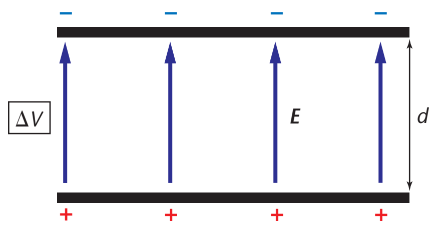
Example Problem

Electric Field Between Two Parallel Plates

Two parallel plates are given opposite charges. A voltmeter measures the electric potential difference to be 60.0 V. The plates are 3.0 cm apart. What is the magnitude of the electric field between them?

Sketch the Problem

- Draw two parallel plates separated by 3.0 cm.
- Identify the lower plate as positively charged and the top plate as negatively charged.
- Indicate that the electric potential difference is located between the two plates.



Calculate Your Answer

Known:

$\Delta V = 60.0$ V

$d = 0.030$ m

Unknown:

$E = ?$

Strategy:

For the uniform field between charged parallel plates, $\Delta V = Ed$.

Therefore, $E = \frac{\Delta V}{d}$

Calculations:

$$E = \frac{\Delta V}{d}$$

$$= \frac{60.0\ \text{V}}{0.030\ \text{m}}$$

$$= 2.0 \times 10^3\ \text{J/C·m}$$

$$= 2.0 \times 10^3\ \text{N/C}$$

The lower plate is at a higher voltage, so the electric field points upward.

Check Your Answer

- Are the units correct? Values are expressed in newtons per coulomb.
- Are the signs correct? The electric field is represented by the electric potential difference divided by the plate separation. The potential is higher near the positively charged plate, and the electric field points away from the positively charged plate.
- Is the magnitude realistic? With ΔV of a few volts and a short distance, high electric field values are expected.

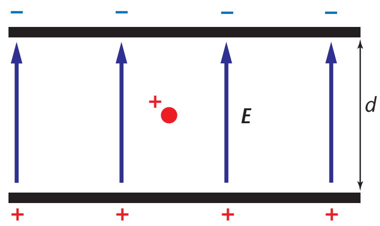
Example Problem

Work Required to Move a Proton Placed Between Charged Parallel Plates

Two large, charged parallel plates are 4.0 cm apart. The magnitude of the electric field between the plates is 625 N/C.

a. What is the electric potential difference between the plates?
b. What work will you do to move a charge equal to that of one proton from the negative to the positive plate?

Sketch the Problem



- Draw two parallel plates separated by 4.0 cm.
- Identify the lower plate as positively charged and the upper plate as negatively charged.
- Place a proton in the electric field.

Calculate Your Answer

Known:	**Unknown:**
$E = 625$ N/C	$\Delta V = ?$
$d = 0.040$ m	$W_{\text{by you}} = ?$
$q = 1.60 \times 10^{-19}$ C	

Strategy:

a. Use $\Delta V = Ed$ to determine the potential difference in the uniform field between parallel plates.

Calculations:

$$\Delta V = Ed = (625\ \text{N/C})(0.040\ \text{m}) = 25\ \text{Nm/C} = 25\ \text{J/C} = 25\ \text{V}$$

b. $W = q\Delta V$ to determine the work.

$$W_{\text{by you}} = q\Delta V = (1.60 \times 10^{-19}\ \text{C})(25\ \text{J/C}) = 4.0 \times 10^{-18}\ \text{J}$$

Check Your Answer

- Are the units correct? Work is in joules and potential is in volts.
- Are the signs correct? You do work to move a positive charge toward a positively charge plate, so sign of the electric potential difference is positive.
- Is the magnitude realistic? With a ΔV of a few volts and a small charge, the amount of work performed will be small.

Practice Problems

5. The electric field intensity between two large, charged, parallel metal plates is 8000 N/C. The plates are 0.05 m apart. What is the electric potential difference between them?
6. A voltmeter reads 500 V across two charged, parallel plates that are 0.020 m apart. What is the electric field between them?
7. What electric potential difference is applied to two metal plates 0.500 m apart if the electric field between them is 2.50×10^3 N/C?
8. What work is done when 5.0 C is moved through an electric potential difference of 1.5 V?

Millikan's Oil-Drop Experiment

One important application of the uniform electric field between two parallel plates is the measurement of the charge of an electron. This was first determined by American physicist Robert A. Millikan in 1909. **Figure 21–9** shows the method used by Millikan to measure the charge carried by a single electron. Fine oil drops were sprayed from an atomizer into the air. These drops were charged by friction with the atomizer as they were sprayed. Gravity acting on the drops caused them to fall. A few entered the hole in the top plate of the apparatus. An electric potential difference was placed across the two plates. The resulting electric field between the plates exerted a force on the charged drops. When the top plate was made positive enough, the electric force caused negatively charged drops to rise. The electric potential difference between the plates was adjusted to suspend a charged drop between the plates. At this point, the downward force of Earth's gravitational field and the upward force of the electric field were equal in magnitude.

