Chapter 21

Electric Fields

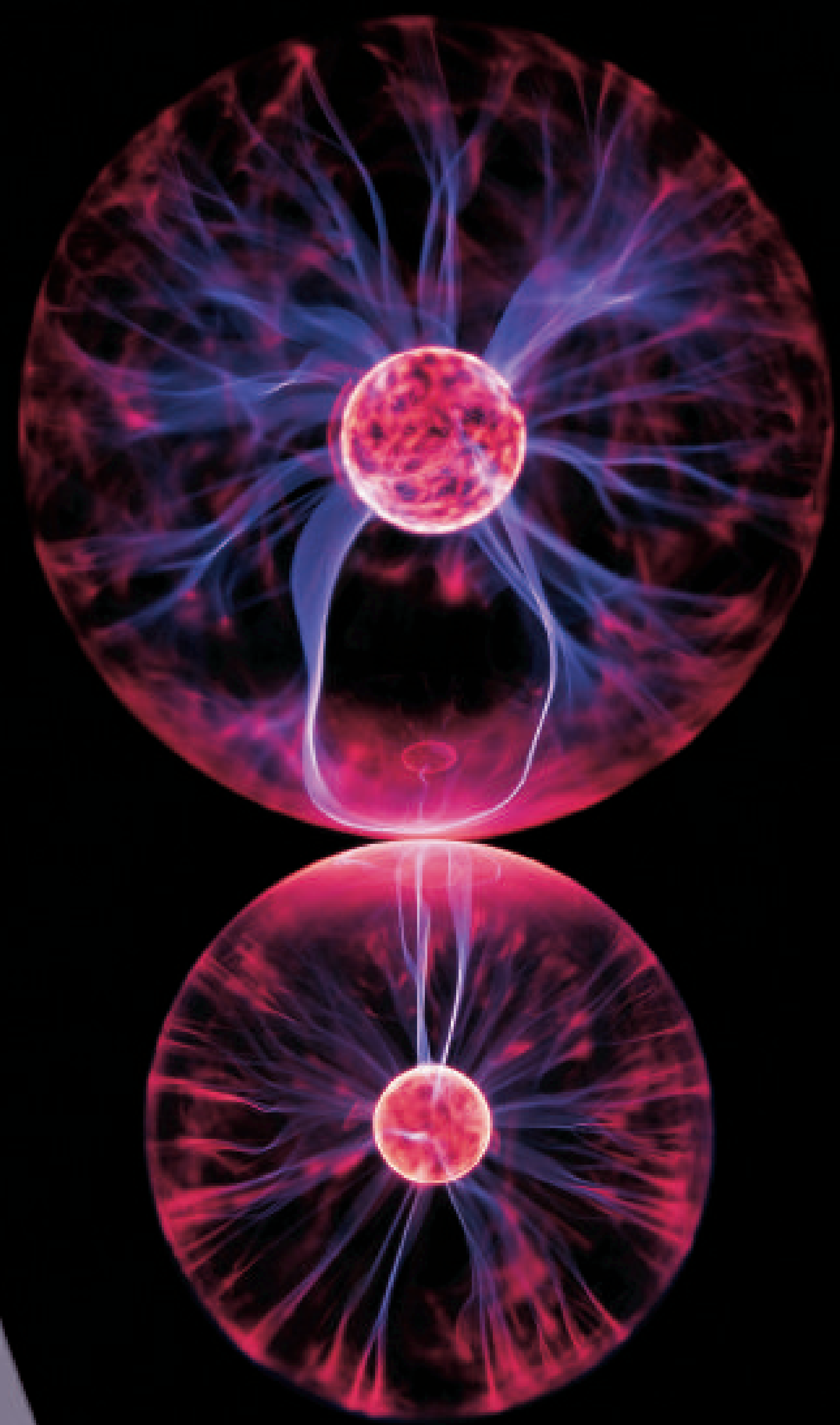
What You'll Learn

- You will relate electric fields to electric forces and distinguish between them.
- You will relate electric potential difference to work and energy.
- You will describe how charges are distributed on conductors.
- You will explain how capacitors store electric charges.

Why It's Important

Electricity is an essential form of energy for modern societies.

High-Energy Discharge A high-voltage generator produces the glow you see inside these discharge spheres.



Think About This ▶

Why doesn't an ordinary lightbulb glow in the same way as these discharge spheres connected to a high-voltage generator?

Physics Online

physicspp.com

LAUNCH Lab

How do charged objects interact at a distance?

Question

How is a charged object affected by interaction with other charged objects at a distance?

Procedure

1. Inflate and tie off two balloons. Attach a $\frac{1}{2}$-m length of string to each balloon.
2. Rub one balloon back and forth on your shirt six to eight times, causing it to become charged. Hang it from a cabinet, table, or other support by the string with a piece of tape.
3. Rub the second balloon the same way and then suspend it from its string.
4. **Observe** Slowly bring the second balloon toward the suspended one. How do the balloons behave? Tape the second balloon so it hangs by its string next to the first balloon.
5. **Observe** Bring your hand toward the charged balloons. What happens?

Analysis

What did you observe as the two balloons were brought near each other? What happened as your hand was brought near the balloons?

Critical Thinking With what two objects have you previously observed similar behaviors of action at a distance?

21.1 Creating and Measuring Electric Fields

Electric force, like gravitational force, which you studied in Chapter 8, varies inversely as the square of the distance between two point objects. Both forces can act from great distances. How can a force be exerted across what seems to be empty space? Michael Faraday suggested that because an electrically charged object, A, creates a force on another charged object, B, anywhere in space, object A must somehow change the properties of space. Object B somehow senses the change in space and experiences a force due to the properties of the space at its location. We call the changed property of space an **electric field.** An electric field means that the interaction is not between two distant objects, but between an object and the field at its location.

The forces exerted by electric fields can do work, transferring energy from the field to another charged object. This energy is something you use on a daily basis, whether you plug an appliance into an electric outlet or use a battery-powered, portable device. In this chapter, you will learn more about electric fields, forces, and electric energy.

▶ Objectives

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

▶ Vocabulary

electric field
electric field line

The Electric Field

How can you measure an electric field? Place a small charged object at some location. If there is an electric force on it, then there is an electric field at that point. The charge on the object that is used to test the field, called the test charge, must be small enough that it doesn't affect other charges.

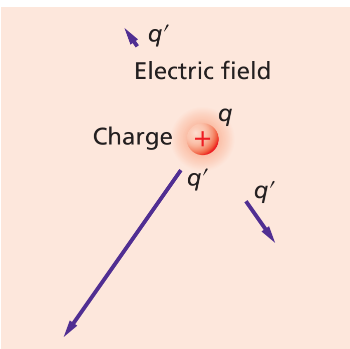
Color Convention

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

Consider **Figure 21-1,** which illustrates a charged object with a charge of q. Suppose you place the positive test charge at some point, A, and measure a force, $\mathbf{F}$. According to Coulomb's law, the force is directly proportional to the strength of the test charge, q'. That is, if the charge is doubled, so is the force. Therefore, the ratio of the force to the charge is a constant. If you divide the force, $\mathbf{F}$, by the test charge, q', you obtain a vector quantity, $\mathbf{F}/q'$. This quantity does not depend on the test charge, only on the force, $\mathbf{F}$, and the location of point A. The electric field at point A, the location of q', is represented by the following equation.

Electric Field Strengh $E = \frac{F_{\text{on } q'}}{q'}$

The strength of an electric field is equal to the force on a positive test charge divided by the strength of the test charge.



■ **Figure 21-1** Arrows can be used to represent the magnitude and direction of the electric field about an electric charge at various locations.

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

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

An electric field should be measured only by a very small test charge. This is because the test charge also exerts a force on q. It is important that the force exerted by the test charge does not cause charge to be redistributed on a conductor, thereby causing q to move to another location and thus, changing the force on q' as well as the electric field strength being measured. A test charge always should be small enough so that its effect on q is negligible.

Table 21-1

Approximate Values of Typical Electric Fields

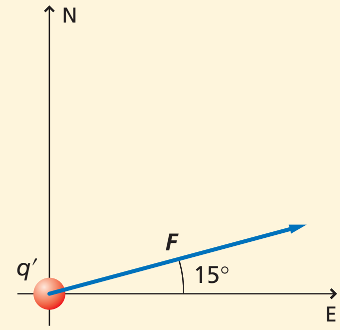
Field	Value (N/C)
Near a charged, hard-rubber rod	1×10^{3}
In a television picture tube	1×10^{5}
Needed to create a spark in air	3×10^{6}
At an electron's orbit in a hydrogen atom	5×10^{11}

▶ EXAMPLE Problem 1

Electric Field Strength An electric field is measured using a positive test charge of 3.0×10^{-6} C. This test charge experiences a force of 0.12 N at an angle of 15° north of east. What are the magnitude and direction of the electric field strength at the location of the test charge?

