CHAPTER

11

Key Concepts

In this chapter, you will learn about:

- vector fields
- electric fields
- electric potential difference
- moving charges in electric fields

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge

- define vector fields
- compare forces and fields
- compare, qualitatively, gravitational and electric potential energy
- define electric potential difference as a change in electric potential energy per unit of charge
- calculate the electric potential difference between two points in a uniform electric field
- explain, quantitatively, electric fields in terms of intensity (strength) and direction relative to the source of the field and to the effect on an electric charge
- describe, quantitatively, the motion of an electric charge in a uniform electric field
- explain electrical interactions, quantitatively, using the law of conservation of charge

Science, Technology, and Society

- explain that the goal of technology is to provide solutions to practical problems
- explain that scientific knowledge may lead to the development of new technologies and new technologies may lead to scientific discovery

Electric field theory describes electrical phenomena.

▲ **Figure 11.1** The eerie glow of St. Elmo's fire on the masts of a ship

On Christopher Columbus's second voyage to the Americas, his ships headed into stormy weather, and the tips of the ships' masts began to glow with a ghostly bluish flame. Sailors of the time believed that this bluish glow was a good sign that the ship was under the protection of St. Elmo, the patron saint of sailors, so they called the blue "flames" St. Elmo's fire (Figure 11.1).

People throughout history have written about this strange glow. Julius Caesar reported that "in the month of February, about the second watch of the night, there suddenly arose a thick cloud followed by a shower of hail, and the same night the points of the spears belonging to the Fifth Legion seemed to take fire." Astronauts have seen similar glows on spacecraft.

What is the cause of this eerie phenomenon? Why does it most often appear during thunderstorms?

You will discover the answers to these questions as you continue to study the phenomena associated with electric charges. In this chapter, you will begin by learning how knowledge of the forces related to electric charges led to the idea of fields, and you will compare different types of electric fields. Then you will learn how force is used to define the strength of electric fields. Finally, you will study the motion of charges in electric fields and explain electrical interactions using the law of conservation of energy.

11-1 QuickLab

Shielding of Cellular Phones

Electronic equipment usually contains material that is used as “shielding.” In this activity, you will discover what this shielding material does.

Problem

How does the shielding of electronic equipment, such as a cellular phone, affect its operation?

Materials

2 cellular phones
sheets (about 20 cm × 20 cm) of various materials, such as aluminium foil, plastic wrap, wax paper, paper, cloth, fur
1 short length of coaxial cable

Procedure

Part A

1. Wrap the sheet of aluminium foil around one of the cellular phones.
2. With the other cellular phone, dial the number of the wrapped cellular phone and record any response.
3. Remove the aluminium foil and again dial the number of the cellular phone.
4. Repeat steps 1 to 3 using the sheets of other materials.

Part B

5. Carefully remove the outer strip of insulated plastic around one end of the coaxial cable and examine the inner coaxial cable wires.

Questions

1. What effect did wrapping a cellular phone with the various materials have on the operation of the cellular phone?
2. Cellular phones receive communication transmissions that are electrical in nature. Speculate why the transmissions are shielded by certain materials. Which materials are most effective for shielding?
3. What material forms the protective wrapping around the inner coaxial transmission wires? Explain the purpose of this protective wrapping.

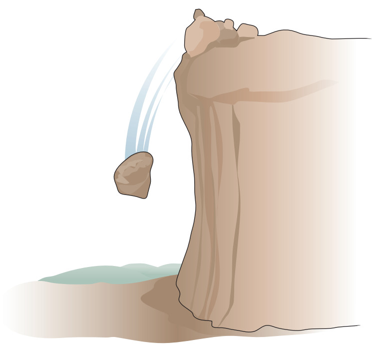
Think About It

1. Desktop computers or computers in vehicles have sensitive electronic components that must be protected from outside electrical interference. Identify a possible source of outside electrical interference. Describe how computer components may be protected from this interference and explain why this protection is necessary.
2. Sometimes, if your debit card fails to scan, the clerk wraps the card with a plastic bag and re-scans it. Explain why a plastic bag wrapped around a card would allow the card to scan properly. Why do clerks not wrap the card with aluminium foil for re-scanning?

Discuss and compare your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes to your ideas.

11.1 Forces and Fields

▲ **Figure 11.2** Forces exerted by the horses attached to the chariot cause the "violent" motion of the chariot.



▲ **Figure 11.3** To return to its natural element, a rock falls with "natural" motion to Earth's surface.

The ancient Greek philosophers explained most types of motion as being the result of either "violent" or "natural" forces. They thought that violent forces cause motion as the result of a force exerted by one object in contact with another (Figure 11.2). They thought that natural forces cause the motion of objects toward their "natural element" (Figure 11.3). However, the Greeks found another kind of motion more difficult to explain. You will observe this kind of motion in the following Minds On activity.

MINDS ON **Action at a Distance**

Charge a rubber rod by rubbing it with fur and slowly bring it close to the hairs on your forearm. Do not touch the hairs or your arm. Observe what happens.

1. What evidence is there that the charged rod affects the hairs on your arm without actual contact?
2. Is the force exerted by the rod on the hairs of your arm attractive or repulsive?

info **BIT**

A new theory in physics, called string theory, proposes that objects interact through "strings" that transmit the forces between the objects. This new theory has a striking similarity to the effluvium theory proposed 2500 years ago.

The rubber rod seems to be able to exert a type of violent force on the hairs of your arm without visible contact. This type of force was classified as "action at a distance," where one object could exert a force on another object without contact. To explain "action at a distance," the Greeks proposed the effluvium theory.

According to this theory, all objects are surrounded by an effluvium. This invisible substance is made up of minute string-like atoms emitted by the object that pulsate back and forth. As the effluvium extends out to other bodies, the atoms of the different objects become entangled. Their effluvium eventually draws them toward each other. The effluvium theory helped to explain what seemed to be "action at a distance." Although the effluvium was invisible, there was still a form of contact between the objects.

Fields

In the 17th century, scientists, including Newton, tried to determine why one object can exert a force on another object without touching it. These scientists attempted to explain "action at a distance," such as the curved path of a thrown ball or the effect of a charged piece of amber on the hair on a person's arm. Finding that "natural" or "violent" forces and "effluvium" could not explain gravity or electrical forces, scientists developed the concept of fields to describe these forces.

A **field** is defined as a region of influence surrounding an object. The concept of fields helps explain the laws of universal gravitation, which you studied in Chapter 4.

field: a region of influence surrounding an object

Consider a space module on its way to the Moon (Figure 11.4). Nearing its lunar destination, the module begins to experience the increasing influence of the Moon. As a result, the module's motion begins to follow a curved path, similar to the projectile motion of an object thrown horizontally through the air near Earth's surface.

As Newton's laws state, the motion of any object can follow a curved path only when acted on by a non-zero force that has a perpendicular component. In space, this happens to the space module when it is near the Moon, so the space near the Moon must be different from the space where no large objects like the Moon are present. From this, we can infer that a field exists around a large object, such as the Moon. When other objects enter this field, they interact with the Moon. Similarly, Earth has a field. Gravitational force acts on other objects that enter this field. Recall from Chapter 4 that this field around objects is called a gravitational field.

Michael Faraday (1791–1867) developed the concept of fields to explain electrostatic phenomena. He determined that the space around a rubber rod must be different when the rubber rod is charged than when it is not. The charges on the rod create an electric field around the rod. An electrostatic force acts on another charged object when it is placed in this field. An electric field exists around every charge or charged object. It can exist in empty space, whether or not another charge or charged object is in the field.

Although field theory is a powerful tool for describing phenomena and predicting forces, physicists are still debating how objects can actually exert forces at a distance. Chapter 17 describes how quantum theory provides an extremely accurate model for describing such forces.

▲ **Figure 11.4** A space module passing near a large planet or the Moon follows a curved path.

Concept Check

Use field theory to explain the path of a baseball thrown from outfield to home plate.

11-2 Inquiry Lab

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Electric Field Patterns — Demonstration

Question

What is the shape of the electric field around various charged objects?

Materials and Equipment

plastic platform with 2 electrode holders
overhead projector
petri dish
canola or olive oil
lawn seeds
single-point electrode
two-point (oppositely charged) electrodes
parallel copper plates about 4 cm × 4 cm
hollow sphere conductor 4–6 cm in diameter
2 Wimshurst generators
connecting wires

Procedure

1. Pour some of the canola or olive oil into the petri dish so the dish is about three-quarters full.
2. Place the petri dish with the oil on the plastic platform on the overhead projector. Carefully sprinkle the lawn seeds evenly over the surface of the oil.
3. Attach the single-point electrode, with a connecting wire, to one contact of the Wimshurst generator. Immerse the electrode in the oil in the centre of the dish.
4. Crank the Wimshurst generator several times and carefully observe the pattern of the seeds in the oil.
5. Remove the electrode and allow sufficient time for the lawn seeds to redistribute on the surface. (Gentle stirring with a pencil might be required.)
6. Repeat steps 3 to 5 with each of the following:
   (a) two electrodes connected to similar contacts on two Wimshurst machines
   (b) two electrodes connected to opposite contacts on one Wimshurst machine
   (c) two parallel copper plates connected to opposite contacts on one Wimshurst machine
   (d) one hollow sphere connected to one contact of one Wimshurst machine

Analysis

1. Describe and analyze the pattern of the lawn seeds created by each of the charged objects immersed in the oil in step 6 of the procedure by answering the following questions:
   (a) Where does the density of the lawn seeds appear to be the greatest? the least?
   (b) Does there appear to be a starting point and an endpoint in the pattern created by the lawn seeds?

2. Are there any situations where there appears to be no observable effect on the lawn seeds?

3. Based on your observations of the patterns created by the lawn seeds on the surface of the oil, what conclusion can you make about the space around charged objects?

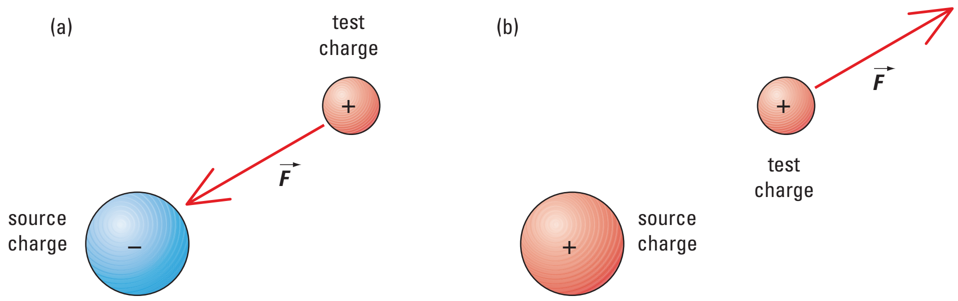
Magnitude and Direction of an Electric Field

The electric field that surrounds a charged object has both magnitude and direction. Therefore, an electric field is classified as a vector field. At any point around a charge, the field can be represented by a vector arrow. The arrow's length represents the magnitude of the electric field and the arrowhead indicates direction at that point.

By definition, the direction of the electric field around a charge is the direction of the force experienced by a small positive **test charge** placed in the electric field (Figure 11.5). A test charge is a charge with a magnitude small enough so that it does not disturb the charge on the **source charge** and thus change its electric field.

test charge: charge with a magnitude small enough that it does not disturb the charge on the source charge and thus change its electric field

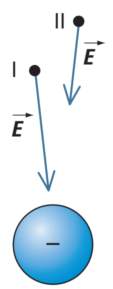
source charge: charge that produces an electric field



▲ **Figure 11.5** The direction of the electric field at a point is the direction of the electric force exerted on a positive test charge at that point. (a) If the source charge is negative, the field is directed toward the source. (b) If the source charge is positive, the field is directed away from the source.

Concept Check

Identify the difference in the electric field strength, $\vec{E}$, at points I and II, as represented by the vector arrows in Figure 11.6.



◀ **Figure 11.6**

You can determine the magnitude of the electric field around a point charge from the effect on another charge placed in the field. If a small positive test charge is placed in the field, this charge will experience a greater force when it is near the charge producing the field than when it is farther away from it.