BIOLOGY CONNECTION

Eel Voltage The electric eel shocks prey with groups of highly compacted nerve endings in its tail. The larger the eel, the larger the nerve-ending cells, and the stronger the voltage. A nine-foot eel can emit 650 volts, enough to stun a person or a large animal. After many discharges, eels must rest to build up voltage. They inhabit the freshwaters of South America.

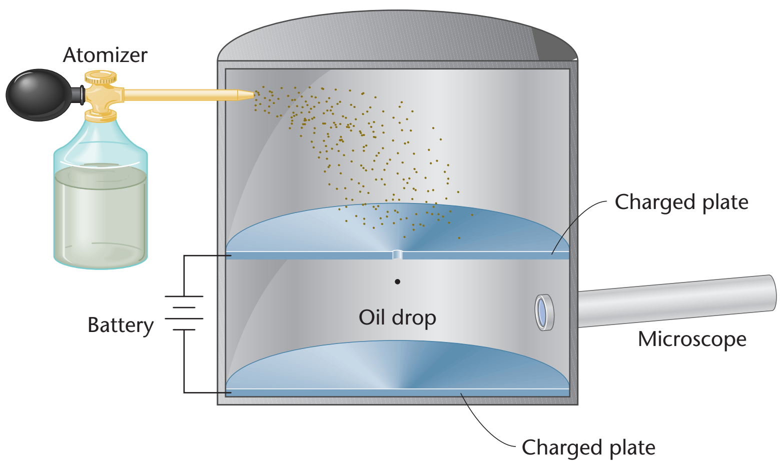


FIGURE 21–9 This illustration shows a cross-sectional view of the apparatus Millikan used to determine the charge on an electron.

F.Y.I.

Even if the inner surface of an object is pitted or bumpy, giving it a larger surface area than the outer surface, the charge still will be entirely on the outside.

The magnitude of the electric field, ***E***, was determined from the electric potential difference between the plates. A second measurement had to be made to find the weight of the drop using the relationship mg, which was too tiny to measure by ordinary methods. To make this measurement, a drop was first suspended. Then the electric field was turned off and the rate of the fall of the drop was measured. Because of friction with the air molecules, the oil drop quickly reached terminal velocity. This velocity was related to the mass of the drop by a complex equation. Using the measured terminal velocity to calculate mg, and knowing ***E***, the charge q could be calculated.

Millikan found that there was a great deal of variation in the charges of the drops. When he used X rays to ionize the air and add or remove electrons from the drops, he noted, however, that the changes in the charge were always a multiple of 1.60×10^{-19} C. The changes were caused by one or more electrons being added to or removed from the drops. He concluded that the smallest change in charge that could occur was the amount of charge of one electron. Therefore, Millikan proposed that each electron always carried the same charge, 1.60×10^{-19} C.

Millikan's experiment showed that charge is quantized. This means that an object can have only a charge with a magnitude that is some integral multiple of the charge of the electron.

The presently accepted theory of matter states that protons are made up of fundamental particles called quarks. The charge on a quark is either $+1/3$ or $-2/3$ the charge on an electron. One theory of quarks states that quarks can never be isolated. Many experimenters have used an updated Millikan apparatus to look for fractional charges on drops or tiny metal spheres. There have been no reproducible discoveries of fractional charges.

Example Problem

Finding the Charge on an Oil Drop

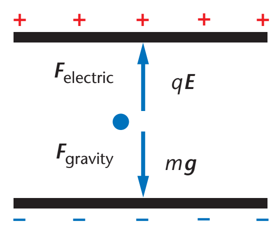
In a Millikan oil drop experiment, a drop has been found to weigh 1.9×10^{-14} N. When the electric field is 4.0×10^{4} N/C, the drop is suspended motionless.

a. What is the charge on the oil drop?

b. If the upper plate is positive, how many excess electrons does the oil drop have?

Sketch the Problem

- Draw two plates with the positive charge on the top plate and the negative charge on the bottom plate.
- Suspend an oil drop in the field and identify the gravitational force downward and the electric force upward.
- The oil drop will be motionless.