1 Analyze and Sketch the Problem

- Draw and label the test charge, q'.
- Show and label the coordinate system centered on the test charge.
- Diagram and label the force vector at 15° north of east.



Known:	**Unknown:**
$q' = +3.0\times10^{-6}$ C	$\mathbf{E}$ = ?
$\mathbf{F}$ = 0.12 N at 15° N of E	

2 Solve for the Unknown

$$E = \frac{F}{q'}$$

$$= \frac{0.12\ \text{N}}{3.0\times10^{-6}\ \text{N/C}}$$ **Substitute F = 0.12 N, $q' = 3.0\times10^{-6}$ C**

$$= 4.0\times10^{4}\ \text{N/C}$$

The force on the test charge and the electric field are in the same direction.

$\mathbf{E} = 4.0\times10^{4}$ N/C at 15° N of E

Math Handbook
Operations with Significant Digits
pages 835–836

3 Evaluate the Answer

- **Are the units correct?** Electric field strength is correctly measured in N/C.
- **Does the direction make sense?** The field direction is in the direction of the force because the test charge is positive.
- **Is the magnitude realistic?** This field strength is consistent with the values listed in Table 21-1.

▶ PRACTICE Problems

Additional Problems, Appendix B

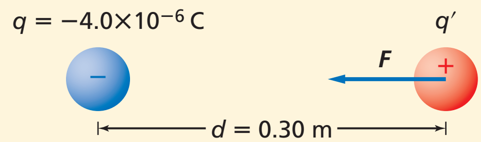
1. A positive test charge of 5.0×10^{-6} C is in an electric field that exerts a force of 2.0×10^{-4} N on it. What is the magnitude of the electric field at the location of the test charge?
2. A negative charge of 2.0×10^{-8} C experiences a force of 0.060 N to the right in an electric field. What are the field's magnitude and direction at that location?
3. A positive charge of 3.0×10^{-7} C is located in a field of 27 N/C directed toward the south. What is the force acting on the charge?
4. A pith ball weighing 2.1×10^{-3} N is placed in a downward electric field of 6.5×10^{4} N/C. What charge (magnitude and sign) must be placed on the pith ball so that the electric force acting on it will suspend it against the force of gravity?
5. You are probing the electric field of a charge of unknown magnitude and sign. You first map the field with a 1.0×10^{-6}-C test charge, then repeat your work with a 2.0×10^{-6}-C test charge.
   a. Would you measure the same forces at the same place with the two test charges? Explain.
   b. Would you find the same field strengths? Explain.

EXAMPLE Problem 2

Electric Field Strength What is the electric field strength at a point that is 0.30 m to the right of a small sphere with a charge of -4.0×10^{-6} C?

1 Analyze and Sketch the Problem

- Draw and label the sphere and its charge, q, and the test charge, q'.
- Show and label the distance between the charges.
- Diagram and label the force vector acting on q'.



Known:
$q = -4.0\times10^{-6}$ C
$d = 0.30$ m

Unknown:
$\boldsymbol{E} = ?$

2 Solve for the Unknown

The force and the magnitude of the test charge are unknown, so use Coulomb's law in combination with the electric field strength.

Math Handbook
Operations with Scientific Notation
pages 842–843

$$E = \frac{F}{q'}$$

$$= K\frac{qq'}{d^2q'}$$ Substitute $F = K\frac{qq'}{d^2}$

$$= K\frac{q}{d^2}$$

$$= \left(9.0\times10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2\right)\frac{(-4.0\times10^{-6}\ \text{C})}{(0.30\ \text{m})^2}$$ Substitute $K = 9.0\times10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2$, $q = -4.0\times10^{-6}$ C, $d = 0.30$ m

$$= -4.0\times10^{5}\ \text{N/C}$$

$\boldsymbol{E} = 4.0\times10^{5}$ N/C toward the sphere, or to the left

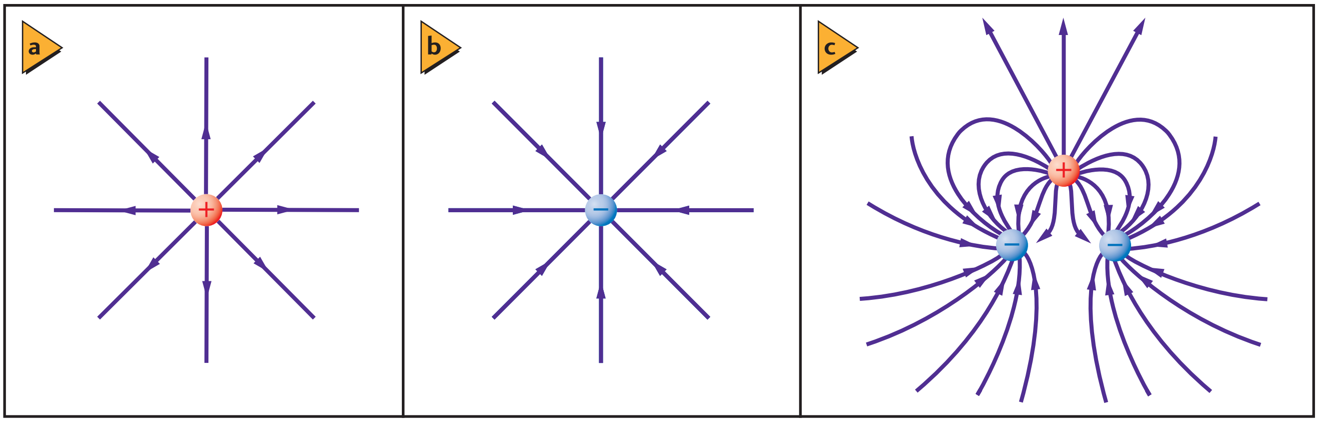
3 Evaluate the Answer

- **Are the units correct?** $(\text{N}\cdot\text{m}^2/\text{C}^2)(\text{C})/\text{m}^2 = \text{N/C}$. The units work out to be N/C, which is correct for electric field strength.
- **Does the direction make sense?** The negative sign indicates that the positive test charge is attracted toward the negative point charge.
- **Is the magnitude realistic?** This field strength is consistent with the values listed in Table 21-1.

PRACTICE Problems

Additional Problems, Appendix B

6. What is the magnitude of the electric field strength at a position that is 1.2 m from a point charge of 4.2×10^{-6} C?
7. What is the magnitude of the electric field strength at a distance twice as far from the point charge in problem 6?
8. What is the electric field at a position that is 1.6 m east of a point charge of $+7.2\times10^{-6}$ C?
9. The electric field that is 0.25 m from a small sphere is 450 N/C toward the sphere. What is the charge on the sphere?
10. How far from a point charge of $+2.4\times10^{-6}$ C must a test charge be placed to measure a field of 360 N/C?



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

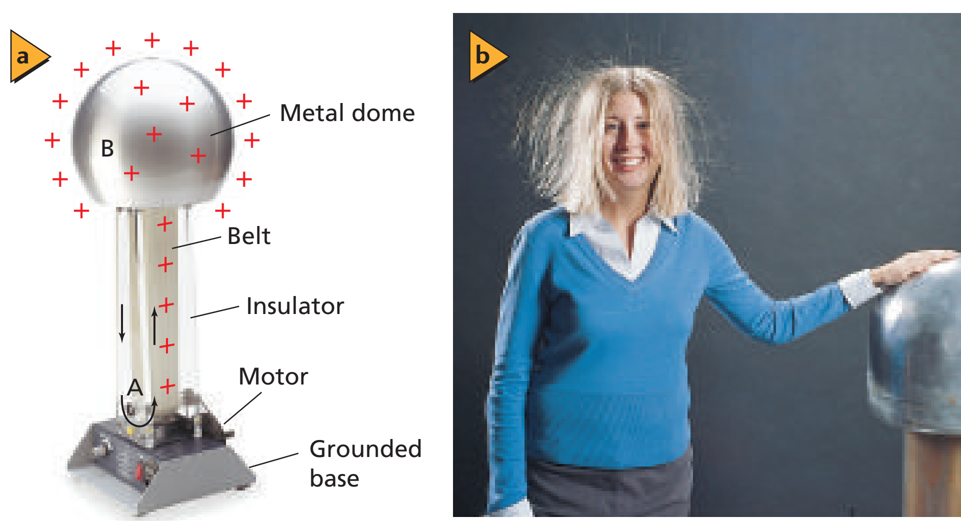
So far, you have measured an electric field at a single point. Now, imagine moving the test charge to another location. Measure the force on it again and calculate the electric field. Repeat this process again and again until you assign every location in space a measurement of the vector quantity of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