By definition, the electric field ($\vec{E}$) at a given point is the ratio of the electric force ($\vec{F}_e$) exerted on a charge (q) placed at that point to the magnitude of that charge. The electric field can be calculated using the equation

$$\vec{E} = \frac{\vec{F}_e}{q}$$

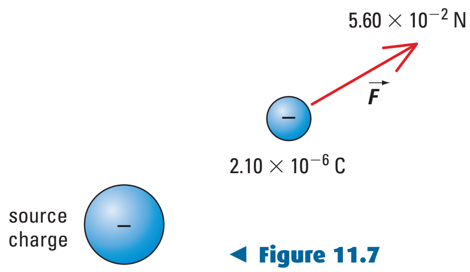
where q is the magnitude of the test charge in coulombs (C); $\vec{F}_e$ is the electric force on the charge in newtons (N); and $\vec{E}$ is the strength of the electric field at that point in newtons per coulomb (N/C), in the direction as defined previously.

info **BIT**

A tremendous range of field strengths occurs in nature. For example, the electric field 30 cm away from a light bulb is roughly 5 N/C, whereas the electron in a hydrogen atom experiences an electric field in the order of 10^{11} N/C from the atom's nucleus.

Example 11.1

A sphere with a negative charge of 2.10×10^{-6} C experiences an electrostatic force of repulsion of 5.60×10^{-2} N when it is placed in the electric field produced by a source charge (Figure 11.7). Determine the magnitude of the electric field the source charge produces at the sphere.



◀ **Figure 11.7**

Given

$q = -2.10 \times 10^{-6}$ C

$\vec{F}_e = 5.60 \times 10^{-2}$ N [repulsion]

Required

magnitude of the electric field ($|\vec{E}|$)

Analysis and Solution

Since $\vec{E} = \dfrac{\vec{F}_e}{q}$,

$$|\vec{E}| = \frac{|\vec{F}_e|}{q}$$

$$= \frac{5.60 \times 10^{-2}\ \text{N}}{2.10 \times 10^{-6}\ \text{C}}$$

$$= 2.67 \times 10^{4}\ \text{N/C}$$

Paraphrase

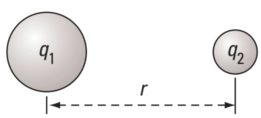
The magnitude of the electric field is 2.67×10^4 N/C at the given point.

Practice Problems

1. An ion with a charge of 1.60×10^{-19} C is placed in an electric field produced by another larger charge. If the magnitude of the field at this position is 1.00×10^{3} N/C, calculate the magnitude of the electrostatic force on the ion.
2. The magnitude of the electrostatic force on a small charged sphere is 3.42×10^{-18} N when the sphere is at a position where the magnitude of the electric field due to another larger charge is 5.34 N/C. What is the magnitude of the charge on the small charged sphere?

Answers

1. 1.60×10^{-16} N
2. 6.40×10^{-19} C



▲ **Figure 11.8** A test charge (q_2) is placed in the electric field of a source charge (q_1). The distance between their centres is r.

PHYSICS INSIGHT

Equations based on Coulomb's law only work for point charges.

The equation for determining the magnitude of the electric field around a point charge, like that shown in Figure 11.8, can be derived mathematically as follows:

If $|\vec{E}| = \dfrac{|\vec{F}_e|}{q_2}$ and $|\vec{F}_e| = \dfrac{kq_1q_2}{r^2}$, then

$$|\vec{E}| = \frac{\frac{kq_1\cancel{q_2}}{r^2}}{}$$

$$|\vec{E}| = \frac{kq}{r^2}$$

where q is the magnitude of the source charge producing the electric field in coulombs (ignore the sign of the charge); r is the distance from the centre of the source charge to a specific point in space in metres; k is Coulomb's constant (8.99×10^9 N·m²/C²); and $|\vec{E}|$ is the magnitude of the electric field in newtons per coulomb.

Example 11.2

Determine the electric field at a position P that is 2.20×10^{-2} m from the centre of a negative point charge of 1.70×10^{-6} C.

Given

$q = -1.70 \times 10^{-6}$ C
$r = 2.20 \times 10^{-2}$ m

Required

electric field $(\vec{E})$

Analysis and Solution

The source charge producing the electric field is q. So,

$$
\begin{aligned}
|\vec{E}| &= \frac{kq}{r^2} \\
&= \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(1.70 \times 10^{-6}\ \cancel{\text{C}})}{(2.20 \times 10^{-2}\ \text{m})^2} \\
&= 3.16 \times 10^7\ \text{N/C}
\end{aligned}
$$

Since the source charge is negative and the field direction is defined as the direction of the electrostatic force acting on a positive test charge, the electric field is directed *toward* the source charge.

Paraphrase

The electric field at point P is 3.16×10^7 N/C [toward the source].

Practice Problems

1. The electric field at a position 2.00 cm from a charge is 40.0 N/C directed away from the charge. Determine the charge producing the electric field.
2. An electron has a charge of 1.60×10^{-19} C. At what distance from the electron would the magnitude of the electric field be 5.14×10^{11} N/C?

Answers

1. $+1.78 \times 10^{-12}$ C
2. 5.29×10^{-11} m

Concept Check

Compare gravitational fields and electrostatic fields by listing two similarities and two differences between the two types of fields.

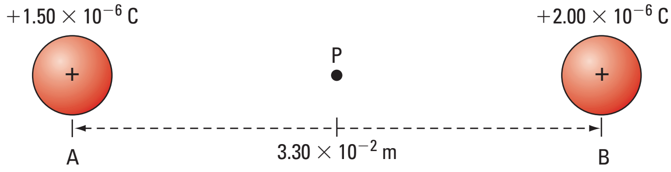
Often, more than one charge creates an electric field at a particular point in space. In earlier studies, you learned the superposition principle for vectors. According to the superposition principle, fields set up by many sources superpose to form a single net field. The vector specifying the net field at any point is simply the vector sum of the fields of all the individual sources, as shown in the following examples. Example 11.3 shows how to calculate the net electric field at a point in one-dimensional situations.

e MATH

The nucleus of an atom exhibits both electric and gravitational fields. To study their similarities and differences graphically, visit www.pearsoned.ca/school/physicssource.

Example 11.3

Two positively charged spheres, A and B, with charges of 1.50×10^{-6} C and 2.00×10^{-6} C, respectively, are 3.30×10^{-2} m apart. Determine the net electric field at a point P located midway between the centres of the two spheres (Figure 11.9).



▲ **Figure 11.9**

Given

$q_A = +1.50 \times 10^{-6}$ C

$q_B = +2.00 \times 10^{-6}$ C

$r = 3.30 \times 10^{-2}$ m

Required

net electric field at point P ($\vec{E}_{net}$)

Analysis and Solution

As shown in Figure 11.10, the electric field created by q_A at point P is directed to the right, while the electric field at point P created by q_B is directed to the left. Consider right to be positive.

The distance between q_A and point P is:

$$r_{q_A \text{ to P}} = \frac{3.30 \times 10^{-2}\ \text{m}}{2} = 1.65 \times 10^{-2}\ \text{m}$$

To calculate the electric field at point P created by q_A, use:

$$|\vec{E}_{q_A}| = k\frac{q_A}{r^2_{q_A \text{ to P}}} = \frac{\left(8.99 \times 10^9\ \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(1.50 \times 10^{-6}\ \cancel{\text{C}})}{(1.65 \times 10^{-2}\ \text{m})^2} = 4.953 \times 10^7\ \text{N/C}$$

To calculate the electric field at point P created by q_B, use:

$$|\vec{E}_{q_B}| = k\frac{q_B}{r^2_{q_B \text{ to P}}} = \frac{\left(8.99 \times 10^9\ \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(2.00 \times 10^{-6}\ \cancel{\text{C}})}{(1.65 \times 10^{-2}\ \text{m})^2} = 6.604 \times 10^7\ \text{N/C}$$

Use vector addition to determine the net electric field at point P:

$$\begin{aligned}\vec{E}_{net} &= \vec{E}_{q_A} + \vec{E}_{q_B} \\ &= 4.953 \times 10^7\ \text{N/C [right]} + 6.604 \times 10^7\ \text{N/C [left]} \\ &= 1.65 \times 10^7\ \text{N/C [left]}\end{aligned}$$

Paraphrase

The net electric field at point P is 1.65×10^7 N/C [left].

Practice Problems

1. Calculate the net electric field at a point 2.10×10^{-2} m to the left of the 1.50×10^{-6} C charge in Figure 11.9.
2. An electron and a proton are 5.29×10^{-11} m apart in a hydrogen atom. Determine the net electric field at a point midway between the two charges.

Answers

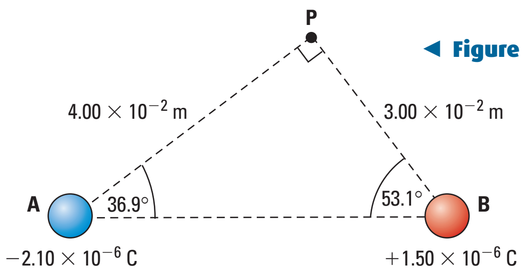
1. 3.67×10^7 N/C [left]
2. 4.11×10^{12} N/C [toward the electron]

▲ **Figure 11.10**

Example 11.4 demonstrates how to determine the net electric field at a point due to two charges in a two-dimensional situation.

Example 11.4

Calculate the net electric field at a point P that is 4.00×10^{-2} m from a small metal sphere A with a negative charge of 2.10×10^{-6} C and 3.00×10^{-2} m from another similar sphere B with a positive charge of 1.50×10^{-6} C (Figure 11.11).



◀ **Figure 11.11**

Given

$q_A = -2.10 \times 10^{-6}$ C $\qquad q_B = +1.50 \times 10^{-6}$ C

$r_{A\text{ to }P} = 4.00 \times 10^{-2}$ m $\qquad r_{B\text{ to }P} = 3.00 \times 10^{-2}$ m

$\theta_A = 36.9°$ to the horizontal $\qquad \theta_B = 53.1°$ to the horizontal

Required

net electric field at point P ($\vec{E}_{net}$)

Analysis and Solution

Since q_A is a negative charge, the electric field created by q_A at point P is directed toward q_A from point P.
Since q_B is a positive charge, the electric field created by q_B at point P is directed away from q_B toward point P.

Determine the electric field created by q_A at point P:

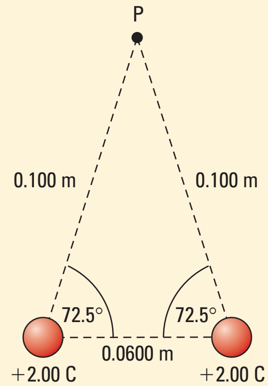
$$
\begin{aligned}
|\vec{E}_A| &= \frac{kq_A}{r^2_{A\text{ to }P}} \\
&= \frac{\left(8.99 \times 10^9 \frac{N \cdot m^2}{C^{\cancel{2}}}\right)(2.10 \times 10^{-6}\ \cancel{C})}{(4.00 \times 10^{-2}\ m)^2} \\
&= 1.180 \times 10^7\ N/C
\end{aligned}
$$

Determine the electric field created by q_B at point P:

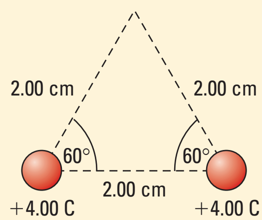
$$
\begin{aligned}
|\vec{E}_B| &= \frac{kq_B}{r^2_{B\text{ to }P}} \\
&= \frac{\left(8.99 \times 10^9 \frac{N \cdot m^2}{C^{\cancel{2}}}\right)(1.50 \times 10^{-6}\ \cancel{C})}{(3.00 \times 10^{-2}\ m)^2} \\
&= 1.498 \times 10^7\ N/C
\end{aligned}
$$

Practice Problems

1. Calculate the net electric field at point P, which is 0.100 m from two similar spheres with positive charges of 2.00 C and separated by a distance of 0.0600 m, as shown in the figure below.



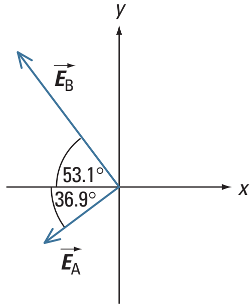
2. Two charges of +4.00 C are placed at the vertices of an equilateral triangle with sides of 2.00 cm, as shown in the figure below. Determine the net electric field at the third vertex of the triangle.



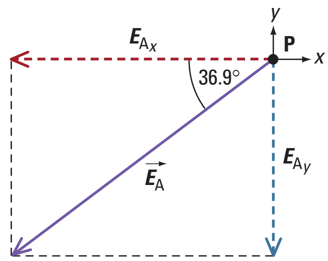
Answers

1. 3.43×10^{12} N/C [90.0°]
2. 1.56×10^{14} N/C [90.0°]

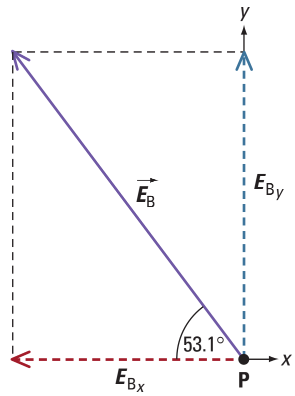
The directions of $\vec{E}_A$ and $\vec{E}_B$ are shown in Figure 11.12.