Calculate Your Answer

Known:

$mg = 1.9 \times 10^{-14}$ N

$E = 4.0 \times 10^{4}$ N/C

$e = 1.60 \times 10^{-19}$ C/electron

Unknown:

charge on drop $q = ?$

number of electrons, $n = ?$

Strategy:

a. When balanced, $F_{\text{electric}} = F_{\text{gravity}}$. Then, $qE = mg$ so use $q = mg/E$

Calculations:

$$q = \frac{mg}{E}$$

$$q = \frac{1.9 \times 10^{-14}\ \text{N}}{4.0 \times 10^{4}\ \text{N/C}} = 4.8 \times 10^{-19}\ \text{C}$$

b. Determine the number of electrons by $n = q/e$

$$n = \frac{q}{e} = \frac{4.8 \times 10^{-19}\ \text{C}}{1.60 \times 10^{-19}\ \text{C/electron}}$$

$$= 3\ \text{electrons}$$

Check Your Answer

- Are the units correct? Charge is measured in coulombs.
- Are the signs correct? Charge is the product of the magnitude of the charge on one electron multiplied by the number of electrons. This is a positive number.
- Is the magnitude realistic? There is an excess of electrons, because the drop is attracted to the positively charged plate.

Practice Problems

9. A drop is falling in a Millikan oil-drop apparatus when the electric field is off.

a. What are the forces acting on the oil drop, regardless of its acceleration?

b. If the drop is falling at constant velocity, what can be said about the forces acting on it?

10. An oil drop weighs 1.9×10^{-15} N. It is suspended in an electric field of 6.0×10^{3} N/C.

a. What is the charge on the drop?

b. How many excess electrons does it carry?

11. A positively charged oil drop weighs 6.4×10^{-13} N. An electric field of 4.0×10^{6} N/C suspends the drop.

a. What is the charge on the drop?

b. How many electrons is the drop missing?

12. If three more electrons were removed from the drop in problem 11, what field would be needed to balance the drop?

Physics Lab

Charges, Energy, and Voltage

Problem

How can you make a model that demonstrates the relationship of charge, energy, and voltage?

Materials

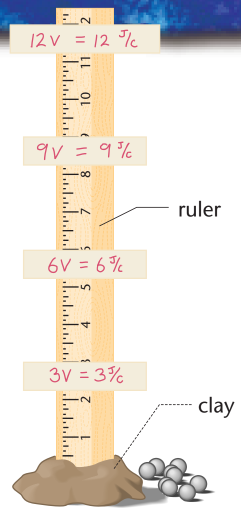
ball of clay
ruler
transparent tape
12 steel balls, 3-mm diameter
paper

Procedure

1. Use the clay to support the ruler vertically on the tabletop. The 0 end should be at the table.
2. Cut a 2 cm × 8 cm rectangular piece of paper and write on it "3 V = 3 J/C."
3. Cut three more rectangles and label them: 6 V = 6 J/C, 9 V = 9 J/C, and 12 V = 12 J/C.
4. Tape the 3-V rectangle to the 3" mark on the ruler, the 6-V to the 6" mark, and so on.
5. Let each steel ball represent 1 C of charge.
6. Lift and tape four steel balls to the 3-V rectangle, three to the 6-V rectangle, and so on.
7. When you are completely finished with the lab, dispose of or recycle appropriate materials. Put away materials that can be reused.

Data and Observations

1. Make a data table with columns labeled "Level," "Charge," "Voltage," and "Energy."
2. Fill in the data table for your model for each level of the model.



Data and Observations			
Level	Charge	Voltage	Energy

3. The model shows different amounts of charges at different energy levels. Where should steel balls be placed to show a zero energy level? Explain.

Analyze and Conclude

1. **Analyzing Data** How much energy is required to lift each coulomb of charge from the tabletop to the 9-V level?
2. **Analyzing Data** What is the total potential energy stored in the 9-V level?
3. **Relating Concepts** The total energy of the charges in the 6-V level is not 6 J. Explain this.
4. **Making Predictions** How much energy would be given off if the charges in the 9-V level fell to the 6-V level? Explain.

Apply

1. A 9-V battery is very small. A 12-V car battery is very big. Use your model to help explain why two 9-V batteries will not start your car.

CONTENTS

Sharing of Charge

All systems come to equilibrium when the energy of the system is at a minimum. For example, if a ball is put on a hill it will finally come to rest in a valley, where its gravitational potential energy is smallest. This would also be the location where its gravitational potential has been reduced the largest amount. This same principle explains what happens when an insulated, negatively charged metal sphere, such as the one shown in **Figure 21–10,** touches a second, uncharged sphere.