Picturing the Electric Field

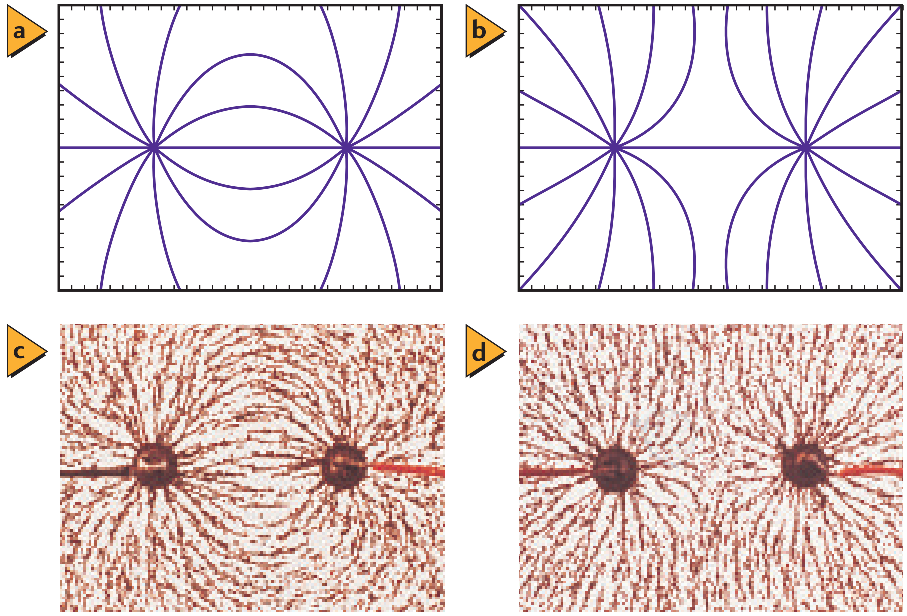
A picture of an electric field is shown in **Figure 21-2.** Each of the lines used to represent the actual field in the space around a charge is called an **electric field line.** The direction of the field at any point is the tangent drawn to a field line at that point. The strength of the electric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

The direction of the force on a positive test charge near another positive charge is away from the other charge. Thus, the field lines extend radially outward like the spokes of a wheel, as shown in **Figure 21-2a.** Near a negative charge, the direction of the force on the positive test charge is toward the negative charge, so the field lines point radially inward, as shown in **Figure 21-2b.** When there are two or more charges, the field is the vector sum of the fields resulting from the individual charges. The field lines become curved and the pattern is more complex, as shown in **Figure 21-2c.** Note that field lines always leave a positive charge and enter a negative charge, and that they never cross each other.

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



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



Robert Van de Graaff devised the high-voltage electrostatic generator in the 1930s. Van de Graaff's machine, shown in **Figure 21-3a** on the previous page, is a device that transfers large amounts of charge from one part of the machine to a metal terminal at the top of the device. Charge is transferred onto a moving belt at the base of the generator, position A, and is transferred off the belt at the metal dome at the top, position B. An electric motor does the work needed to increase the electric potential energy. A person touching the terminal of a Van de Graaff machine is charged electrically. The charges on the person's hairs repel each other, causing the hairs to follow the field lines, as shown in **Figure 21-3b.**

Another method of visualizing field lines is to use grass seed in an insulating liquid, such as mineral oil. The electric forces cause a separation of charge in each long, thin grass seed. The seeds then turn so that they line up along the direction of the electric field. The seeds thus form a pattern of the electric field lines, as in **Figure 21-4.** Field lines do not really exist. They are simply a means of providing a model of an electric field. Electric fields, on the other hand, do exist. Although they provide a method of calculating the force on a charged body, they do not explain why charged bodies exert forces on each other.

21.1 Section Review

11. Measuring Electric Fields Suppose you are asked to measure the electric field in space. How do you detect the field at a point? How do you determine the magnitude of the field? How do you choose the magnitude of the test charge? What do you do next?

12. Field Strength and Direction A positive test charge of magnitude 2.40×10^{-8} C experiences a force of 1.50×10^{-3} N toward the east. What is the electric field at the position of the test charge?

13. Field Lines In Figure 21-4, can you tell which charges are positive and which are negative? What would you add to complete the field lines?

14. Field Versus Force How does the electric field, ***E***, at the test charge differ from the force, ***F***, on it?

15. Critical Thinking Suppose the top charge in Figure 21-2c is a test charge measuring the field resulting from the two negative charges. Is it small enough to produce an accurate measure? Explain.

Physics Online physicspp.com/self_check_quiz

CONTENTS

21.2 Applications of Electric Fields

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

Energy and Electric Potential

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

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

Although the force on the test charge depends on its magnitude, q', the electric field it experiences does not. The electric field, $\mathbf{E} = \mathbf{F}/q'$, is the force per unit charge. In a similar way, the **electric potential difference,** ΔV, is defined as the work done moving a positive test charge between two points in an electric field divided by the magnitude of the test charge.

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

The difference in electrical potential is the ratio of the work needed to move a charge to the strength of that charge.

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

Consider the situation shown in **Figure 21-6** on the next page. The negative charge creates an electric field toward itself. Suppose you place a small positive test charge in the field at position A. It will experience a force in the direction of the field. If you now move the test charge away from the negative charge to position B, as in **Figure 21-6a,** you will have to exert a force, $\mathbf{F}$, on the charge. Because the force that you exert is in the same direction as the displacement, the work that you do on the test charge is positive. Therefore, there also will be a positive change in the electric potential difference. The change in potential difference does not depend on the magnitude of the test charge. It depends only on the field and the displacement.

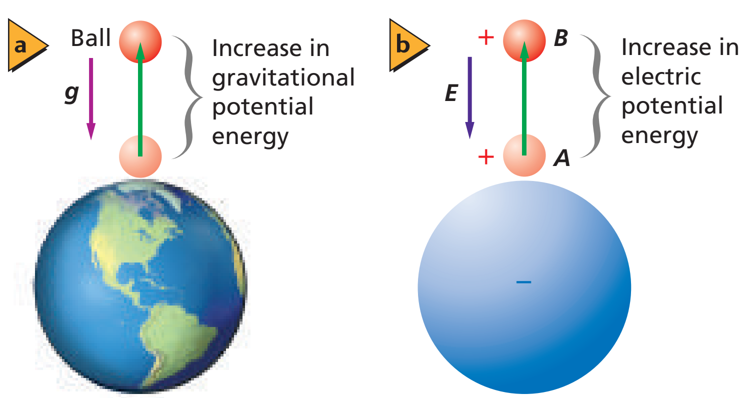
▶ **Objectives**

- **Define** electric potential difference.
- **Calculate** potential difference from the work required to move a charge.
- **Describe** how charges are distributed on solid and hollow conductors.
- **Solve** problems pertaining to capacitance.

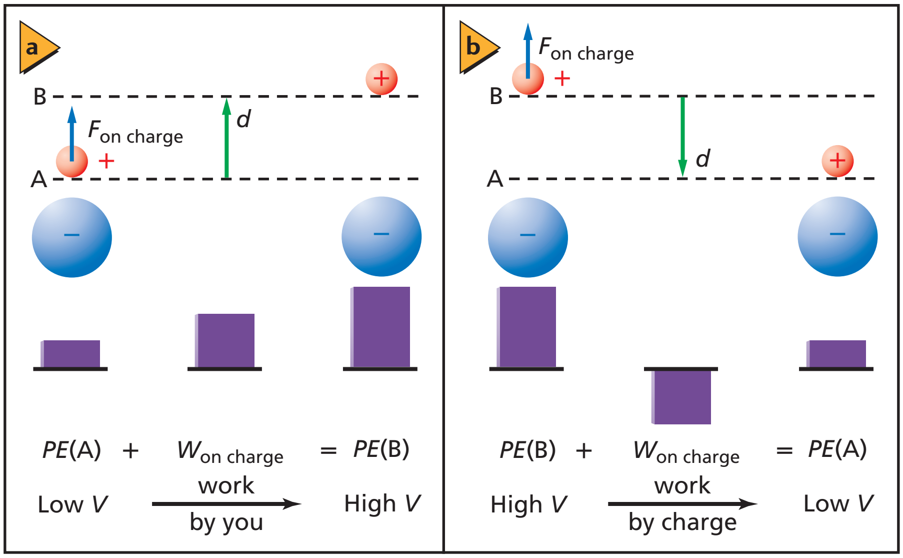
▶ **Vocabulary**

electric potential difference
volt
equipotential
capacitor
capacitance

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



■ **Figure 21-6** Electric potential difference is determined by measuring the work per unit charge. If you move unlike charges apart, you increase the electric potential difference **(a).** If you move unlike charges closer together, you reduce the electric potential difference **(b).**