▲ **Figure 11.12**



▲ **Figure 11.13**



▲ **Figure 11.14**

Resolve each electric field into x and y components (see Figures 11.13 and 11.14). Use vector addition to determine the resultant electric field.

$$\begin{aligned} E_{A_x} &= -(1.180 \times 10^7 \text{ N/C})(\cos 36.9°) & E_{A_y} &= -(1.180 \times 10^7 \text{ N/C})(\sin 36.9°) \\ &= -9.436 \times 10^6 \text{ N/C} & &= -7.085 \times 10^6 \text{ N/C} \\ E_{B_x} &= -(1.498 \times 10^7 \text{ N/C})(\cos 53.1°) & E_{B_y} &= (1.498 \times 10^7 \text{ N/C})(\sin 53.1°) \\ &= -8.994 \times 10^6 \text{ N/C} & &= 1.198 \times 10^7 \text{ N/C} \end{aligned}$$

Add the x components:

$$\begin{aligned} E_{\text{net}_x} &= E_{A_x} + E_{B_x} \\ &= (-9.436 \times 10^6 \text{ N/C}) + (-8.994 \times 10^6 \text{ N/C}) \\ &= -1.843 \times 10^7 \text{ N/C} \end{aligned}$$

Add the y components:

$$\begin{aligned} E_{\text{net}_y} &= E_{A_y} + E_{B_y} \\ &= (-7.085 \times 10^6 \text{ N/C}) + (1.198 \times 10^7 \text{ N/C}) \\ &= 4.895 \times 10^6 \text{ N/C} \end{aligned}$$

Use the Pythagorean theorem to solve for the magnitude of the electric field:

$$\begin{aligned} |\vec{E}_{\text{net}}| &= \sqrt{(1.843 \times 10^7 \text{ N/C})^2 + (4.895 \times 10^6 \text{ N/C})^2} \\ &= 1.91 \times 10^7 \text{ N/C} \end{aligned}$$

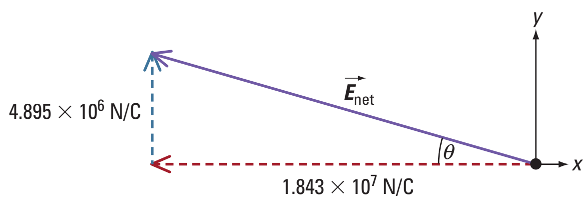
Use the tangent function to determine the direction of the net electric field at point P (Figure 11.15).

$$\tan\theta = \frac{4.895 \times 10^6 \cancel{\text{N/C}}}{1.843 \times 10^7 \cancel{\text{N/C}}}$$

$$\theta = 14.9°$$

The direction of the net field is

$180° - 14.9° = 165°$



▲ **Figure 11.15**

Paraphrase

The net electric field at point P is 1.91×10^7 N/C [165°].

In chapter 10, you learned that there are two types of electric charges that interact and are affected by electrostatic forces. In this section, you have learned that these charges are surrounded by electric fields—regions of electric influence around every charge. Electrostatic forces affect charges placed in these fields. Fields explain how two charges can interact, even though there is no contact between them. Since electric fields are vector fields, you can use vector addition to determine a net electric field at a point in the presence of more than one charge in one-dimensional and two-dimensional situations.

11.1 Check and Reflect

Knowledge

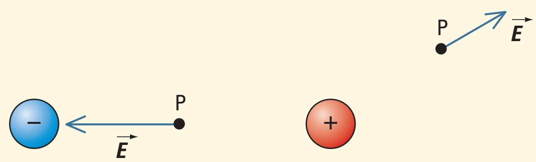
1. What is the difference between an electric force and an electric field?

2. Why was it necessary to introduce a "field theory"?

3. How is the direction of an electric field defined?

4. Why is an electric field classified as a vector field?

5. If vector arrows can represent an electric field at a point surrounding a charge, identify the two ways that the vector arrows, shown below, represent differences in the electric fields around the two source charges.



6. Describe the effect on the electric field at a point

(a) if the magnitude of the charge producing the field is halved

(b) if the sign of the charge producing the field is changed

(c) if the magnitude of the test charge in the field is halved

Applications

7. Given a small sphere with a positive charge of 4.50×10^{-6} C, determine:

(a) the magnitude and direction of the electric field at a point 0.300 m to the right of the charge

(b) the magnitude and direction of the electric force acting on a positive charge of 2.00×10^{-8} C placed at the point in (a)

8. A small test sphere with a negative charge of 2.50 μC experiences an electrostatic attractive force of magnitude 5.10×10^{-2} N when it is placed at a point 0.0400 m from another larger charged sphere. Calculate

(a) the magnitude and direction of the electric field at this point

(b) the magnitude and the sign of charge on the larger charged sphere

9. A negative charge of 3.00 mC is 1.20 m to the right of another negative charge of 2.00 mC. Calculate

(a) the net electric field at a point along the same line and midway between the two charges

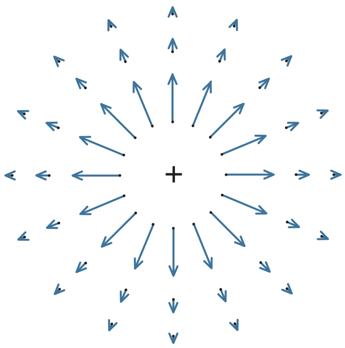
(b) the point along the same line between the two charges where the net electric field will be zero

Extension

10. Four similarly charged spheres of -5.00 μC are placed at the corners of a square with sides of 1.20 m. Determine the electric field at the point of intersection of the two diagonals of the square.

e TEST

To check your understanding of forces and fields, follow the eTest links at www.pearsoned.ca/school/physicssource.



▲ **Figure 11.16** A three-dimensional map of the electric field around a source charge

11.2 Electric Field Lines and Electric Potential

In section 11.1, you learned that the electric field from a charge q at a point P can be represented by a vector arrow, as shown in Figure 11.16. The length and direction of the vector arrow represent the magnitude and direction of the electric field ($\vec{E}$) at that point. By measuring the electric force exerted on a test charge at an infinite number of points around a source charge, a vector value of the electric field can be assigned to every point in space around the source charge. This creates a three-dimensional map of the electric field around the source charge (Figure 11.16).

info **BIT**

A lightning rod works because of the concentration of charges on the point of a conductor. This concentration of charge creates an electric field that ionizes air molecules around the point. The ionized region either makes contact with an upward streamer to a cloud, thus preventing the formation of a damaging return lightning stroke, or intercepts a downward leader from the clouds and provides a path for the lightning to the ground to prevent damage to the structure.

Electric Field Lines

For many applications, however, a much simpler method is used to represent electric fields. Instead of drawing an infinite number of vector arrows, you can draw lines, called **electric field lines,** to represent the electric field. Field lines are drawn so that exactly one field line goes through any given point within the field, and the tangent to the field line at the point is in the direction of the electric field vector at that point. You can give the field lines a direction such that the direction of the field line through a given point agrees with the direction of the electric field at that point.

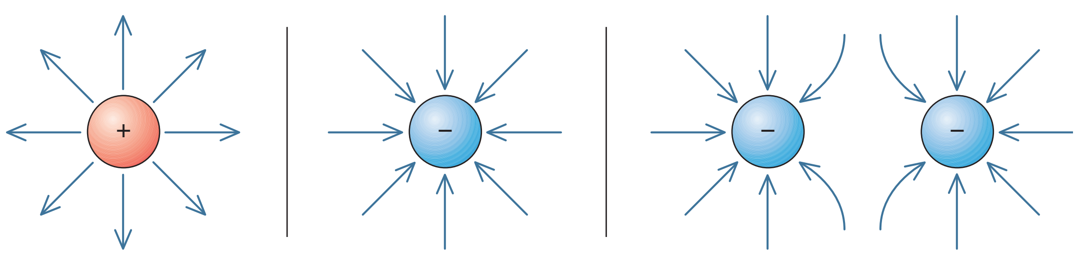
Use the following rules when you draw electric field lines around a point charge:

- Electric field lines due to a positive source charge start from the charge and extend radially away from the charge to infinity.
- Electric field lines due to a negative source charge come from infinity radially into and terminate at the negative source charge.
- The density of lines represents the magnitude of the electric field. In other words, the more closely spaced and the greater the number of lines, the stronger is the electric field.

e **SIM**

Explore the electric fields around a point charge and two charges. Follow the eSim links at www.pearsoned.ca/school/physicssource.

Figure 11.17 shows how to draw electric field lines around one and two negative point charges.



▲ **Figure 11.17** The field lines around these charges were drawn using the rules given above.

MINDS ON Drawing Electric Field Lines

Rarely is the electric field at a point in space influenced by a single charge. Often, you need to determine the electric field for a complicated arrangement of charges. Electric field lines can be used to display these electric fields.

In Figure 11.18, lawn seeds have been sprinkled on the surface of a container of cooking oil. In each case, a different charged object has been put into the oil.

- On a sheet of paper, sketch the electric field lines in each situation using the rules for drawing electric field lines given on page 554.
- Use concise statements to justify the pattern you drew in each of the sketches.

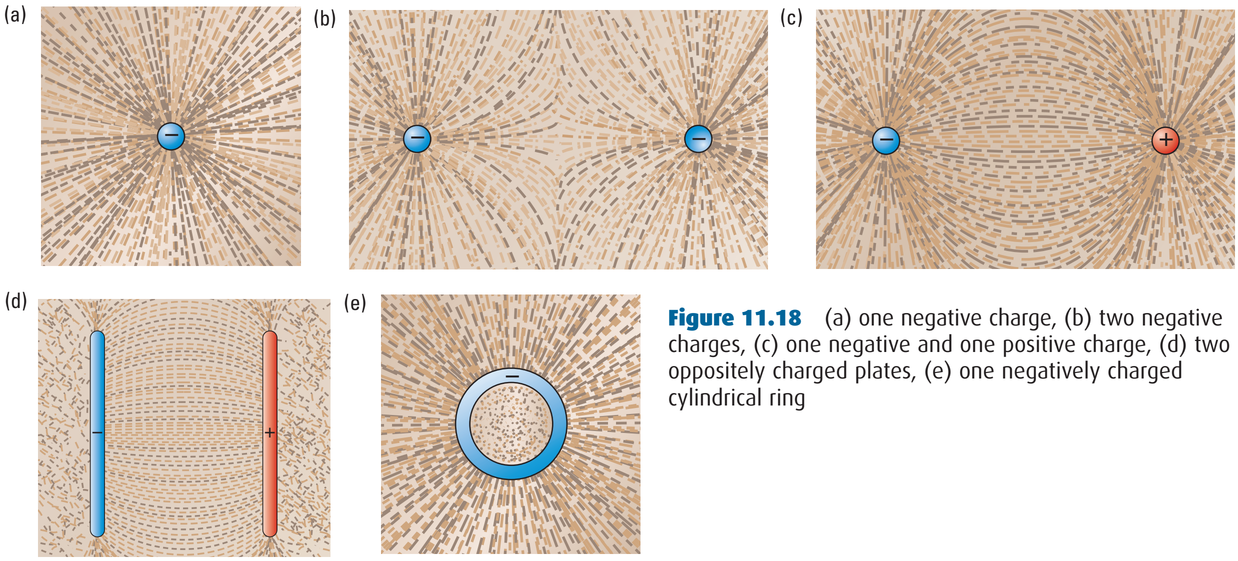


Figure 11.18 (a) one negative charge, (b) two negative charges, (c) one negative and one positive charge, (d) two oppositely charged plates, (e) one negatively charged cylindrical ring

Conductors and Electric Field Lines

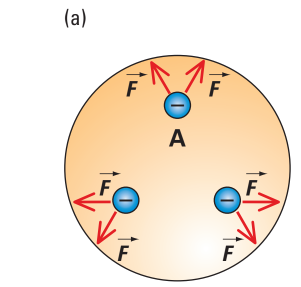
In a conductor, electrons move freely until they reach a state of static equilibrium. For static equilibrium to exist, all charges must be at rest and thus must experience no net force. Achieving static equilibrium creates interesting distributions of charge that occur only in conducting objects and not in non-conducting objects. Following are five different situations involving charge distribution on conductors and their corresponding electric field lines.