The excess negative charges on sphere A repel each other, so when the neutral sphere B touches A, there is a net force on the charges on A toward B. If you were to move the first charge from A to B, you would have to exert a force opposing the force of the other charges. The force you exert on the first charge is in the direction opposite its displacement. Therefore, you do negative work on it, and the electric potential difference is negative. When the next few charges are moved, they feel a repulsive force from the charges already on B, so the negative work you do on these charge is smaller, that is, the electric potential difference is less negative. At some point, the force pushing the charge off A equals the repulsive force from the charges on B. No work is done moving that charge, and the electric potential difference is zero. You would have to do work to move the next charge to B, so the electric potential difference would now be higher. But, moving that charge would require an increase in energy, so it would not occur. Thus charges move until there is no electric potential difference between the two spheres.

Suppose two spheres have different sizes, as in **Figure 21–11.** Although the total number of charges on the two spheres are the same, the larger sphere has a larger surface area, so charges can spread farther apart. With the charges farther apart, the repulsive force between them is reduced. So, if the two spheres are now touched together, there will be a net force that will move charges from the smaller to the larger sphere. Again, the charges will move to the sphere with the lower electric potential until there is no electric potential difference between the two spheres. In this case, the larger sphere will have a larger charge when equilibrium is reached.

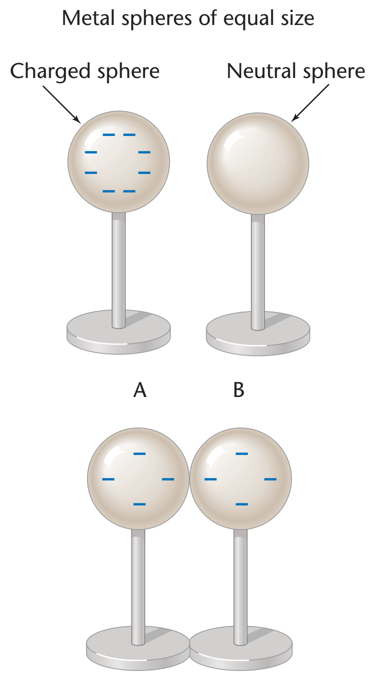


FIGURE 21–10 A charged sphere shares charge equally with a neutral sphere of equal size.

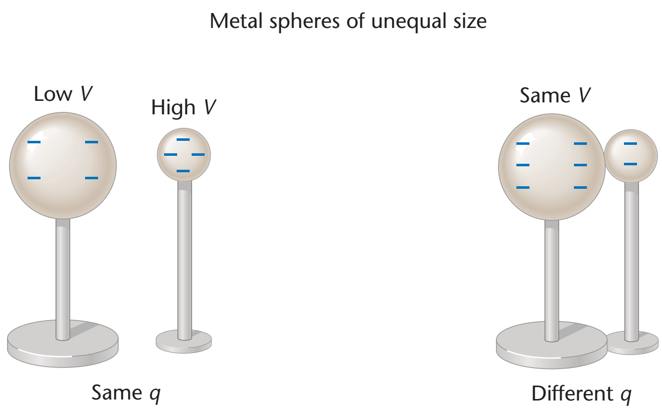


FIGURE 21–11 A charged sphere gives much of its charge to a larger sphere.

FIGURE 21–12 The ground wire on a fuel truck prevents explosion of the gasoline vapors.

The same principle explains how charges move on the individual spheres, or on any conductor. They distribute themselves so that the net force on each charge is zero. With no force, there is no electric field along the surface of the conductor. Therefore, there is no electric potential difference anywhere on the surface. The surface of a conductor is, therefore, an equipotential surface.

Earth is a very large sphere. If a charged body is touched to Earth, almost any amount of charge can flow to Earth until the electric potential difference between that body and Earth is reduced to zero. Thus, Earth can absorb all excess charge on a body. When this charge has flowed to Earth, the body becomes neutral. Touching a body to Earth to eliminate excess charge is called **grounding.** Gasoline trucks can become charged by friction. If that charge were to jump to Earth through gasoline vapor, it could cause an explosion. Instead, a metal wire on the truck safely conducts the charge to the ground, as shown in **Figure 21–12.** If a computer or other sensitive instrument were not grounded, static charges could accumulate, creating an electric potential difference between the computer and Earth. If a person touched the computer, charges could flow through the computer to the person, damaging the equipment or hurting the person.

F.Y.I.

Fewer modern cars and trucks are equipped with static strips because tires are now made to be slightly conductive.

Electric Fields Near Conductors

The charges on a conductor are spread as far apart as they can be to make the energy of the system as low as possible. The result is that all charges are on the surface of a solid conductor. If the conductor is hollow, excess charges will move to the outer surface. If a closed metal container is charged, there will be no charges on the inside surfaces of the container. In this way, a closed metal container shields the inside from electric fields. For example, people inside a car are protected from the electric fields generated by lightning. On an open coffee can there will be very few charges inside, and none near the bottom.