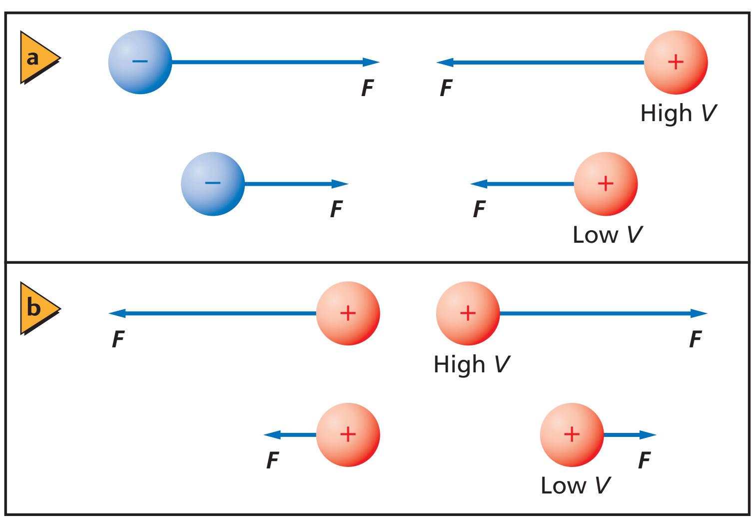
APPLYING PHYSICS

▶ **Static Electricity** Modern electronic devices, such as personal computers, contain components that are easily damaged by static electric discharges. To prevent damage to these sensitive components during repair, a technician will wear a conductive strap around his or her wrist. The other end of this strap is clipped to a grounded piece of metal. The strap conducts charge away from the technician and eliminates any possible potential difference with the grounded equipment. ◀

Suppose you now move the test charge back to position A from position B, as in **Figure 21-6b.** The force that you exert is now in the direction opposite the displacement, so the work that you do is negative. The electric potential difference is also negative. In fact, it is equal and opposite to the potential difference for the move from position A to position B. The electric potential difference does not depend on the path used to go from one position to another. It does depend on the two positions.

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

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



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

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

As you learned in Chapter 11, the potential energy of a system can be defined as zero at any reference point. In the same way, the electric potential of any point can be defined as zero. No matter what reference point is chosen, the value of the electric potential difference from point A to point B always will be the same.

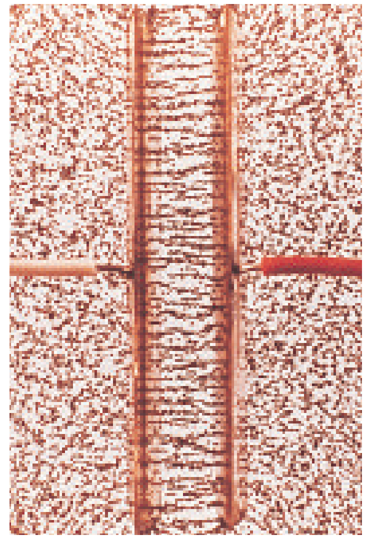


Figure 21-8 A representation of an electric field between parallel plates is shown.

The Electric Potential in a Uniform Field

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

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

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

The electrical potential difference in a uniform field is equal to the product of electric field intensity and the distance moved by a charge.

The electric potential increases in the direction opposite the electric field direction. That is, the electric potential is higher near the positively charged plate. By dimensional analysis, the product of the units of E and d is (N/C)(m). This is equivalent to one J/C, which is the definition of 1 V.

PRACTICE Problems

Additional Problems, Appendix B

16. The electric field intensity between two large, charged, parallel metal plates is 6000 N/C. The plates are 0.05 m apart. What is the electric potential difference between them?

17. A voltmeter reads 400 V across two charged, parallel plates that are 0.020 m apart. What is the electric field between them?

18. What electric potential difference is applied to two metal plates that are 0.200 m apart if the electric field between them is 2.50×10^3 N/C?

19. When a potential difference of 125 V is applied to two parallel plates, the field between them is 4.25×10^3 N/C. How far apart are the plates?

20. A potential difference of 275 V is applied to two parallel plates that are 0.35 cm apart. What is the electric field between the plates?

EXAMPLE Problem 3

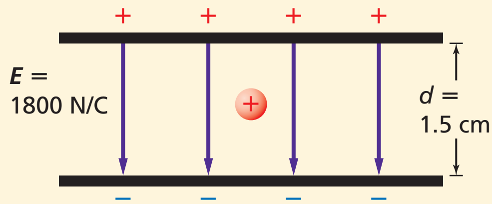
Work Required to Move a Proton Between Charged Parallel Plates Two charged parallel plates are 1.5 cm apart. The magnitude of the electric field between the plates is 1800 N/C.

a. What is the electric potential difference between the plates?

b. What work is required to move a proton from the negative plate to the positive plate?

1 Analyze and Sketch the Problem

- Draw the plates separated by 1.5 cm.
- Label one plate with positive charges and the other with negative charges.
- Draw uniformly spaced electric field lines from the positive plate to the negative plate.
- Indicate the electric field strength between the plates.
- Place a proton in the electric field.



Known:

$E = 1800$ N/C

$d = 1.5$ cm

$q = 1.60\times10^{-19}$ C

Unknown:

$\Delta V = ?$

$W = ?$

Math Handbook
Operations with Scientific Notation
pages 842–843

2 Solve for the Unknown

$$\Delta V = Ed$$
$$= (1800 \text{ N/C})(0.015 \text{ m}) \quad \text{Substitute } E = 1800 \text{ N/C}, d = 0.015 \text{ m}$$
$$= 27 \text{ V}$$

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

$$W = q\Delta V$$
$$= (1.60\times10^{-19} \text{ C})(27 \text{ V}) \quad \text{Substitute } q = 1.60\times10^{-19} \text{ C}, \Delta V = 27 \text{ V}$$
$$= 4.3\times10^{-18} \text{ J}$$

3 Evaluate the Answer

- **Are the units correct?** (N/C)(m) = N·m/C = J/C = V. The units work out to be volts. C·V = C(J/C) = J, the unit for work.
- **Does the sign make sense?** Positive work must be done to move a positive charge toward a positive plate.
- **Is the magnitude realistic?** With such a small charge moved through a potential difference of a few volts, the work performed will be small.

PRACTICE Problems

Additional Problems, Appendix B

21. What work is done when 3.0 C is moved through an electric potential difference of 1.5 V?

22. A 12-V car battery can store 1.44×10^{6} C when it is fully charged. How much work can be done by this battery before it needs recharging?

23. An electron in a television picture tube passes through a potential difference of 18,000 V. How much work is done on the electron as it passes through that potential difference?

24. If the potential difference in problem 18 is between two parallel plates that are 2.4 cm apart, what is the magnitude of the electric field between them?

25. The electric field in a particle-accelerator machine is 4.5×10^{5} N/C. How much work is done to move a proton 25 cm through that field?

Millikan's Oil-Drop Experiment

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

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

Charge on an electron Millikan found that there was a great deal of variation in the charges of the drops. When he used X rays to ionize the air and add or remove electrons from the drops, he noted, however, that the changes in the charge on the drops were always a multiple of 1.60×10^{-19} C. The changes were caused by one or more electrons being added to or removed from the drops. Millikan concluded that the smallest change in charge that could occur was the amount of charge of one electron. Therefore, Millikan proposed that each electron always has the same charge, 1.60×10^{-19} C. Millikan's experiment showed that charge is quantized. This means that an object can have only a charge with a magnitude that is some integral multiple of the charge of an electron.

MINI LAB

Electric Fields

Tie a pith ball on the end of a 20-cm nylon thread and tie the other end to a plastic straw. Holding the straw horizontally, notice that the ball hangs straight down. Now rub a piece of wool on a 30 cm × 30 cm square of plastic foam to charge both objects. Stand the foam vertically. Hold the straw and touch the pith ball to the wool.