Solid Conducting Sphere

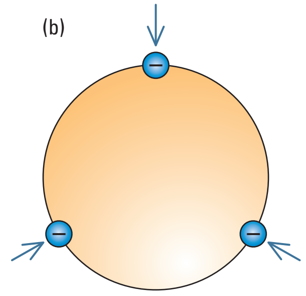
When a solid metal sphere is charged, either negatively or positively, does the charge distribute evenly throughout the sphere?

To achieve static equilibrium, all excess charges move as far apart as possible because of electrostatic forces of repulsion. A charge on the sphere at position A in Figure 11.19(a), for example, would experience a net force of electrostatic repulsion from the other charges. Consequently, all excess charges on a solid conducting sphere are repelled. These excess charges distribute evenly on the surface of the metal conducting sphere.

Figure 11.19(b) shows the electric field lines created by the distribution of charge on the surface of a solid conducting sphere. Because electric field lines cannot have a component tangential to this surface, the lines at the outer surface must always be perpendicular to the surface.



▲ **Figure 11.19(a)** Charges on a solid sphere



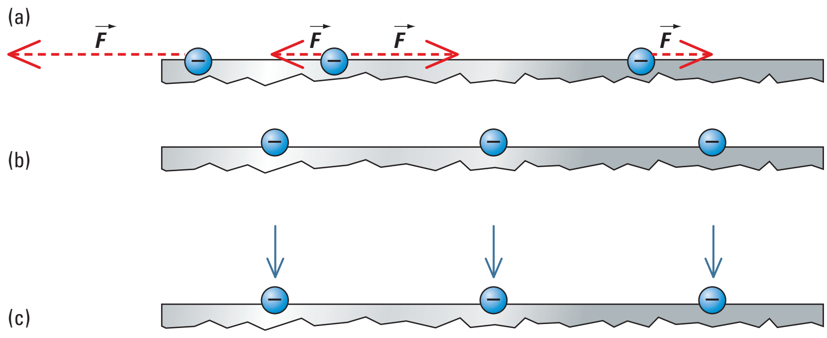
▲ **Figure 11.19(b)** Electric field lines for a charged solid sphere

Solid, Flat, Conducting Plate

How do excess charges, either positive or negative, distribute on a solid, flat, conducting plate like the one in Figure 11.20(a)?

On a flat surface, the forces of repulsion are similarly parallel or tangential to the surface. Thus, electrostatic forces of repulsion acting on charges cause the charges to spread and distribute evenly along the outer surface of a charged plate, as shown in Figure 11.20(b).

Electric field lines extend perpendicularly toward a negatively charged plate. The electric field lines are uniform and parallel, as shown in Figure 11.20(c).



▲ **Figure 11.20**
(a) Forces among three charges on the top surface of a flat, conducting plate
(b) Uniform distribution of charges on a charged, flat, conducting plate
(c) Uniform distribution of charges, shown with electric field lines

Irregularly Shaped Solid Conducting Object

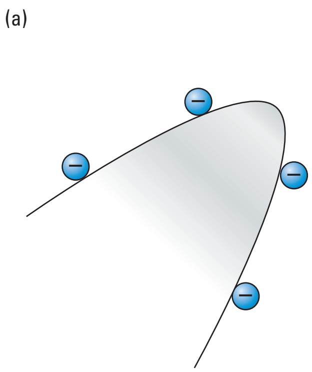
For an irregularly shaped solid conductor, the charges are still repelled and accumulate on the outer surface. But do the charges distribute evenly on the outer surface? Figure 11.21(a) is an example of a charged, irregularly shaped object.

On a flatter part of the surface, the forces of repulsion are nearly parallel or tangential to the surface, causing the charges to spread out more, as shown in Figure 11.21(b). At a pointed part of a convex surface, the forces are directed at an angle to the surface, so a smaller component of the forces is parallel or tangential to the surface. With less repulsion along the surface, more charge can accumulate closer together. As a rule, the net electrostatic forces on charges cause the charges to accumulate at the points of an irregularly shaped convex conducting object. Conversely, the charges will spread out on an irregularly shaped concave conducting object.

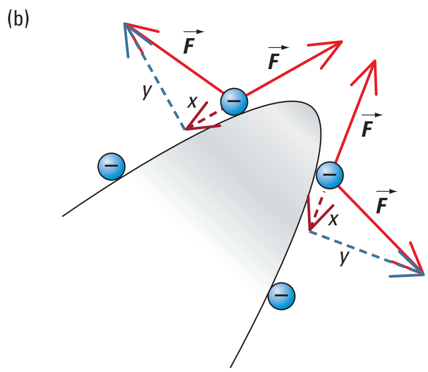
On irregularly shaped conductors, the charge density is greatest where the surface curves most sharply (Figure 11.21(c)). The density of electric field lines is also greatest at these points.

info BIT

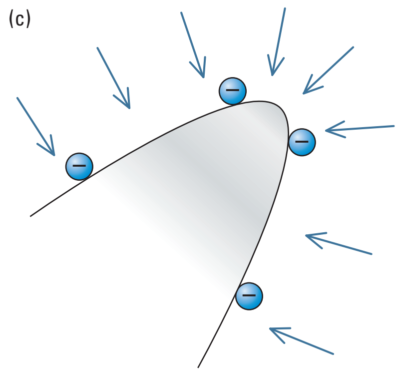
The accumulation of charge on a pointed surface is the explanation for St. Elmo's fire, which you read about at the beginning of this chapter. St. Elmo's fire is a plasma (a hot, ionized gas) caused by the powerful electric field from the charge that accumulates on the tips of raised, pointed conductors during thunderstorms. St. Elmo's fire is known as a form of *corona discharge* or *point discharge*.



▲ **Figure 11.21(a)** A charged, irregularly shaped convex object



▲ **Figure 11.21(b)** Forces affecting charges on the surface of an irregularly shaped convex object

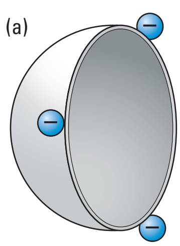


▲ **Figure 11.21(c)** Electric field lines around a charged irregularly shaped convex object

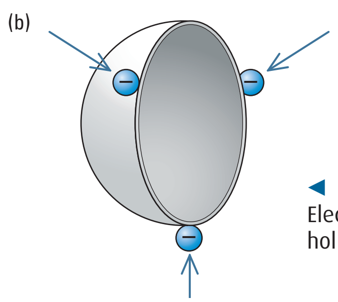
Hollow Conducting Object

When a hollow conducting object is charged, either negatively or positively, does the charge distribute evenly throughout the inner and outer surfaces of the object?

As you saw in Figures 11.19, 11.20, and 11.21, excess charges move to achieve static equilibrium, and they move as far apart as possible because of electrostatic forces of repulsion. In a hollow conducting object, all excess charges are still repelled outward, as shown in Figure 11.22(a). However, they distribute evenly only on the outer surface of the conducting object. There is no excess charge on the inner surface of the hollow object, no matter what the shape of the object is. The corresponding electric field lines created by the distribution of charge on the outer surface of a hollow object are shown in Figure 11.22(b). The electric field lines at the outer surface must always be perpendicular to the outer surface.



◀ **Figure 11.22(a)** A charged hollow conducting object



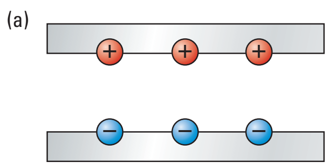
◀ **Figure 11.22(b)** Electric field lines on a hollow conducting object info BIT

Coaxial cable wires are used to transmit electric signals such as cable TV to your home. To prevent electric and magnetic interference from outside, a covering of conducting material surrounds the coaxial wires. Any charge applied to the conducting layer accumulates on the outside of the covering. No electric field is created inside a hollow conductor, so there is no influence on the signals transmitted in the wires.

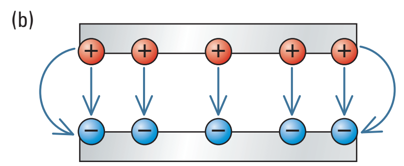
Most surprisingly, the electric field is zero everywhere inside the conductor, so there are no electric field lines anywhere inside a hollow conductor. As previously described, this effect can be explained using the superposition principle. Fields set up by many sources superpose, forming a single net field. The vector specifying the magnitude of the net field at any point is simply the vector sum of the fields of each individual source. Anywhere within the interior of a hollow conducting object, the vector sum of all the individual electric fields is zero. For this reason, the person inside the Faraday cage, shown in the photograph on page 508, is not affected by the tremendous charges on the outside surface of the cage.

Parallel Plates

If two parallel metal plates, such as those in Figure 11.23(a), are oppositely charged, how are the charges distributed? Electrostatic forces of repulsion of like charges, within each plate, cause the charges to distribute evenly within each plate, and electrostatic forces of attraction of opposite charges on the two plates cause the charges to accumulate on the inner surfaces. Thus, the charges spread and distribute evenly on the inner surfaces of the charged plates.



▲ **Figure 11.23(a)**
The distribution of net charge on oppositely charged parallel plates



▲ **Figure 11.23(b)**
Electric field lines between two oppositely charged parallel plates

e WEB

Research the operation of an ink-jet printer. What is the function of charged plates in these printers? Begin your search at www.pearsoned.ca/school/physicssource.

The magnitude of the resulting electric field can be shown to be the vector sum of each individual field, so it can be shown that the electric field anywhere between the plates is uniform. Thus, between two oppositely charged and parallel plates, electric field lines exist only between the charged plates. These lines extend perpendicularly from the plates, starting at the positively charged plate and terminating at the negatively charged plate. The electric field lines are uniform in both direction and density between the two oppositely charged plates, except near the edges of the plates. Such a system is called a parallel-plate capacitor. This type of capacitor is found in many different types of electrical equipment, including printers and televisions (where it is part of the "instant on" feature). It is also used in particle accelerators, such as cathode-ray tubes and mass spectrometers. You will learn about mass spectrometers in Unit VIII.

THEN, NOW, AND FUTURE Defibrillators Save Lives

During a heart attack, the upper and lower parts of the heart can begin contracting at different rates. Often these contractions are extremely rapid. This fluttery unsynchronized beating, called *fibrillation*, pumps little or no blood and can damage the heart. A defibrillator uses a jolt of electricity to momentarily stop the heart so that it can return to a normal beat (Figure 11.24).

▲ **Figure 11.24** A defibrillator stops the fibrillation of the heart muscle by applying an electric shock.

A defibrillator consists of two parallel charged plates (see Figure 11.23(b)), called a parallel-plate capacitor, connected to a power supply and discharging pads. A typical defibrillator stores about 0.4 C on the plates, creating a potential difference of approximately 2 kV between the plates.

When discharged through conductive pads placed on the patient's chest, the capacitor delivers about 0.4 kJ of electrical energy in 0.002 s. Roughly 200 J of this energy passes through the patient's chest.

A defibrillator uses a high-voltage capacitor to help save lives. Such capacitors have many other applications in other electrical and electronic devices, such as the high-voltage power supplies for cathode-ray tubes in older televisions and computer monitors.

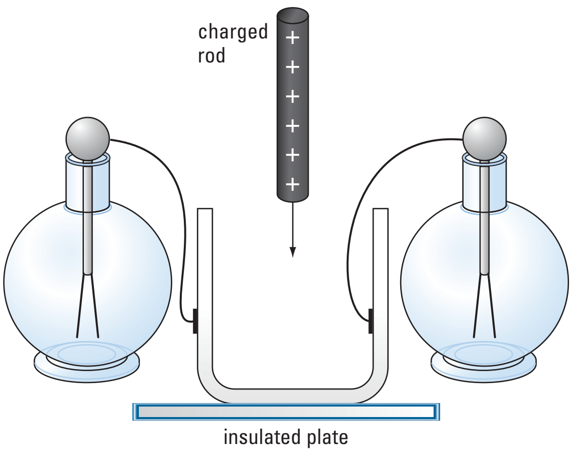
The charge stored in such capacitors can be dangerous. Products containing such high-voltage capacitors are designed to protect the users from any dangerous voltages. However, service technicians must be careful when working on these devices. Since the capacitors store charge, they can deliver a nasty shock even after the device is unplugged.

Questions

1. How does the magnitude of the power delivered by the plates compare with the actual power delivered to the chest by the jolt?
2. Identify a feature of televisions that demonstrates an important application of parallel-plate capacitors.
3. If a defibrillator can store 0.392 C of charge in 30 s, how many electrons are stored in this time period?