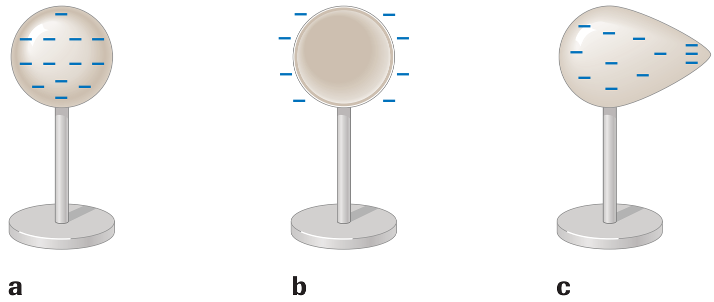


FIGURE 21–13 The electric field around a conducting body depends on the structure and shape (**b** is hollow) of the body.

So why is the electric charge visible as a corona on a power line but not in the electric wires in houses? Even though the surface of a conductor is at an equipotential, the electric field around the outside of it depends on the shape of the body as well as the electric potential difference between it and Earth. The charges are closer together at sharp points of a conductor, as indicated in **Figure 21–13.** Therefore, the field lines are closer together; and the field is stronger. This field can become so strong that nearby air molecules are separated into electrons and positive ions. As the electrons and ions recombine, energy is released and light is produced. The result is the blue glow of a corona. The electrons and ions are accelerated by the field. If the field is strong enough, when the particles hit other molecules, they will produce more ions and electrons. The stream of ions and electrons that results is a plasma, which is a conductor. The result is a spark, or, in extreme cases, lightning. To reduce coronae and sparking, conductors that are highly charged or operate at high potentials, especially those that service houses, are made smooth in shape to reduce the electric fields.

On the other hand, lightning rods are pointed so that the electric field will be strong near the end of the rod. Air molecules are pulled apart near the rod, forming the start of a conducting path from the rod to the clouds. As a result of the rod's sharply pointed shape, charges in the clouds spark to the rod rather than to a chimney or other high point on a house or other buildings. From the rod, a conductor takes the charges safely to the ground.

High-Energy Halo

Answers question from page 480.

Storing Charges: The Capacitor

When you lift a book, you increase its gravitational potential energy. This can be interpreted as storing energy in a gravitational field. In a similar way, you can store energy in an electric field. In 1746, Dutch physician and physicist Pieter Van Musschenbroek invented a device that could store a large electric charge in a small device. In honor of the city in which he worked, it was called a Leyden jar. Benjamin Franklin used a Leyden jar to store the charge from lightning and in many other experiments. A version of the Leyden jar is still in use today in electric equipment. This version has a new form, a much smaller size, and a new name. It is called the capacitor.

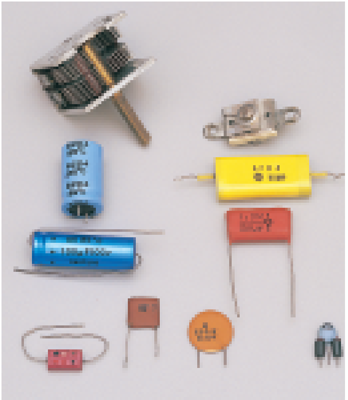


FIGURE 21–14 Various types of capacitors are pictured.

As charge is added to an object, the electric potential difference between that object and Earth increases. For a given shape and size of the object, the ratio of charge stored to electric potential difference, $q/\Delta V$, is a constant called the **capacitance,** C. For a small sphere far from the ground, even a small amount of added charge will increase the electric potential difference. Thus, C is small. The larger the sphere, the greater the charge that can be added for the same increase in electric potential difference, and thus the larger the capacitance.

The **capacitor** is a device that is designed to have a specific capacitance. All capacitors are made up of two conductors, separated by an insulator. The two conductors have equal and opposite charges. Capacitors are used today in electrical circuits to store charge. Commercial capacitors, such as those shown in **Figure 21–14,** contain strips of aluminum foil separated by thin plastic that are tightly rolled up to conserve space.

The capacitance of a capacitor is independent of the charge on it. Capacitance can be measured by first placing charge q on one plate and charge $-q$ on the other, and then measuring the electric potential difference, ΔV, that results. The capacitance is then found by using the following equation.

Capacitance $$C = \frac{q}{\Delta V}$$

Capacitance is measured in farads, F, named after Michael Faraday. One farad is one coulomb per volt (C/V). Just as one coulomb is a large amount of charge, one farad is an enormous capacitance. Capacitors usually contain capacitances between 10 picofarads (10×10^{-12} F) and 500 microfarads (500×10^{-6} F). Note that if the charge is increased, the electric potential difference also increases. The capacitance depends only on the construction of the capacitor, not on the charge, q.