1. Predict what will happen when the ball is close to the foam.

2. Test your prediction by slowly bringing the hanging ball toward the charged plastic foam.

3. Predict the ball's behavior at different locations around the foam, and test your prediction.

4. Observe the angle of the thread as you move the pith ball to different regions around the foam.

Analyze and Conclude

5. Explain, in terms of the electric field, why the ball swings toward the charged plastic.

6. Compare the angle of the thread at various points around the foam. Why did it change?

7. Infer what the angle of the thread indicates about the strength and the direction of the electric field.

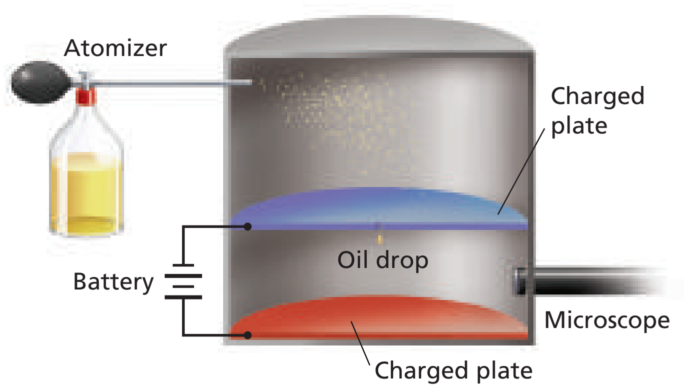


Figure 21-9 This illustration shows a cross-sectional view of the apparatus that Millikan used to determine the charge on an electron.

EXAMPLE Problem 4

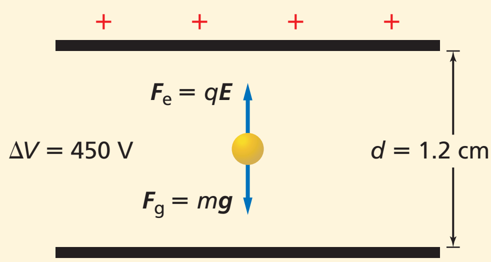
Finding the Charge on an Oil Drop In a Millikan oil-drop experiment, a drop has been found to weigh 2.4×10^{-14} N. The parallel plates are separated by a distance of 1.2 cm. When the potential difference between the plates is 450 V, the drop is suspended, motionless.

a. What is the charge on the oil drop?

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

1 Analyze and Sketch the Problem

- Draw the plates with the oil drop suspended between them.
- Draw and label vectors representing the forces.
- Indicate the potential difference and the distance between the plates.



Known:

$\Delta V = 450$ V

$F_g = 2.4\times10^{-14}$ N

$d = 1.2$ cm

Unknown:

charge on drop, $q = ?$

number of electrons, $n = ?$

2 Solve for the Unknown

To be suspended, the electric force and gravitational force must be balanced.

$$F_e = F_g$$

$$qE = F_g \qquad \text{Substitute } F_e = qE$$

$$\frac{q\Delta V}{d} = F_g \qquad \text{Substitute } E = \frac{\Delta V}{d}$$

Math Handbook
Isolating a Variable
page 845

Solve for q.

$$q = \frac{F_g d}{\Delta V}$$

$$= \frac{(2.4\times10^{-14}\text{ N})(0.012\text{ m})}{450\text{ V}} \qquad \text{Substitute } F_g = 2.4\times10^{-14}\text{ N}, d = 0.012\text{ m}, \Delta V = 450\text{ V}$$

$$= 6.4\times10^{-19}\text{ C}$$

Solve for the number of electrons on the drop.

$$n = \frac{q}{e}$$

$$= \frac{6.4\times10^{-19}\text{ C}}{1.6\times10^{-19}\text{ C}} \qquad \text{Substitute } q = 6.4\times10^{-19}\text{ C}, e = 1.6\times10^{-19}\text{ C}$$

$$= 4$$

3 Evaluate the Answer

- **Are the units correct?** N·m/V = J/(J/C) = C, the unit for charge.
- **Is the magnitude realistic?** This is a small whole number of elementary charges.

PRACTICE Problems

Additional Problems, Appendix B

26. A drop is falling in a Millikan oil-drop apparatus with no electric field. What forces are acting on the oil drop, regardless of its acceleration? If the drop is falling at a constant velocity, describe the forces acting on it.

27. An oil drop weighs 1.9×10^{-15} N. It is suspended in an electric field of 6.0×10^{3} N/C. What is the charge on the drop? How many excess electrons does it carry?

28. An oil drop carries one excess electron and weighs 6.4×10^{-15} N. What electric field strength is required to suspend the drop so it is motionless?

29. A positively charged oil drop weighing 1.2×10^{-14} N is suspended between parallel plates separated by 0.64 cm. The potential difference between the plates is 240 V. What is the charge on the drop? How many electrons is the drop missing?

Sharing of Charge

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

The excess charges on sphere A repel each other, so when the neutral sphere, B, touches sphere A, there is a net force on the charges on A toward B. Suppose that you were to physically move the charges, individually, from A to B. When you move the first charge, the other charges on A would push it toward B, so, to control its speed, you would have to exert a force in the opposite direction. Therefore, you do negative work on it, and the electric potential difference from A to B is negative. When the next few charges are moved, they feel a small repulsive force from the charges already on B, but there is still a net positive force in that direction. At some point, the force pushing a charge off A will equal the repulsive force from the charges on B, and the electric potential difference is zero. After this point of equilibrium, work would have to be done to move the next charge to B, so this would not happen by itself and would require an increase in the energy of the system. However, if you did continue to move charges, the electric potential difference from A to B would then be positive. Thus, you can see that charges would move from A to B without external forces until there is no electric potential difference between the two spheres.

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

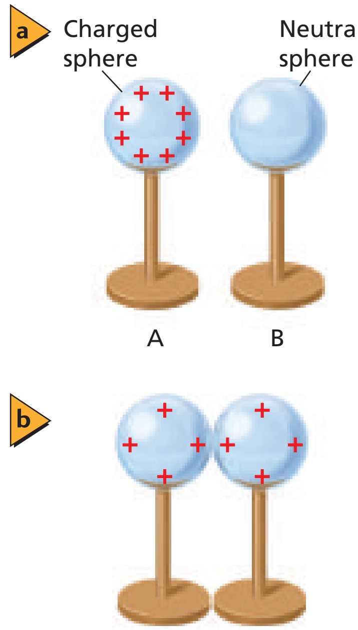


Figure 21-10 A charged sphere shares charge equally with a neutral sphere of equal size when they are placed in contact with each other.

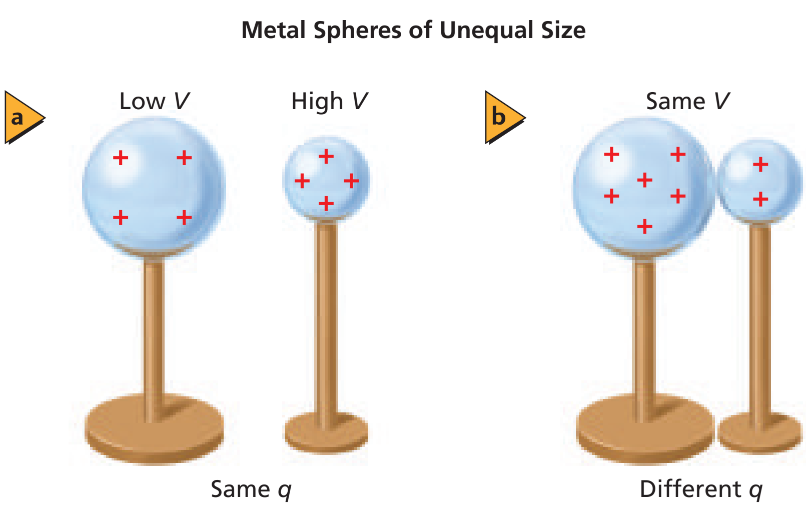
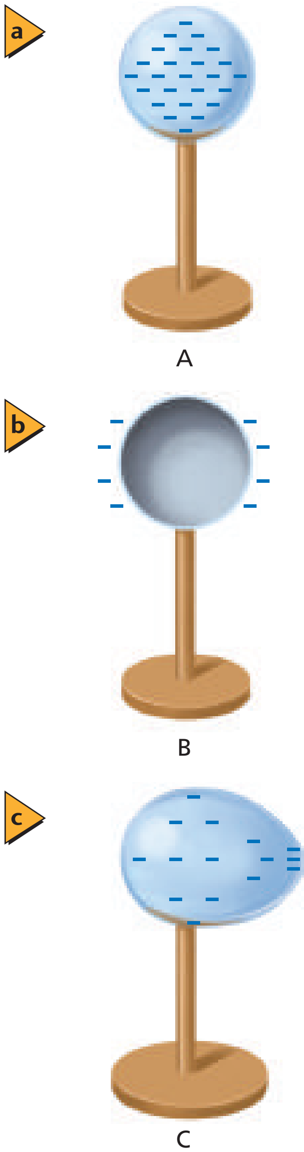


Figure 21-11 Charges are transferred from a sphere with high potential to a sphere with lower potential when they touch. The charges move to create no potential difference.