MINDS ON Faraday's Ice Pail

In the early 1800s, Michael Faraday performed an experiment to investigate the electric fields inside a hollow metal container. He used ice pails, so this experiment is often called "Faraday's ice pail experiment."



▲ **Figure 11.25** An ice pail is a metal container. It is placed on an insulated surface, and electroscopes are attached to the inside and outside surfaces of the metal container.

This activity is called a conceptual experiment because you will not perform the experiment. Instead, you will predict and justify the results of an experimental procedure that duplicates Faraday's investigation.

The purpose of the experiment is to determine what type of electric field exists on the inside and the outside of a hollow metal container.

A positively charged rod is placed into position inside the metal container, near the centre, as shown in Figure 11.25. The rod is then moved to a position inside the metal container, near one of the inner surfaces.

- Which of the electroscopes would show a deflection when the rod is near the centre of the metal container?
- Clearly explain your reasoning and the physical principles you used in determining your answers to these questions.

▲ **Figure 11.26** The charged dome of a Van de Graaff generator exposes a person to very large voltages.

Electric Potential Energy and Electric Potential

A Van de Graaff generator can generate up to 250 kV. Touching the dome not only produces the spectacular results shown in Figure 11.26, it can also cause a mild, harmless shock. On the other hand, touching the terminals of a wall socket, which has a voltage of 120 V, can be fatal.

An understanding of this dramatic difference between the magnitude of the voltage and its corresponding effect requires a study of the concepts of electric potential energy and electric potential. These concepts are important in the study of electric fields. Even though the terms seem similar, they are very different. To explain the difference, you will study these concepts in two types of electric fields: non-uniform electric fields around point charges, and uniform electric fields between parallel charged plates.

Electric Potential Energy

In previous grades, you learned about the relationship between work and potential energy. Work is done when a force moves an object in the direction of the force such that:

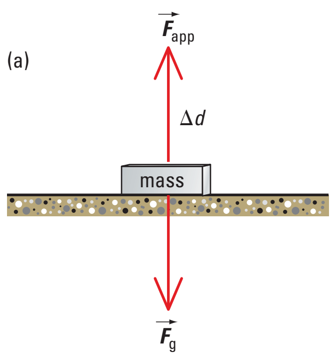
$$W = |\vec{F}|\Delta d$$

where W is work, and $|\vec{F}|$ and Δd are the magnitudes of the force and the displacement of the object.

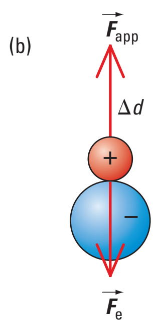
In a gravitational system like the one shown in Figure 11.27(a), lifting a mass a vertical distance against Earth's gravitational field requires work to stretch an imaginary "gravitational spring" connecting the mass and Earth. Further, because the force required to do the work is a conservative force, the work done against the gravitational field increases the gravitational potential energy of the system by an amount equal to the work done. Therefore:

gravitational potential energy gain = work done

$$\Delta E_p = W$$



▲ **Figure 11.27(a)** Work is required to lift a mass to a certain position above Earth's surface.

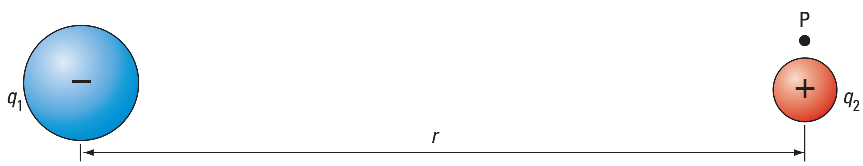


▲ **Figure 11.27(b)** Work is required to move a small positive charge away from a larger negative charge.

Similarly, in an electrostatic system like the one shown in Figure 11.27(b), moving a small charge through a certain distance in a non-uniform electric field produced by another point charge requires work to either compress or stretch an imaginary "electrostatic spring" connecting the two charges. Since the force required to do this work is also a conservative force, the work done in the electric field must increase the electric potential energy of the system.

Electric potential energy is the energy stored in the system of two charges a certain distance apart (Figure 11.28). Electric potential energy change equals work done to move a small charge:

$$\Delta E_{p} = W$$



▲ **Figure 11.28** Electric potential energy is the energy stored in the system of two charges a certain distance apart.

Example 11.5

Moving a small charge from one position in an electric field to another position requires 3.2×10^{-19} J of work. How much electric potential energy will be gained by the charge?

Analysis and Solution

The work done against the electrostatic forces is W.
The electric potential energy gain is ΔE_{p}.
In a conservative system,
$\Delta E_{p} = W$

So,
$$\begin{aligned}\Delta E_{p} &= W\\ &= 3.2 \times 10^{-19}\ \text{J}\end{aligned}$$

The electric potential energy gain of the charge is 3.2×10^{-19} J.

Practice Problems

1. A small charge gains 1.60×10^{-19} J of electric potential energy when it is moved to a point in an electric field. Determine the work done on the charge.
2. A charge moves from one position in an electric field, where it had an electric potential energy of 6.40×10^{-19} J, to another position where it has an electric potential energy of 8.00×10^{-19} J. Determine the work necessary to move the charge.

Answers

1. 1.60×10^{-19} J
2. 1.60×10^{-19} J

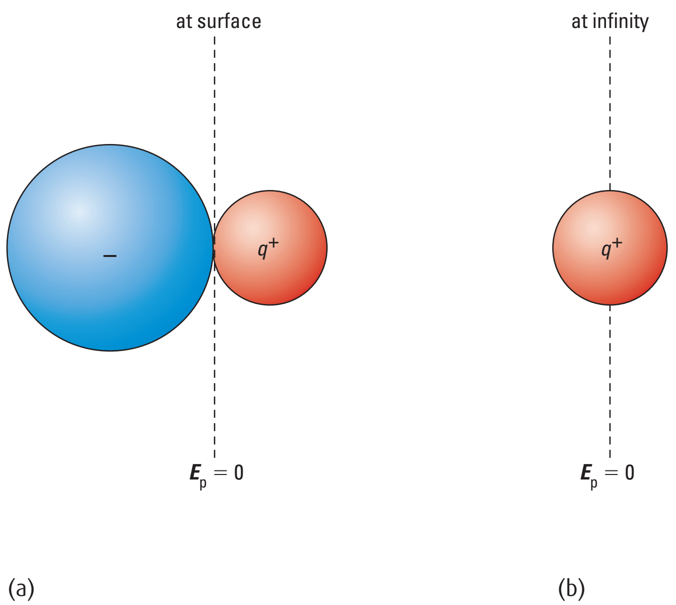
Choosing a Reference Point

In Chapter 7, you learned that commonly used reference points for zero gravitational potential energy are Earth's surface or infinity. Choosing a zero reference point is necessary so you can analyze the relationship between work and gravitational potential energy.

Consider a zero reference point at Earth's surface. An object at rest on Earth's surface would have zero gravitational potential energy relative to Earth's surface. If the object is lifted upward, opposite to the direction of the gravitational force it experiences, then work is being done on the object. The object thus gains gravitational potential energy. If the object falls back to the surface in the same direction as the gravitational force, then the object loses gravitational potential energy.

As with gravitational potential energy, the value of electric potential energy at a certain position is meaningless unless it is compared to a reference point where the electric potential energy is zero. The choice of a zero reference point for electric potential energy is arbitrary. For example, suppose an electric field is being produced by a large negative charge. A small positive charge would be attracted and come to rest on the surface of the larger negative charge, where it would have zero electric potential energy. This position could be defined as a zero electric potential energy reference point (Figure 11.29(a)). Then, the test charge has positive electric potential energy at all other locations.

Alternatively, the small positive test charge may be moved to a position so far away from the larger negative charge that there is no electrostatic attraction between them. This position would be an infinite distance away. This point, at infinity, is often chosen as the zero electric potential energy reference point. Then, the test charge has negative electric potential energy at all other locations. This text uses *infinity* as the zero electric potential energy reference point for all calculations (Figure 11.29(b)).



▲ **Figure 11.29** Two commonly used reference points for electric potential energy:
(a) test charge defined as having zero electric potential energy at the surface of the source charge
(b) test charge defined as having zero electric potential energy at infinity

Work and Electric Potential Energy

Whenever work is done on a charge to move it against the electric force caused by an electric field, the charge gains electric potential energy. The following examples illustrate the relationship between work and electric potential energy.

Electric Potential Energy Between Parallel Charged Plates

Except at the edges, the electric field between two oppositely charged plates is uniform in magnitude and direction. Suppose a small positive charge in the field between the plates moves from the negative plate to the positive plate with a constant velocity. This motion requires an external force to overcome the electrostatic forces the charged plates exert on the positive charge. The work done on the charge increases the system's electric potential energy:

$$\Delta E_p = W = |\vec{F}|\Delta d$$

Example 11.6

When a small positive charge moves from a negative plate to a positive plate, 2.3×10^{-19} J of work is done. How much electric potential energy will the charge gain?

Analysis and Solution

In a conservative system, $\Delta E_p = W$.

$$\begin{aligned}\Delta E_p &= W \\ &= 2.3 \times 10^{-19}\ \text{J}\end{aligned}$$

Paraphrase

The electric potential energy gain of the charge is 2.3×10^{-19} J.

Practice Problem

1. A charge gained 4.00×10^5 J of electric potential energy when it was moved between two oppositely charged plates. How much work was done on the charge?

Answer

1. 4.00×10^5 J

Electric Potential

Suppose two positive charges are pushed toward a positive plate. In this case, twice as much work is done, and twice as much electric potential energy is stored in the system. However, just as much electric potential energy is still stored per charge. Storing 20 J of energy in two charges is the same as storing 10 J of energy in each charge.

At times, it is necessary to determine the total electric potential energy at a certain location in an electric field. At other times, it is convenient to consider just the electric potential energy *per unit charge* at a location. The electric potential energy stored per unit charge at a given point is the amount of work required to move a unit charge to that

electric potential: the electric potential energy stored per unit charge at a given point in an electric field

info **BIT**

The SI unit of electric potential is the volt, named in honour of the Italian physicist Count Alessandro Volta (1745–1827), who developed the first electric battery in the early 1800s.

point from a zero reference point (infinity). This quantity has a special name: **electric potential**. To determine the electric potential at a location, use this equation:

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

$$V = \frac{E_p}{q}$$

where V is in volts, E_p is in joules, and q is in coulombs.

Since electric potential energy is measured in joules and charge is measured in coulombs,

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

Thus, if the electric potential at a certain location is 10 V, then a charge of 1 C will possess 10 J of electric potential energy, a charge of 2 C will possess 20 J of electric potential energy, and so on. Even if the total electric potential energy (E_p) at a location changes, depending on the amount of charge placed in the electric field, the electric potential (V) at that location remains the same.

A balloon can be used as an example to help explain the difference between the concepts of electric potential energy and electric potential. Suppose you rub a balloon with fur. The balloon acquires an electric potential of a few thousand volts. In other words, the electric energy stored *per coulomb of charge* on the balloon is a few thousand volts. Written as an equation,

$$V = \frac{E_p}{q}$$

Now suppose the balloon were to gain a large charge of 1 C during the rubbing process. In order for the electric potential to stay the same, a few thousand joules of work would be needed to produce the electrical energy that would allow the balloon to maintain that electric potential. However, the amount of charge a balloon acquires during rubbing is usually only in the order of a few microcoulombs. So, acquiring this potential requires a small amount of work to produce the energy needed. Even though the electric potential is high, the electric potential energy is low because of the extremely small charge.

Concept Check

Suppose the magnitude of a charge placed in an electric field were doubled. How much would the electric potential energy and the electric potential change?

Electric Potential Difference

When a charge moves from one location to another in an electric field, it experiences a change in electric potential. This change in electric potential is called the **electric potential difference**, ΔV, between the two points and

$$\Delta V = V_{\text{final}} - V_{\text{initial}}$$

since $V = \frac{E_p}{q}$

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

where ΔE_p is the amount of work required to move the charge from one location to the other.

The potential difference depends only on the two locations. It does not depend on the charge or the path taken by the charge as it moves from one location to another. Electric potential difference is commonly referred to as just potential difference or voltage.