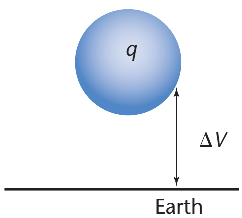
Example Problem

Finding the Capacitance

A sphere has an electric potential difference between it and Earth of 60.0 V when it has been charged to 3.0×10^{-6} C. What is its capacitance?

Sketch the Problem

- Draw a sphere above Earth identifying the electric potential difference and the charge.



Calculate Your Answer

Known:

$\Delta V = 60.0$ V

$q = 3.0 \times 10^{-6}$ C

Unknown:

$C = ?$

CONTENTS

Strategy:

Use the relationship $C = \frac{q}{\Delta V}$.

Calculations:

$$C = \frac{q}{\Delta V} = \frac{3.0 \times 10^{-6}\ \text{C}}{60.0\ \text{V}} = 5.0 \times 10^{-8}\ \text{C/V}$$
$$= 0.050\ \mu\text{F}$$

Check Your Answer

- Are the units correct? Capacitance is measured in farads.
- Are the signs correct? Values are positive.
- Is the magnitude realistic? A small capacitance has a moderate potential difference when a moderate charge is added.

Practice Problems

13. A 27-μF capacitor has an electric potential difference of 25 V across it. What is the charge on the capacitor?

14. Both a 3.3-μF and a 6.8-μF capacitor are connected across a 15-V electric potential difference. Which capacitor has a greater charge? What is it?

15. The same two capacitors are each charged to 2.5×10^{-4} C. Which has the larger electric potential difference? What is it?

16. A 2.2-μF capacitor is first charged so that the electric potential difference is 6.0 V. How much additional charge is needed to increase the electric potential difference to 15.0 V?

21.2 Section Review

1. An oil drop is motionless in a Millikan oil drop apparatus.

a. What is the direction of the electric field?

b. Which plate, upper or lower, is positively charged?

2. If the charge on a capacitor is changed, what is the effect on

a. the capacitance, C?

b. the electric potential difference, ΔV?

3. If a large, charged sphere is touched by a smaller, uncharged sphere, what can be said about

a. the potentials of the two spheres?

b. the charges on the two spheres?

4. **Critical Thinking** Suppose you have a large, hollow sphere that has been charged. Through a small hole in the sphere, you insert a small, uncharged sphere into the hollow interior. The two touch. What is the charge on the small sphere?

CHAPTER 21 REVIEW

Key Terms

21.1
- electric field
- electric field lines

21.2
- electric potential difference
- volt
- equipotential
- grounding
- capacitance
- capacitor

Summary

21.1 Creating and Measuring Electric Fields

- An electric field exists around any charged object. The field produces forces on other charged bodies.
- The electric field intensity is the force per unit charge. The direction of the electric field is the direction of the force on a tiny, positive test charge.
- Electric field lines provide a picture of the electric field. They are directed away from positive charges and toward negative charges.

21.2 Applications of Electric Fields

- Electric potential difference is the change in potential energy per unit charge in an electric field. Electric potential differences are measured in volts.
- The electric field between two parallel plates is uniform between the plates except near the edges.
- Robert Millikan's experiments showed that electric charge is quantized and that the negative charge carried by an electron is 1.60×10^{-19} C.
- Charges will move in conductors until the electric potential is the same everywhere on the conductor.
- A charged object can have its excess charge removed by touching it to Earth or to an object touching Earth. This is called grounding.
- Electric fields are strongest near sharply pointed conductors.
- Capacitance is the ratio of the charge on a body to its electric potential difference. It is independent of the charge on the body and the electric potential difference across it.

Key Equations

21.1

$$\boldsymbol{E} = \frac{\boldsymbol{F}_{\text{on } q'}}{q'}$$

21.2

$$\Delta V = \frac{W_{\text{on } q'}}{q'} \qquad \Delta V = Ed \qquad C = \frac{q}{\Delta V}$$

Reviewing Concepts

Section 21.1

1. Draw some of the electric field lines between
   a. two like charges.
   b. two unlike charges.
   c. two parallel plates of opposite charge.
2. What are the two properties a test charge must have?
3. How is the direction of an electric field defined?
4. What are electric field lines?
5. How is the strength of an electric field indicated with electric field lines?

Section 21.2

6. What SI unit is used to measure electric potential energy? What SI unit is used to measure electric potential difference?
7. Define *volt* in terms of the change in potential energy of a charge moving in an electric field.