■ **Figure 21-12** The ground wire on a fuel truck prevents ignition of the gasoline vapors.

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

If a charged body is grounded by touching Earth, almost any amount of charge can flow to Earth until the electric potential difference between that body and Earth is reduced to zero. Gasoline trucks, for example, can become charged by friction. If the charge on a gasoline truck were to jump to Earth through gasoline vapor, it could cause an explosion. To prevent this, a metal wire on the truck safely conducts the charge to the ground, as shown in **Figure 21-12.** Similarly, if a computer is not grounded, an electric potential difference between the computer and Earth can occur. If a person then touches the computer, charges could flow through the computer to the person and damage the equipment or hurt the person.



■ **Figure 21-13** On a conducting sphere, **(a),** the charge is evenly distributed around the surface. The charges on the hollow sphere, **(b),** are entirely on the outer surface. In irregular shapes, **(c),** the charges will be closest together at sharp points.

Electric Fields Near Conductors

The charges on a conductor are spread as far apart as they can be to make the energy of the system as low as possible. The result is that all charges are on the surface of a solid conductor. If the conductor is hollow, excess charges will move to the outer surface. If a closed metal container is charged, there will be no charges on the inside surfaces of the container. In this way, a closed metal container shields the inside from electric fields. For example, people inside a car are protected from the electric fields generated by lightning. Likewise, on an open coffee can, there will be very few charges inside and none near the bottom. Even if the inner surface of an object is pitted or bumpy, giving it a larger surface area than the outer surface, the charge still will be entirely on the outside.

On the outside of a conductor, however, the electric field often is not zero. Even though the surface of a conductor is at an equipotential, the electric field around the outside of it depends on the shape of the conductor, as well as on the electric potential difference between it and Earth. The charges are closer together at sharp points of a conductor, as indicated in **Figure 21-13.** Therefore, the field lines are closer together and the field is stronger. This field can become so strong that when electrons are knocked off of atoms by passing cosmic rays, the electrons and resulting ions are accelerated by the field, causing them to strike other atoms, resulting in more ionization of atoms. This chain reaction is what results in the pink glow, such as that seen inside a gas-discharge sphere. If the field is strong enough, when the particles hit other molecules they will produce a stream of ions and electrons that form a plasma, which is a conductor. The result is a spark, or, in extreme cases, lightning. To reduce discharges and sparking, conductors that are highly charged or that operate at high potentials are made smooth in shape to reduce the electric fields.

In contrast, a lightning rod is pointed so that the electric field will be strong near the end of the rod. As the field accelerates electrons and ions, they form the start of a conducting path from the rod to the clouds. As a result of the rod's sharply pointed shape, charges in the clouds spark to the rod, rather than to a chimney or other high point on a house or other building. From the rod, a conductor takes the charges safely to the ground.

Lightning usually requires a potential difference of millions of volts between Earth and the clouds. Even a small gas-discharge tube operates at several thousand volts. Household wiring, on the other hand, does not normally carry a high enough potential difference to cause such discharges.

Storing Charges: The Capacitor

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

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

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

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

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

Capacitance is the ratio of charge on one plate to potential difference.

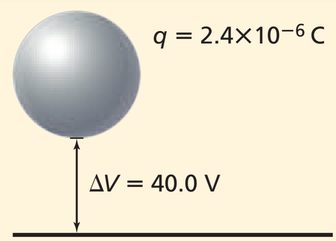
Figure 21-14 Various types of capacitors are pictured below.

Horizons Companies

The farad as a unit of measure One farad, F, named after Michael Faraday, is one coulomb per volt, C/V. Just as 1 C is a large amount of charge, 1 F is also a fairly large capacitance. Most capacitors used in modern electronics have capacitances between 10 picofarads (10×10^{-12} F) and 500 microfarads (500×10^{-6} F). However, memory capacitors that are used to prevent loss of memory in some computers can have capacitance from 0.5 F to 1.0 F. Note that if the charge is increased, the electric potential difference also increases. The capacitance depends only on the construction of the capacitor, not on the charge, q.

EXAMPLE Problem 5

Finding Capacitance A sphere has an electric potential difference between it and Earth of 40.0 V when it has been charged to 2.4×10^{-6} C. What is its capacitance?



1 Analyze and Sketch the Problem

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

Known:	Unknown:
$\Delta V = 40.0$ V	$C = ?$
$q = 2.4\times10^{-6}$ C	

2 Solve for the Unknown

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

$$= \frac{2.4\times10^{-6}\ \text{C}}{40.0\ \text{V}}$$ Substitute $\Delta V = 40.0$ V, $q = 2.4\times10^{-6}$ C

$$= 6.0\times10^{-8}\ \text{F}$$

$$= 0.060\ \mu\text{F}$$

Math Handbook
Operations with Significant Digits
pages 835–836

3 Evaluate the Answer

- **Are the units correct?** C/V = F. The units are farads.
- **Is the magnitude realistic?** A small capacitance would store a small charge at a low voltage.

PRACTICE Problems

Additional Problems, Appendix B

30. A 27-μF capacitor has an electric potential difference of 45 V across it. What is the charge on the capacitor?

31. Both a 3.3-μF and a 6.8-μF capacitor are connected across a 24-V electric potential difference. Which capacitor has a greater charge? What is it?

32. The same two capacitors as in problem 31 are each charged to 3.5×10^{-4} C. Which has the larger electric potential difference across it? What is it?

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

34. When a charge of 2.5×10^{-5} C is added to a capacitor, the potential difference increases from 12.0 V to 14.5 V. What is the capacitance of the capacitor?

CHALLENGE PROBLEM

The plates of a capacitor attract each other because they carry opposite charges. A capacitor consisting of two parallel plates that are separated by a distance, d, has capacitance, C.

1. Derive an expression for the force between the two plates when the capacitor has charge, q.

2. What charge must be stored on a 22-μF capacitor to have a force of 2.0 N between the plates if they are separated by 1.5 mm?

Varieties of capacitors Capacitors have many shapes and sizes, as shown in Figure 21-14. Some are large enough to fill whole rooms and can store enough charge to create artificial lightning or power giant lasers that release thousands of joules of energy in a few billionths of a second. Capacitors in television sets can store enough charge at several hundred volts to be very dangerous if they are touched. These capacitors can remain charged for hours after the televisions have been turned off. This is why you should not open the case of a television or a computer monitor even if it is unplugged.

The capacitance of a capacitor is controlled by varying the surface area of the two conductors, or plates, within a capacitor, by the distance between the plates, and by the nature of the insulating material. Capacitors are named for the type of insulator, or dielectric, used to separate the plates, and include ceramic, mica, polyester, paper, and air. Higher capacitance is obtained by increasing the surface area and decreasing the separation of the plates. Certain dielectrics have the ability to effectively offset some of the charge on the plates and allow more charge to be stored.

21.2 Section Review

35. Potential Difference What is the difference between electric potential energy and electric potential difference?

36. Electric Field and Potential Difference Show that a volt per meter is the same as a newton per coulomb.

37. Millikan Experiment When the charge on an oil drop suspended in a Millikan apparatus is changed, the drop begins to fall. How should the potential difference on the plates be changed to bring the drop back into balance?

38. Charge and Potential Difference In problem 37, if changing the potential difference has no effect on the falling drop, what does this tell you about the new charge on the drop?

39. Capacitance How much charge is stored on a 0.47-μF capacitor when a potential difference of 12 V is applied to it?

40. Charge Sharing If a large, positively charged, conducting sphere is touched by a small, negatively charged, conducting sphere, what can be said about the following?

a. the potentials of the two spheres

b. the charges on the two spheres

41. Critical Thinking Referring back to Figure 21-3a, explain how charge continues to build up on the metal dome of a Van de Graaff generator. In particular, why isn't charge repelled back onto the belt at point B?

PHYSICS LAB

Alternate CBL instructions can be found on the Web site.
physicspp.com

Charging of Capacitors

A capacitor is an electric device that is made from two conductors, or plates, that are separated by an insulator. It is designed to have a specific capacitance. The capacitance depends on the physical characteristics and geometric arrangement of the conductors and the insulator. In the circuit schematic, the capacitor appears to create an open circuit, even when the switch is in the closed position. However, because capacitors store charge, when the switch is closed, charge from the battery will move to the capacitor. The equal, but opposite charges on the two plates within the capacitor establishes a potential difference, or voltage. As charge is added to the capacitor, the electric potential difference increases. In this laboratory activity you will examine the charging of several different capacitors.