An **electron volt (eV)** is the quantity of energy an electron gains or loses when passing through a potential difference of exactly 1 V. An electron volt is vastly less than a joule:

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Although not an SI unit, the electron volt is sometimes convenient for expressing tiny quantities of energy, especially in situations involving a single charged particle such as an electron or a proton. The energy difference in Example 11.6 could be given as

$$(2.3 \times 10^{-19} \cancel{\text{J}})\left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \cancel{\text{J}}}\right) = 1.4 \text{ eV}$$

electric potential difference: change in electric potential experienced by a charge moving between two points in an electric field

electron volt: the change in energy of an electron when it moves through a potential difference of 1 V

PHYSICS INSIGHT

The notation V_{AB} is widely used instead of ΔV to represent the potential difference at point A relative to point B. When the points in question are clear from the context, the subscripts are generally omitted. For example, the equation for Ohm's law is usually written as $V = IR$, where it is understood that V represents the potential difference between the ends of the resistance R.

Example 11.7

Moving a small charge of 1.6×10^{-19} C between two parallel plates increases its electric potential energy by 3.2×10^{-16} J. Determine the electric potential difference between the two parallel plates.

Analysis and Solution

To determine the electric potential difference between the plates, use the equation

$$\Delta V = \frac{\Delta E_p}{q} = \frac{3.2 \times 10^{-16} \text{ J}}{1.6 \times 10^{-19} \text{ C}} = 2.0 \times 10^3 \text{ V}$$

The electric potential difference between the plates is 2.0×10^3 V.

Practice Problems

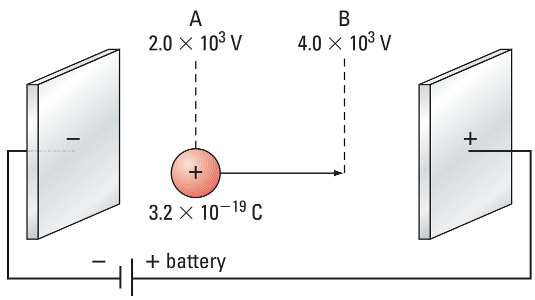
1. In moving a charge of 5.0 C from one terminal to the other, a battery raises the electric potential energy of the charge by 60 J. Determine the potential difference between the battery terminals.
2. A charge of 2.00×10^{-2} C moves from one charged plate to an oppositely charged plate. The potential difference between the plates is 500 V. How much electric potential energy will the charge gain?

Answers

1. 12 V
2. 10.0 J

Example 11.8

A small charge of 3.2×10^{-19} C is moved between two parallel plates from a position with an electric potential of 2.0×10^3 V to another position with an electric potential of 4.0×10^3 V (Figure 11.30).



◀ **Figure 11.30**

Determine:
(a) the potential difference between the two positions
(b) the electric potential energy gained by moving the charge, in joules (J) and electron volts (eV)

Given

$V_{\text{initial}} = 2.0 \times 10^3$ V
$V_{\text{final}} = 4.0 \times 10^3$ V
$q = 3.2 \times 10^{-19}$ C

Required

(a) potential difference between points B and A (ΔV)
(b) electric potential energy gained by the charge (ΔE_p)

Analysis and Solution

(a)
$$\begin{aligned}\Delta V &= V_{\text{final}} - V_{\text{initial}} \\ &= (4.0 \times 10^3\ \text{V}) - (2.0 \times 10^3\ \text{V}) \\ &= 2.0 \times 10^3\ \text{V}\end{aligned}$$

(b) To calculate the electric potential energy, use the equation

$$\Delta V = \frac{\Delta E_p}{q}.$$

$$\begin{aligned}\Delta E_p &= \Delta V q \\ &= (2.0 \times 10^3\ \text{V})(3.2 \times 10^{-19}\ \text{C}) \\ &= 6.4 \times 10^{-16}\ \text{J}\end{aligned}$$

Since $1\ \text{eV} = 1.60 \times 10^{-19}$ J,

$$\begin{aligned}\Delta E_p &= (6.4 \times 10^{-16}\ \cancel{\text{J}})\left(\frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \cancel{\text{J}}}\right) \\ &= 4.0 \times 10^3\ \text{eV} \\ &= 4.0\ \text{keV}\end{aligned}$$

Paraphrase

(a) The potential difference between the two positions is 2.0×10^3 V.
(b) The energy gained by moving the charge between the two positions is 6.4×10^{-16} J or 4.0×10^3 eV.

Practice Problems

1. A sphere with a charge of magnitude 2.00 C is moved between two positions between oppositely charged plates. It gains 160 J of electric potential energy. What is the potential difference between the two positions?
2. An electron moves between two positions with a potential difference of 4.00×10^4 V. Determine the electric potential energy gained by the electron, in joules (J) and electron volts (eV).

Answers

1. 80.0 V
2. 6.40×10^{-15} J or 4.00×10^4 eV

The Electric Field Between Charged Plates

Earlier in this section, you determined the electric field strength surrounding a point charge using the following equations:

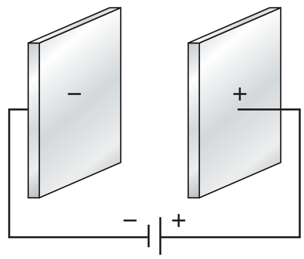
$$|\vec{E}| = \frac{kq}{r^2} \quad \text{or} \quad |\vec{E}| = \frac{|\vec{F}_{\mathrm{e}}|}{q}$$

You also learned that the electric field around a point charge is a non-uniform electric field. Its magnitude depends on the distance from the charge. Later, you learned that a special type of electric field exists between two charged parallel plates. The magnitude of the electric field between the plates is uniform anywhere between the plates and it can be determined using the general equation for an electric field, $|\vec{E}| = \frac{|\vec{F}_{\mathrm{e}}|}{q}$. You cannot use the equation $|\vec{E}| = \frac{kq}{r^2}$ because it is used only for point charges.

e WEB

One of the technological applications of parallel-plate capacitors is in disposable cameras. Research the role of capacitors in these cameras. Begin your search at www.pearsoned.ca/school/physicssource.

Now, after studying electric potential difference, you can see how another equation for determining the electric field strength between plates arises from an important relationship between the uniform electric field and the electric potential difference between two charged parallel plates (Figure 11.31).



▲ **Figure 11.31** Electrically charged parallel plates

If a small positively charged particle (q) is moved through the uniform electric field ($\vec{E}$), a force is required, where $\vec{F} = \vec{E}q$. This force is the force exerted on the particle due to the presence of the electric field. If this force moves the charged particle a distance (Δd) between the plates, then the work done is:

$$W = |\vec{F}|\Delta d$$

$$\text{or } W = |\vec{E}|q\Delta d$$

Since this system is conservative, the work done is stored in the charge as electric potential energy:

$$W = \Delta E_{\mathrm{p}} = |\vec{E}|q\Delta d$$

The electric potential difference between the plates is:

$$\begin{aligned} \Delta V &= \frac{\Delta E_{\mathrm{p}}}{q} \\ &= \frac{|\vec{E}|q\Delta d}{q} \\ &= |\vec{E}|\Delta d \end{aligned}$$

To calculate the magnitude of the uniform electric field between charged plates, use the equation

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

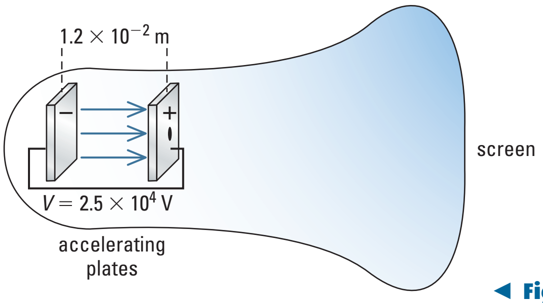
where ΔV is the electric potential difference between two charged plates in volts; Δd is the distance in metres between the plates; and $|\vec{E}|$ is the magnitude of the electric field in volts per metre.

Note that 1 V/m equals 1 N/C because

$$\begin{aligned}
1\ \text{V/m} &= \frac{1\ \text{J/C}}{1\ \text{m}} \\
&= \frac{\dfrac{1\ \text{N}\cdot\cancel{\text{m}}}{1\ \text{C}}}{1\ \cancel{\text{m}}} \\
&= 1\ \text{N/C}
\end{aligned}$$

Example 11.9

A cathode-ray-tube (CRT) computer monitor accelerates electrons between charged parallel plates (Figure 11.32). These electrons are then directed toward a screen to create an image. If the plates are 1.2×10^{-2} m apart and have a potential difference of 2.5×10^{4} V between them, determine the magnitude of the electric field between the plates.



◀ **Figure 11.32**

Given

$\Delta V = 2.5 \times 10^{4}$ V

$\Delta d = 1.2 \times 10^{-2}$ m

Required

magnitude of the electric field between the plates ($|\vec{E}|$)

Analysis and Solution

To calculate the magnitude of the electric field between the plates, use the equation

$$\begin{aligned}
|\vec{E}| &= \frac{\Delta V}{\Delta d} \\
&= \frac{2.5 \times 10^{4}\ \text{V}}{1.2 \times 10^{-2}\ \text{m}} \\
&= 2.1 \times 10^{6}\ \text{V/m}
\end{aligned}$$

Paraphrase

The magnitude of the electric field between the plates is 2.1×10^{6} V/m.

Practice Problems

1. Two charged parallel plates, separated by 5.0×10^{-4} m, have an electric field of 2.2×10^{4} V/m between them. What is the potential difference between the plates?
2. Spark plugs in a car have electrodes whose faces can be considered to be parallel plates. These plates are separated by a gap of 5.00×10^{-3} m. If the electric field between the electrodes is 3.00×10^{6} V/m, calculate the potential difference between the electrode faces.

Answers

1. 11 V
2. 1.50×10^{4} V

11.2 Check and Reflect

Knowledge

1. Describe the difference between an electric field vector and an electric field line.

2. Sketch electric field lines around the following charges:
   (a) a positive charge
   (b) a negative charge
   (c) two positive charges
   (d) two negative charges
   (e) a positive charge and a negative charge

3. Describe the difference between electric potential and electric potential energy.

Applications

4. At a point in Earth's atmosphere, the electric field is 150 N/C downward and the gravitational field is 9.80 N/kg downward.
   (a) Determine the electric force on a proton (p^+) placed at this point.
   (b) Determine the gravitational force on the proton at this point. The proton has a mass of 1.67×10^{-27} kg.

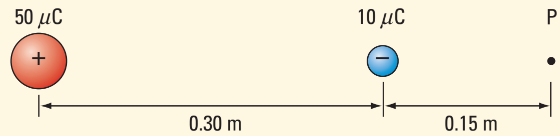
5. A metal box is charged by touching it with a negatively charged object.
   (a) Compare the distribution of charge at the corners of the box with the faces of the box.
   (b) Draw the electric field lines inside and surrounding the box.

6. What is the electric field intensity 0.300 m away from a small sphere that has a charge of 1.60×10^{-8} C?

7. Calculate the electric field intensity midway between two negative charges of 3.2 μC and 6.4 μC separated by 0.40 m.

8. A 2.00-C charge jumps across a spark gap in a spark plug across which the potential difference is 1.00×10^3 V. How much energy is gained by the charge?

9. Determine the magnitude and direction of the net electric field at point P shown in the diagram below.

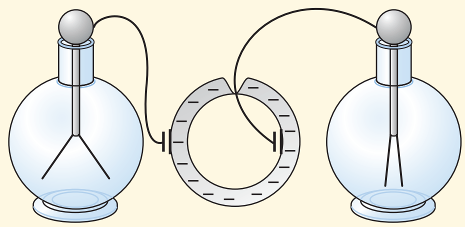


10. A uniform electric field exists between two oppositely charged parallel plates connected to a 12.0-V battery. The plates are separated by 6.00×10^{-4} m.
    (a) Determine the magnitude of the electric field between the plates.
    (b) If a charge of -3.22×10^{-6} C moves from one plate to another, calculate the change in electric potential energy of the charge.

Extensions

11. A metal car is charged by contact with a charged object. Compare the charge distribution on the outside and the inside of the metal car body. Why is this property useful to the occupants of the car if the car is struck by lightning?

12. Explain why only one of the electroscopes connected to the hollow conductive sphere in the illustration below indicates the presence of a charge.



13. Two points at different positions in an electric field have the same electric potential. Would any work be required to move a test charge from one point to another? Explain your answer.

e TEST

To check your understanding of electric field lines, follow the eTest links at www.pearsoned.ca/school/physicssource.

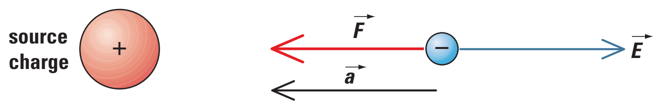
11.3 Electrical Interactions and the Law of Conservation of Energy

info BIT

Living cells "pump" positive sodium ions (Na^+) from inside a cell to the outside through a membrane that is 0.10 μm thick. The electric potential is 0.70 V higher outside the cell than inside it. To move the sodium ions, work must be done. It is estimated that 20% of the energy consumed by the body in a resting state is used to operate these "pumps."