CONTENTS

8. Why does a charged object lose its charge when it is touched to the ground?
9. A charged rubber rod placed on a table maintains its charge for some time. Why is the charged rod not grounded immediately?
10. A metal box is charged. Compare the concentration of charge at the corners of the box to the charge concentration on the sides.
11. In your own words, describe a capacitor.

Applying Concepts

12. What happens to the size of the electric field if the charge on the test charge is halved?
13. Does it require more energy or less energy to move a fixed positive charge through an increasing electric field?
14. What will happen to the electric potential energy of a charged particle in an electric field when the particle is released and free to move?
15. **Figure 21–15** shows three spheres with charges of equal magnitude, with signs as shown. Spheres Y and Z are held in place but sphere X is free to move. Initially sphere X is equidistant from spheres Y and Z. Choose the path that sphere X will follow, assuming no other forces are acting.

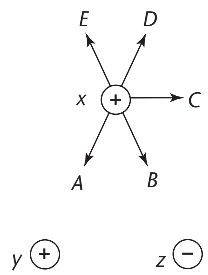


FIGURE 21–15

16. What is the unit of electric potential difference in terms of m, kg, s, and C?
17. What do the electric field lines look like when the electric field has the same strength at all points in a region?
18. When doing a Millikan oil-drop experiment, it is best to work with drops that have small charges. Therefore, when the electric field is turned on, should you try to find drops that are moving rapidly or slowly? Explain.
19. If two oil drops can be held motionless in a Millikan oil-drop experiment,
   a. can you be sure that the charges are the same?
   b. the ratios of what two properties of the drops would have to be equal?
20. Tim and Sue are standing on an insulating platform and holding hands when they are given a charge. Tim is larger than Sue. Who has the larger amount of charge, or do they both have the same amount?
21. Which has a larger capacitance, an aluminum sphere with a 1-cm diameter or one with a 10-cm diameter?
22. How can you store a different amount of charge in a capacitor?

Problems

Section 21.1

The charge of an electron is -1.60×10^{-19} C.

23. A positive charge of 1.0×10^{-5} C experiences a force of 0.20 N when located at a certain point. What is the electric field intensity at that point?
24. What charge exists on a test charge that experiences a force of 1.4×10^{-8} N at a point where the electric field intensity is 2.0×10^{-4} N/C?
25. A test charge experiences a force of 0.20 N on it when it is placed in an electric field intensity of 4.5×10^{5} N/C. What is the magnitude of the charge?
26. The electric field in the atmosphere is about 150 N/C, downward.
   a. What is the direction of the force on a charged particle?
   b. Find the electric force on a proton with charge $+1.6 \times 10^{-19}$ C.
   c. Compare the force in ***b*** with the force of gravity on the same proton (mass $= 1.7 \times 10^{-27}$ kg).
27. Carefully sketch
   a. the electric field produced by a $+1.0$-μC charge.
   b. the electric field resulting from a $+2.0$-μC charge. Make the number of field lines proportional to the change in charge.

28. Charges X, Y, and Z are all equidistant from each other. X has a $+1.0$-μC charge, Y has a $+2.0$-μC charge, and Z has a small negative charge.
a. Draw an arrow showing the force on charge Z.
b. Charge Z now has a small positive charge on it. Draw an arrow showing the force on it.

29. A positive test charge of 8.0×10^{-5} C is placed in an electric field of 50.0-N/C intensity. What is the strength of the force exerted on the test charge?

30. Electrons are accelerated by the electric field in a television picture tube, whose value is given in **Table 21-1.**
a. Find the force on an electron.
b. If the field is constant, find the acceleration of the electron (mass $= 9.11 \times 10^{-31}$ kg).

31. A lead nucleus has the charge of 82 protons.
a. What are the direction and magnitude of the electric field at 1.0×10^{-10} m from the nucleus?
b. What are the direction and magnitude of the force exerted on an electron located at this distance?

Section 21.2

32. If 120 J of work are performed to move one coulomb of charge from a positive plate to a negative plate, what potential difference exists between the plates?

33. How much work is done to transfer 0.15 C of charge through an electric potential difference of 9.0 V?

34. An electron is moved through an electric potential difference of 500 V. How much work is done on the electron?

35. A 12-V battery does 1200 J of work transferring charge. How much charge is transferred?

36. The electric field intensity between two charged plates is 1.5×10^{3} N/C. The plates are 0.080 m apart. What is the electric potential difference, in volts, between the plates?

37. A voltmeter indicates that the electric potential difference between two plates is 50.0 V. The plates are 0.020 m apart. What electric field intensity exists between them?