QUESTION

How do the charging times of different capacitors vary with capacitance?

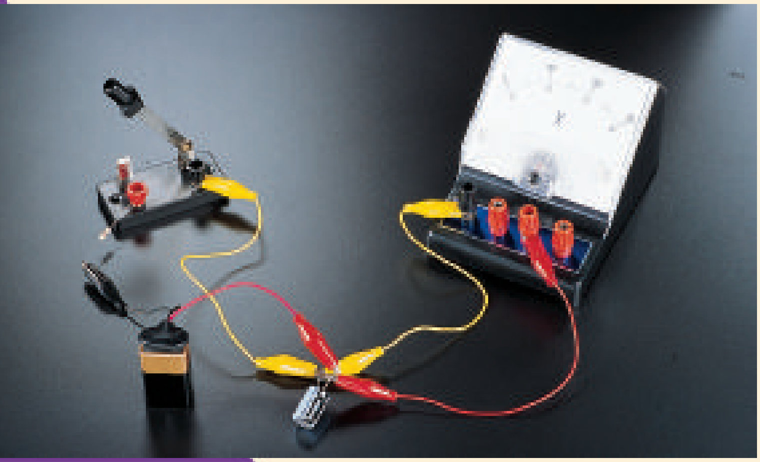
Objectives

- **Collect and organize** data on the rate of charge of different capacitors.
- **Compare and contrast** the rate of charging for different capacitances.
- **Make and use graphs** of potential difference versus time for several capacitors.

Safety Precautions

Materials

9-V battery
9-V battery clip
hook-up wires
switch
voltmeter
47-kΩ resistor
stopwatch
capacitors: 1000 μF, 500 μF, 240 μF



Procedure

1. Before you begin, leave the switch open (off). Do not attach the battery at this time. ***CAUTION: Be careful to avoid a short circuit, especially by permitting the leads from the battery clip to touch each other.*** Connect the circuit, as illustrated. Do this by connecting either end of the resistor to one side of the switch. The resistor is used to reduce the charging of the capacitor to a measurable rate. Connect the other end of the resistor to the negative side of the 9-V battery clip. Inspect your 1000-μF capacitor to determine whether either end is marked with a negative sign, or an arrow with negative signs on it, that points to the lead that is to be connected to the negative side of the battery. Connect this negative lead to the other side of the switch. Attach the unconnected (positive) lead of the capacitor to the positive lead from the battery clip.
2. Connect the positive terminal of the voltmeter to the positive side of the capacitor and the negative terminal to the negative side of the capacitor. Compare your circuit to the photo to verify your connections. Attach the battery after your teacher has inspected the circuit.
3. Prepare a data table having columns for time and potential difference on each of the three different capacitors.
4. One person should watch the time and another should record potential difference at the designated times. Close the switch and measure the voltage at 5-s intervals. Open the switch after you have collected data.

Horizons Companies

Data Table

Time (s)	Voltage (V) across 1000 μF	Voltage (V) across 500 μF	Voltage (V) across 240 μF	Time (s)	Voltage (V) across 1000 μF	Voltage (V) across 500 μF	Voltage (V) across 240 μF
0				55			
5				60			
10				65			
15				70			
20				75			
25				80			
30				85			
35				90			
40				95			
45				100			
50				105			

5. When you have completed the trial, take a short piece of wire and place it across both ends of the capacitor. This will cause the capacitor to discharge.
6. Replace the 1000-μF capacitor with a 500-μF capacitor. Repeat steps 4–5 and enter data into the appropriate columns of your data table for the 500-μF capacitor.
7. Replace the 500-μF capacitor with a 240-μF capacitor. Repeat steps 4–5 and enter data into the appropriate column of your data table for this last capacitor.

Analyze

1. **Observe and Infer** Does each capacitor charge to 9 V? Propose an explanation for the observed behavior.
2. **Make and Use Graphs** Prepare a graph that plots the time horizontally and the potential difference vertically. Make a separate labeled line for each capacitor.

Conclude and Apply

1. **Interpret Data** Does the voltage on the capacitor immediately jump to the battery's potential difference (9-V)? Explain the reason for the observed behavior.
2. **Infer** Does the larger capacitor require a longer time to become fully charged? Explain why or why not.

Going Further

1. The time for a capacitor to charge to the voltage of the battery depends upon its capacitance and the opposition to the flow of charge in the circuit. In this lab, the opposition to the flow of charge was controlled by the 47-kΩ resistor that was placed in the circuit. In circuits with a capacitor and resistance, such as in this activity, the time in seconds to charge the capacitor to 63.3 percent of the applied voltage is equal to the product of the capacitor and resistance. This is called the time constant. Therefore, $T = RC$, where T is in seconds, R is in ohms, and C is in microfarads. Calculate the time constant for each of the capacitors with the 47-kΩ resistor.
2. Compare your time constants to the values from your graph.

Real-World Physics

Explain Small, disposable, flash cameras, as well as regular electronic flash units, require time before the flash is ready to be used. A capacitor stores the energy for the flash. Explain what might be going on during the time you must wait to take your next picture.

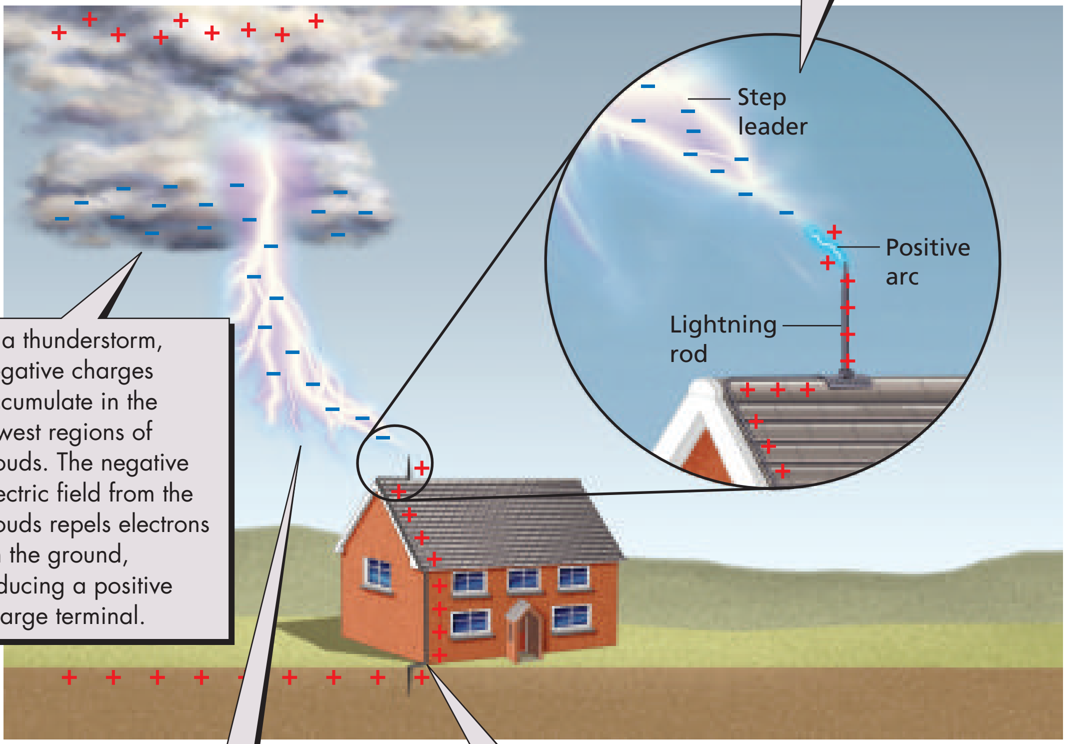
Physics Online

To find out more about electric fields, visit the Web site: physicspp.com

How it Works Lightning Rods

Lightning can be very destructive because it creates huge currents in materials that are poor conductors and generates a great deal of heat. In addition to protecting a structure by dissipating some of the charge before lightning strikes, lightning rods are excellent conductors that provide a safe path for the current. Benjamin Franklin is credited with inventing the lightning rod in the 1750s.

3 Positive charges spark out from the lightning rod, meeting the step leader. The conducting path is complete and current neutralizes the separation of charges. Even if the strike does not hit the lightning rod directly, the massive current still can leap to the rod, which is the path of least resistance to the ground.