A charge in an electric field experiences an electrostatic force. If the charge is free to move, it will accelerate in the direction of the electrostatic force, as described by Newton's second law. The acceleration of the charge in the non-uniform electric field around a point charge is different from the acceleration motion of a charge in a uniform electric field between charged plates.

Figure 11.33 shows a charge in the non-uniform field of a point charge. The electrostatic force on a charge placed in the field varies inversely as the square of the distance between the charges. A varying force causes non-uniform acceleration. Describing the motion of the charge in this type of situation requires applying calculus to Newton's laws of motion, which is beyond the scope of this text. However, to determine the particle's speed at a given point, you can use the law of conservation of energy.



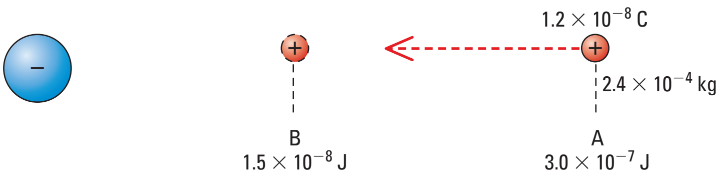
▲ **Figure 11.33** The electrostatic force on a point charge in a non-uniform electric field causes non-uniform acceleration of the charge.

If the forces acting on an object are conservative forces, then the work done on a system changes the potential energy of the system. Electric potential energy, like gravitational potential energy, can be converted to kinetic energy. A charged particle placed in an electric field will accelerate from a region of high potential energy to a region of low potential energy. According to the law of conservation of energy, the moving charge gains kinetic energy at the expense of potential energy. If you assume that no energy is lost to friction and the forces are conservative, the kinetic energy gained equals the potential energy lost, so the sums of the two energies are always equal:

$$E_{p_i} + E_{k_i} = E_{p_f} + E_{k_f}$$

Example 11.10

A pith ball of mass 2.4×10^{-4} kg with a positive charge of 1.2×10^{-8} C is initially at rest at location A in the electric field of a larger charge (Figure 11.34). At this location, the charged pith ball has 3.0×10^{-7} J of electric potential energy. When released, the ball accelerates toward the larger charge. At position B, the ball has 1.5×10^{-8} J of electric potential energy. Find the speed of the pith ball when it reaches position B.



▲ **Figure 11.34**

Given

$m = 2.4 \times 10^{-4}$ kg $\quad q = +1.2 \times 10^{-8}$ C

$E_{p_i} = 3.0 \times 10^{-7}$ J $\quad E_{p_f} = 1.5 \times 10^{-8}$ J

Required

speed of the ball at position B (v)

Analysis and Solution

The pith ball is at rest at A, so its initial kinetic energy is zero. Its electric potential energy at B is lower than at A. Since this system is conservative, the loss of electric potential energy when the ball moves from A to B is equal to a gain in kinetic energy, according to the law of conservation of energy:

$$E_{p_i} + E_{k_i} = E_{p_f} + E_{k_f}$$

Substitute the given values and solve for E_{k_f}.

$$(3.0 \times 10^{-7}\ \text{J}) + 0 = (1.5 \times 10^{-8}\ \text{J}) + E_{k_f}$$

$$E_{k_f} = 2.85 \times 10^{-7}\ \text{J}$$

Since the kinetic energy of an object is $E_k = \frac{1}{2}mv^2$,

$$v^2 = \frac{2E_k}{m}$$

$$v = \sqrt{\frac{2E_k}{m}}$$

$$= \sqrt{\frac{2(2.85 \times 10^{-7}\ \text{J})}{2.4 \times 10^{-4}\ \text{kg}}}$$

$$= 4.9 \times 10^{-2}\ \text{m/s}$$

Paraphrase

The speed of the pith ball at position B is 4.9×10^{-2} m/s.

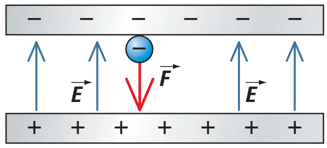
Practice Problems

1. A negative charge of 3.00×10^{-9} C is at rest at a position in the electric field of a larger positive charge and has 3.20×10^{-12} J of electric potential energy at this position. When released, the negative charge accelerates toward the positive charge. Determine the kinetic energy of the negative charge just before it strikes the larger positive charge.
2. A small sphere with a charge of $-2.00\ \mu$C and a mass of 1.70×10^{-3} kg accelerates from rest toward a larger positive charge. If the speed of the sphere just before it strikes the positive charge is 5.20×10^4 m/s, how much electric potential energy did the negative charge lose?

Answers

1. 3.20×10^{-12} J
2. 2.30×10^6 J

It is easier to describe the motion of a charge in a uniform electric field between two parallel plates, as shown in Figure 11.35. In this case, the acceleration is constant because of the constant force, so either the work–energy theorem or the laws of dynamics can be used. (Because the electric field is constant (uniform), the force acting on a charge q is also constant because $\vec{F}_e = q\vec{E}$.)



▲ **Figure 11.35** In a uniform electric field between two parallel plates, the acceleration of a charge is constant.

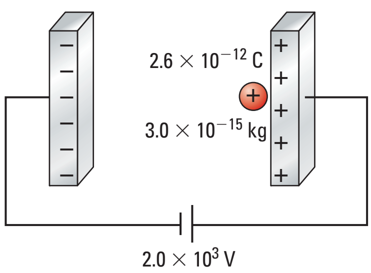
Concept Check

Electrostatic forces and gravitational forces are similar, so the motion of objects due to these forces should be similar. Consider a charge in an electric field between two parallel plates. Sketch the direction of the motion of the charge when its initial motion is:

- perpendicular to the plates (the electrostatic force is similar to the gravitational force on falling masses)
- parallel to the plates (the electrostatic force is similar to the gravitational force that causes the parabolic projectile motion of a mass close to the surface of a large planet or moon)

Example 11.11

Two vertical parallel plates are connected to a DC power supply, as shown in Figure 11.36. The electric potential between the plates is 2.0×10^3 V. A sphere of mass 3.0×10^{-15} kg with a positive charge of 2.6×10^{-12} C is placed at the positive plate and released. It accelerates toward the negative plate. Determine the speed of the sphere at the instant before it strikes the negative plate. Ignore any gravitational effects.



▲ **Figure 11.36**

Given

$q = +2.6 \times 10^{-12}$ C
$V = 2.0 \times 10^{3}$ V
$m = 3.0 \times 10^{-15}$ kg

Required

speed of the sphere at the negative plate (v)

Analysis and Solution

This system is conservative. You can use kinetic energy of the charge to find its speed.

The initial electric potential energy of the sphere at the positive plate is $E_{p_i} = Vq$. Since the sphere was at rest, its initial kinetic energy, E_{k_i}, is 0 J.

The final electric potential energy of the sphere at the negative plate is $E_{p_f} = 0$ J.

According to the law of conservation of energy,

$$\begin{aligned} E_{p_i} + E_{k_i} &= E_{p_f} + E_{k_f} \\ Vq + 0\text{ J} &= 0\text{ J} + E_{k_f} \\ (2.0 \times 10^{3}\text{ V})(2.6 \times 10^{-12}\text{ C}) + 0\text{ J} &= 0\text{ J} + E_{k_f} \\ E_{k_f} &= 5.2 \times 10^{-9}\text{ J} \end{aligned}$$

Since $E_k = \frac{1}{2}mv^2$,

$$\begin{aligned} v &= \sqrt{\frac{2E_k}{m}} \\ &= \sqrt{\frac{2(5.2 \times 10^{-9}\text{ J})}{3.0 \times 10^{-15}\text{ kg}}} \\ &= 1.9 \times 10^{3}\text{ m/s} \end{aligned}$$

Paraphrase

The speed of the sphere at the negative plate is 1.9×10^{3} m/s.

Practice Problems

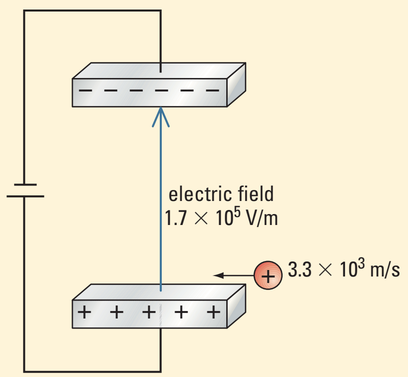
1. An alpha particle with a charge of $+3.20 \times 10^{-19}$ C and a mass of 6.65×10^{-27} kg is placed between two oppositely charged parallel plates with an electric potential difference of 4.00×10^{4} V between them. The alpha particle is injected at the positive plate with an initial speed of zero, and it accelerates toward the negative plate. Determine the final speed of the alpha particle just before it strikes the negative plate.
2. If a charge of -6.00×10^{-6} C gains 3.20×10^{-4} J of kinetic energy as it accelerates between two oppositely charged plates, what is the potential difference between the two parallel plates?

Answers

1. 1.96×10^{6} m/s
2. 53.3 V

Practice Problems

1. Two horizontal parallel plates, 1.2×10^{-2} m apart, are connected to a DC power supply, as shown in the figure below. The electric field between the plates is 1.7×10^{5} V/m. A sphere of mass 3.0×10^{-15} kg with a positive charge of 2.6×10^{-12} C is injected into the region between the plates, with an initial speed of 3.3×10^{3} m/s, as shown. It accelerates toward the negative plate. Copy the diagram into your notebook, sketch the motion of the positive charge through the region between the plates, and determine the distance the positive charge moves toward the negative plate after 6.0×10^{-6} s have elapsed. Gravitational effects may be ignored in this case.



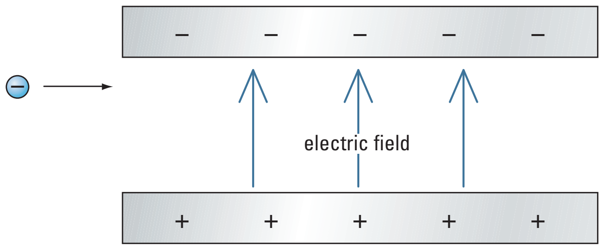
2. An electron, travelling at 2.3×10^{3} m/s, enters perpendicular to the electric field between two horizontal charged parallel plates. If the electric field strength is 1.5×10^{2} V/m, calculate the time taken for the electron to deflect a distance of 1.0×10^{-2} m toward the positive plate. Ignore gravitational effects.

Answers

1. 2.7×10^{-3} m
2. 2.7×10^{-8} s

Example 11.12

An electron enters the electric field between two charged parallel plates, as shown in Figure 11.37.



▲ **Figure 11.37**

(a) Copy Figure 11.37 into your notebook and sketch the motion of the electron between the plates.
(b) If the electron experiences a downward acceleration of 2.00×10^{17} m/s² due to the electric field between the plates, determine the time taken for the electron to travel 0.0100 m to the positive plate.

Given

$\vec{a} = 2.00 \times 10^{17}$ m/s² [down]

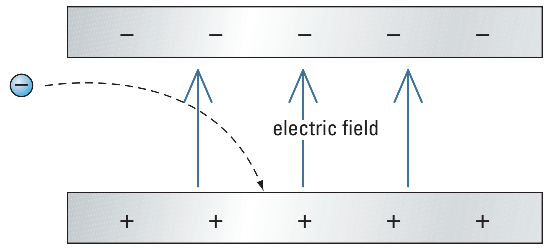
$\Delta d = 0.0100$ m

Required

(a) sketch of the electron's motion
(b) time (Δt)

Analysis and Solution

(a) The electron's acceleration is downward, so the motion of the electron will follow a parabolic path to the positive plate (Figure 11.38), similar to the projectile motion of an object travelling horizontally to the surface of Earth and experiencing downward acceleration due to gravity.



▲ **Figure 11.38**

(b) Use the equation $\Delta d = v_i\Delta t + \frac{1}{2}a(\Delta t)^2$ to determine the time it takes the electron to fall to the positive plate. Since $v_i = 0$,

$$\Delta d = \frac{1}{2}a(\Delta t)^2$$

$$\Delta t = \sqrt{\frac{2\Delta d}{a}}$$

$$= \sqrt{\frac{2(0.0100\ \cancel{\text{m}})}{2.00 \times 10^{17}\ \frac{\cancel{\text{m}}}{\text{s}^2}}}$$

$$= 3.16 \times 10^{-10}\ \text{s}$$

Paraphrase

(a) The path of the electron between the parallel plates is parabolic.