38. An oil drop is negatively charged and weighs 8.5×10^{-15} N. The drop is suspended in an electric field intensity of 5.3×10^{3} N/C.
a. What is the charge on the drop?
b. How many electrons does it carry?

39. A capacitor that is connected to a 45.0-V source contains 90.0 μC of charge. What is the capacitor's capacitance?

40. What electric potential difference exists across a 5.4-μF capacitor that has a charge of 2.7×10^{-3} C?

41. What is the charge in a 15.0-pF capacitor when it is connected across a 75.0-V source?

42. A force of 0.053 N is required to move a charge of 37 μC a distance of 25 cm in an electric field. What is the size of the electric potential difference between the two points?

43. In an early set of experiments in 1911, Millikan observed that the following measured charges, among others, appeared at different times on a single oil drop. What value of elementary charge can be deduced from these data?
a. 6.563×10^{-19} C
b. 8.204×10^{-19} C
c. 11.50×10^{-19} C
d. 13.13×10^{-19} C
e. 16.48×10^{-19} C
f. 18.08×10^{-19} C
g. 19.71×10^{-19} C
h. 22.89×10^{-19} C
i. 26.13×10^{-19} C

44. The energy stored in a capacitor with capacitance C, having an electric potential difference ΔV, is represented by $W = 1/2C\,\Delta V^2$. One application of this is in the electronic photoflash of a strobe light. In such a unit, a capacitor of 10.0 μF is charged to 300 V. Find the energy stored.

45. Suppose it took 30 s to charge the capacitor in problem 44.
a. Find the power required to charge it in this time.
b. When this capacitor is discharged through the strobe lamp, it transfers all its energy in 1.0×10^{-4} s. Find the power delivered to the lamp.
c. How is such a large amount of power possible?

46. Lasers are used to try to produce controlled fusion reactions that might supply large amounts of electrical energy. The lasers require brief pulses of energy that are stored in large rooms filled with capacitors. One such room has a capacitance of 61×10^{-3} F charged to a potential difference of 10.0 kV.

a. Find the energy stored in the capacitors, given that $W = 1/2C\Delta V^2$.

b. The capacitors are discharged in 10 ns (1.0×10^{-8} s). What power is produced?

c. If the capacitors are charged by a generator with a power capacity of 1.0 kW, how many seconds will be required to charge the capacitors?

47. Two point charges, one at $+3.00 \times 10^{-5}$ C and the other at -5.00×10^{-5} C are placed at adjacent corners of a square 0.800 m on a side. A third charge of $+6.00 \times 10^{-5}$ C is placed at the corner diagonally opposite to the negative charge. Calculate the magnitude and direction of the force acting on the third charge. For the direction, determine the angle the force makes with the edge of the square parallel to the line joining the first two charges.

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

48. In an ink-jet printer, drops of ink are given a certain amount of charge before they move between two large parallel plates. The purpose of the plates is to deflect the charges so that they are stopped by a gutter and do not reach the paper. This is shown in **Figure 21–16.** The plates are 1.5 cm long and have an electric field of $E = 1.2 \times 10^6$ N/C between them. Drops with a mass $m = 0.10$ ng and a charge $q = 1.0 \times 10^{-16}$ C are moving horizontally at a speed v = 15 m/s parallel to the plates. What is the vertical displacement of the drops when they leave the plates? To answer this question, go through the following steps.

a. What is the vertical force on the drops?

b. What is their vertical acceleration?

c. How long are they between the plates?

d. Given that acceleration and time, how far are they displaced?

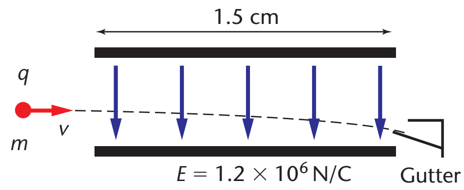


FIGURE 21–16

49. Suppose the moon had a net negative charge equal to $-q$ and Earth had a net positive charge equal to $+10q$. What value of q would yield the same magnitude force that you now attribute to gravity?

Going Further

Determining Unit Charge Millikan discovered that the electric charge always seemed to exist in multiples of a unit charge. How did he know this? What reasoning did he use to reach his conclusions? Design a modeling activity using a balance and several groups of different numbers of steel balls to determine a unit value of mass that can be used to determine the mass of a single ball. Make a bar graph of the masses versus the trials. Suggest other mass values that might result if more trial measurements were made. Consider whether the actual unit mass could be smaller or larger than your determination. Write a short summary of your findings.

Essay Research and describe the history of static electricity. Be sure to include Millikan's contributions, and evaluate the impact of his research on scientific thought.

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