(b) The time taken for the electron to fall to the positive plate is 3.16×10^{-10} s.

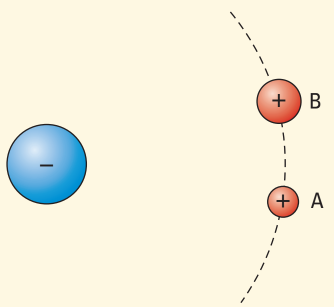
11.3 Check and Reflect

Knowledge

1. In what direction will a positively charged particle accelerate in an electric field?

2. Electric potential energy exists only where a charge is present at a point in an electric field. Must a charge also be present at that point for there to be electric potential? Why or why not?

3. Two positively charged objects are an equal distance from a negatively charged object, as shown in the diagram below. Charge B is greater than charge A. Compare the electric potential and electric potential energy of the positively charged objects.



Applications

4. Calculate the speed of an electron and a proton after each has accelerated from rest through an electric potential of 220 V.

5. Electrons in a TV picture tube are accelerated by a potential difference of 25 kV. Find the maximum speed the electrons would reach if relativistic effects are ignored.

6. A charge gains 1.92×10^{-14} J of electric potential energy when it moves through a potential difference of 3.20×10^4 V. What is the magnitude of the charge?

7. How much work must be done to increase the electric potential of a charge of 2.00×10^{-6} C by 120 V?

8. A deuterium ion (H^{1+}), a heavy isotope of hydrogen, has a charge of 1.60×10^{-19} C and a mass of 3.34×10^{-27} kg. It is placed between two oppositely charged plates with a voltage of 2.00×10^4 V. Find the final maximum speed of the ion if it is initially placed at rest
   (a) at the positive plate
   (b) midway between the two plates

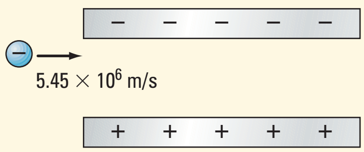
9. A small charge of $+3.0 \times 10^{-8}$ C with a mass of 3.0×10^{-5} kg is slowly pulled through a potential difference of 6.0×10^{2} V. It is then released and allowed to accelerate toward its starting position. Calculate

(a) the initial work done to move the charge

(b) the maximum kinetic energy of the returning charge

(c) the final speed of the returning charge

10. An electron, travelling horizontally at a speed of 5.45×10^{6} m/s, enters a parallel-plate capacitor with an electric field of 125 N/C between the plates, as shown in the figure below.



(a) Copy the diagram into your notebook and sketch

(i) the electric field lines between the plates

(ii) the motion of the electron through the capacitor

(b) Determine the force due to the electric field on the electron.

(c) Ignoring gravitational effects, calculate the acceleration of the electron.

(d) If the electron falls a vertical distance of 6.20×10^{-3} m toward the positive plate, how far will the electron travel horizontally between the plates?

Extensions

11. Determine whether an electron or a proton would take less time to reach one of a pair of oppositely charged parallel plates when starting from midway between the plates. Explain your reasoning.

12. How can the electric potential at a point in an electric field be high when the electric potential energy is low?

13. In question 10, explain why the resulting motion of an electron, initially travelling perpendicular to the uniform electric field between the two charged parallel plates, will be parabolic and not circular.

e TEST

To check your understanding of electrical interactions and the law of conservation of energy, follow the eTest links at www.pearsoned.ca/school/physicssource.

Key Terms and Concepts

field
test charge
source charge
electric field line
electric potential energy
electric potential (voltage)
electron volt
electric potential difference

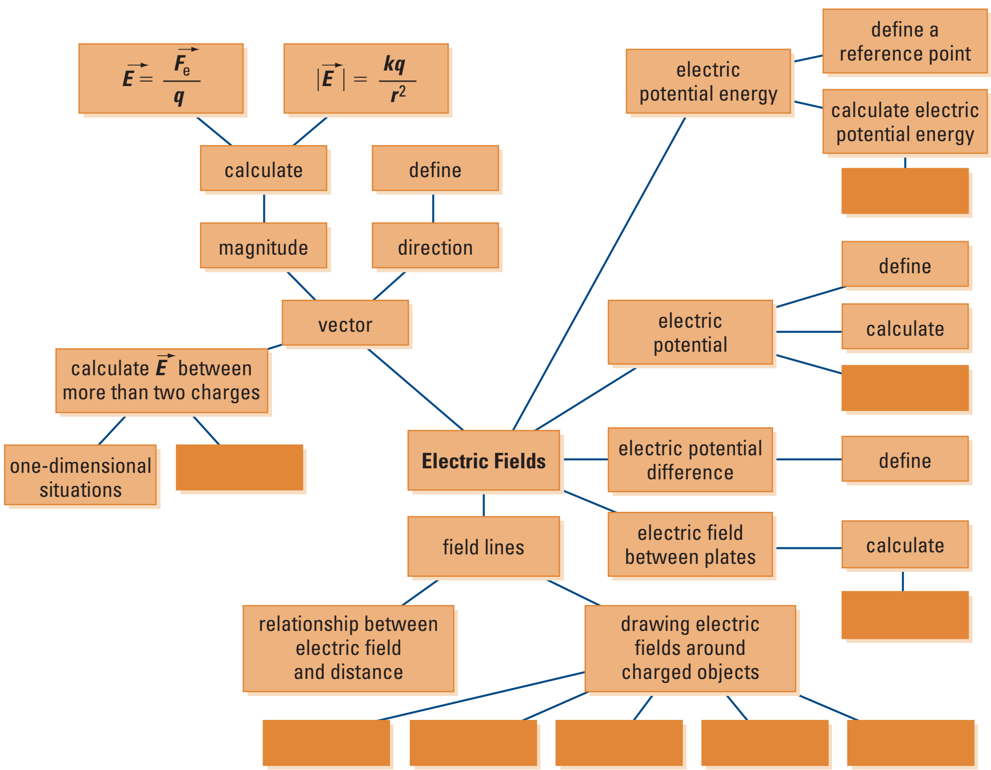
Key Equations

$$\vec{E} = \frac{\vec{F}_e}{q} \qquad |\vec{E}| = \frac{kq}{r^2} \qquad \Delta E_p = W \qquad \Delta E_p = W = |\vec{F}|\Delta d$$

$$V = \frac{E_p}{q} \qquad \Delta V = \frac{\Delta E_p}{q} \qquad \Delta V = V_{final} - V_{initial} \qquad |\vec{E}| = \frac{\Delta V}{\Delta d} \qquad E_{p_i} + E_{k_i} = E_{p_f} + E_{k_f}$$

Conceptual Overview

The concept map below summarizes many of the concepts and equations in this chapter. Copy and complete the map to have a full summary of the chapter.



Knowledge

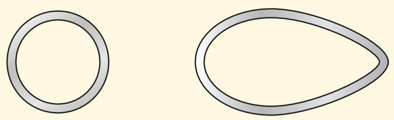
1. (11.1) Identify the three theories that attempt to explain "action at a distance."

2. (11.1) How can it be demonstrated that the space around a charged object is different from the space around an uncharged object?

3. (11.1) How does a vector arrow represent both the magnitude and direction of a vector quantity?

4. (11.2) What is the difference between an electric field vector and an electric field line?

5. (11.2) Two hollow metal objects, with shapes shown below, are charged with a negatively charged object. In your notebook, sketch the distribution of charge on both objects and the electric field lines surrounding both objects.



6. (11.2) How do electric field lines represent the magnitude of an electric field?

7. (11.2) Where do electric field lines originate for
(a) a negative point charge?
(b) a positive point charge?

8. (11.2) Identify two equations that can be used to calculate the magnitude of an electric field around a point charge.

9. (11.2) When do electric charges achieve static equilibrium in a charged object?

10. (11.2) Why do electric charges accumulate at a point in an irregularly shaped object?

11. (11.2) State a convenient zero reference point for electric potential energy
(a) around a point charge
(b) between two oppositely charged parallel plates

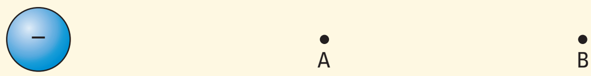
12. (11.2) What equation would you use to calculate the electric potential energy at a certain position around a point charge?

13. (11.3) Describe the key differences between the electric field surrounding a point charge and the electric field between charged parallel plates?

14. (11.3) Assuming forces in a system are conservative, explain how
(a) work done in the system is related to potential energy of the system
(b) the kinetic and potential energy of the system are related

Applications

15. Compare the electric potential energy of a positive test charge at points A and B near a charged sphere, as shown below.

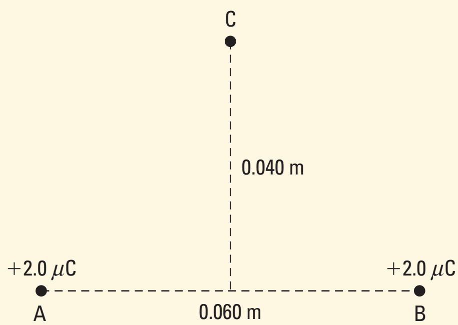


16. A large metal coffee can briefly contacts a charged object. Compare the results when uncharged electroscopes are touched to the inside and outside surfaces of the can.

17. A point charge has a charge of $+2.30\ \mu C$. Calculate
(a) the electric field at a position 2.00 m from the charge
(b) the electric force on a charge of $-2.00\ \mu C$ placed at this point

18. A charge of -5.00 C is separated from another charge of -2.00 C by a distance of 1.20 m. Calculate
(a) the net electric field midway between the two charges
(b) the position where the net electric field is zero

19. Find the net electric field intensity at point C in the diagram below.



20. A force of 15.0 N is required to move a charge of $-2.0\ \mu C$ through a distance of 0.20 m in a uniform electric field.
    (a) How much work is done on the charge?
    (b) How much electric potential energy does the charge gain in joules?

21. How much electric potential energy would an object with a charge of $-2.50\ \mu C$ have when it is 1.20 m from a point charge of +3.00 C? (Hint: Consider how much electric potential energy the negatively charged object would have when touching the point charge.)

22. Two parallel plates are separated by a distance of 3.75 cm. Two points, A and B, lie along a perpendicular line between the parallel plates and are 1.10 cm apart. They have a difference in electric potential of 6.00 V.
    (a) Calculate the magnitude of the electric field between the plates.
    (b) Determine the electric potential between the parallel plates.

23. How much work is required to move a charge perpendicular to the electric field between two oppositely charged parallel plates?

24. A cell membrane is 1.0×10^{-7} m thick and has an electric potential difference between its surfaces of 0.070 V. What is the electric field within the membrane?

25. A lithium nucleus (Li^{+3}) that has a charge of 4.80×10^{-19} C is accelerated by a voltage of 6.00×10^{5} V between two oppositely charged plates. Calculate the energy, in joules (J) and electron volts (eV), gained by the nucleus.

26. How much electric potential energy, in joules (J) and electron volts (eV), does an alpha particle gain when it moves between two oppositely charged parallel plates with a voltage of 20 000 V?

27. Consider a sphere with a known charge in the electric field around a larger unknown charge. What would happen to the electric field at a point if
    (a) the magnitude of the test charge were doubled?
    (b) the magnitude of the charge producing the field were doubled?
    (c) the sign of the charge producing the field were changed?

Extensions

28. Explain why electric field lines can never cross.

29. A bird is inside a metal birdcage that is struck by lightning. Is the bird likely to be harmed? Explain.

30. Explain why charge redistributes evenly on the outside surface of a spherical charged object and accumulates at a point on an irregularly shaped charged object.

31. Why can there never be excess charges inside a charged conductive sphere?

32. Describe a simple experiment to demonstrate that there are no excess charges on the inside of a hollow charged sphere.

33. Identify a technology that uses the principle that electric charges accumulate at the point of an irregularly shaped object. Describe how the technology applies this principle.

Consolidate Your Understanding

Create your own summary of electric field theory by answering the questions below. If you want to use a graphic organizer, refer to Student Reference 3: Using Graphic Organizers. Use the Key Terms and Concepts listed on page 577 and the Learning Outcomes on page 542.

1. Create a flowchart to describe the differences between electric fields, electric potential energy, and electric potential, using non-uniform and uniform electric fields.

2. Write a paragraph comparing the electric fields around various objects and surfaces. Include diagrams in your comparisons. Share your report with a classmate.

Think About It

Review your answers to the Think About It questions on page 543. How would you answer each question now?

eTEST

To check your understanding of concepts presented in Chapter 11, follow the eTest links at www.pearsoned.ca/school/physicssource.