1 In a thunderstorm, negative charges accumulate in the lowest regions of clouds. The negative electric field from the clouds repels electrons on the ground, inducing a positive charge terminal.

2 The strong electric field accelerates electrons and ions, causing a chain reaction in the air, forming plasma. The ionized air is a conductor, and it branches out from the cloud forming what are called step leaders.

4 The current travels safely through the conductor to the ground terminal.

Thinking Critically

1. **Hypothesize** Along what path would the current travel if a house without a lightning rod were struck by lightning?
2. **Evaluate** Should the resistance between the ground terminal and Earth be high or low?
3. **Infer** What are the dangers of an incorrectly installed lightning rod system?

Chapter 21

Study Guide

21.1 Creating and Measuring Electric Fields

Vocabulary

- electric field (p. 563)
- electric field line (p. 567)

Key Concepts

- An electric field exists around any charged object. The field produces forces on other charged objects.
- The electric field is the force per unit charge.

$$\boldsymbol{E} = \frac{\boldsymbol{F}}{q'}$$

- The direction of the electric field is the direction of the force on a tiny, positive test charge.
- Electric field lines provide a picture of the electric field. They are directed away from positive charges and toward negative charges. They never cross, and their density is related to the strength of the field.

21.2 Applications of Electric Fields

Vocabulary

- electric potential difference (p. 569)
- volt (p. 569)
- equipotential (p. 570)
- capacitor (p. 577)
- capacitance (p. 577)

Key Concepts

- Electric potential difference is the change in potential energy per unit charge in an electric field.

$$\Delta V = \frac{W}{q'}$$

- Electric potential differences are measured in volts.
- The electric field between two parallel plates is uniform between the plates, except near the edges. In a uniform field, the potential difference is related to the field strength by the following.

$$\Delta V = Ed$$

- Robert Millikan's experiments showed that electric charge is quantized.
- Robert Millikan also showed that the negative charge carried by an electron is 1.60×10^{-19} C.
- Charges will move in a conductor until the electric potential is the same everywhere on the conductor.
- Grounding makes the potential difference between an object and Earth equal to zero.
- Grounding can prevent sparks resulting from a neutral object making contact with objects that have built-up charge on them.
- Electric fields are strongest near sharply pointed conductors.
- Capacitance is the ratio of the charge on an object to its electric potential difference.

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

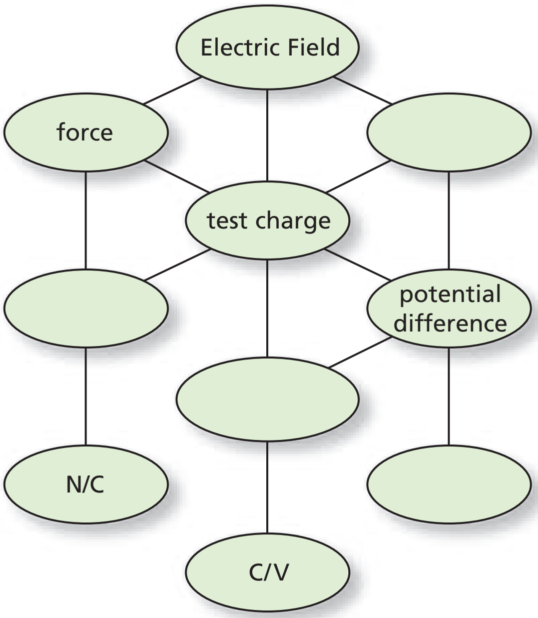
- Capacitance is independent of the charge on an object and the electric potential difference across it.
- Capacitors are used to store charge.

Chapter 21

Assessment

Concept Mapping

42. Complete the concept map below using the following terms: *capacitance, field strength, J/C, work.*



Mastering Concepts

43. What are the two properties that a test charge must have? (21.1)

44. How is the direction of an electric field defined? (21.1)

45. What are electric field lines? (21.1)

46. How is the strength of an electric field indicated with electric field lines? (21.1)

47. Draw some of the electric field lines between each of the following. (21.1)
   a. two like charges of equal magnitude
   b. two unlike charges of equal magnitude
   c. a positive charge and a negative charge having twice the magnitude of the positive charge
   d. two oppositely charged parallel plates

48. In **Figure 21-15,** where do the electric field lines leave the positive charge end? (21.1)

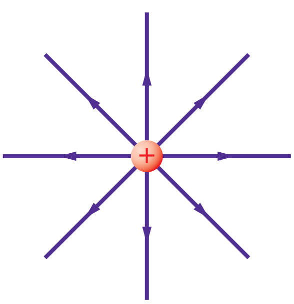


Figure 21-15

49. What SI unit is used to measure electric potential energy? What SI unit is used to measure electric potential difference? (21.2)

50. Define *volt* in terms of the change in potential energy of a charge moving in an electric field. (21.2)

51. Why does a charged object lose its charge when it is touched to the ground? (21.2)

52. A charged rubber rod that is placed on a table maintains its charge for some time. Why is the charged rod not discharged immediately? (21.2)

53. A metal box is charged. Compare the concentration of charge at the corners of the box to the charge concentration on the sides of the box. (21.2)

54. **Computers** Delicate parts in electronic equipment, such as those pictured in **Figure 21-16,** are contained within a metal box inside a plastic case. Why? (21.2)

Figure 21-16

Applying Concepts

55. What happens to the strength of an electric field when the charge on the test charge is halved?

56. Does it require more energy or less energy to move a constant positive charge through an increasing electric field?

57. What will happen to the electric potential energy of a charged particle in an electric field when the particle is released and free to move?

58. **Figure 21-17** shows three spheres with charges of equal magnitude, with their signs as shown. Spheres y and z are held in place, but sphere x is free to move. Initially, sphere x is equidistant from spheres y and z. Choose the path that sphere x will begin to follow. Assume that no other forces are acting on the spheres.

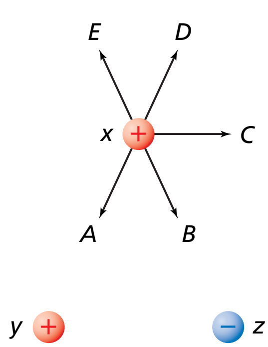


Figure 21-17

Horizons Companies

59. What is the unit of electric potential difference in terms of m, kg, s, and C?

60. What do the electric field lines look like when the electric field has the same strength at all points in a region?

61. **Millikan Oil-Drop Experiment** When doing a Millikan oil-drop experiment, it is best to work with drops that have small charges. Therefore, when the electric field is turned on, should you try to find drops that are moving rapidly or slowly? Explain.

62. Two oil drops are held motionless in a Millikan oil-drop experiment.
   a. Can you be sure that the charges are the same?
   b. The ratios of which two properties of the oil drops have to be equal?

63. José and Sue are standing on an insulating platform and holding hands when they are given a charge, as in **Figure 21-18.** José is larger than Sue. Who has the larger amount of charge, or do they both have the same amount?

Figure 21-18

64. Which has a larger capacitance, an aluminum sphere with a 1-cm diameter or one with a 10-cm diameter?

65. How can you store different amounts of charge in a capacitor?

Mastering Problems

21.1 Creating and Measuring Electric Fields

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

66. What charge exists on a test charge that experiences a force of 1.4×10^{-8} N at a point where the electric field intensity is 5.0×10^{-4} N/C?

67. A positive charge of 1.0×10^{-5} C, shown in **Figure 21-19,** experiences a force of 0.30 N when it is located at a certain point. What is the electric field intensity at that point?

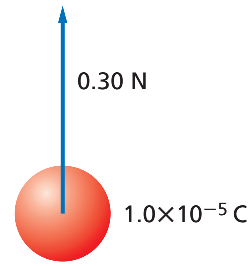


Figure 21-19

68. A test charge experiences a force of 0.30 N on it when it is placed in an electric field intensity of 4.5×10^{5} N/C. What is the magnitude of the charge?

69. The electric field in the atmosphere is about 150 N/C downward.
   a. What is the direction of the force on a negatively charged particle?
   b. Find the electric force on an electron with charge -1.6×10^{-19} C.
   c. Compare the force in part **b** with the force of gravity on the same electron (mass $= 9.1\times10^{-31}$ kg).

70. Carefully sketch each of the following.
   a. the electric field produced by a $+1.0$-μC charge
   b. the electric field resulting from a $+2.0$-μC charge (Make the number of field lines proportional to the change in charge.)

71. A positive test charge of 6.0×10^{-6} C is placed in an electric field of 50.0-N/C intensity, as in **Figure 21-20.** What is the strength of the force exerted on the test charge?

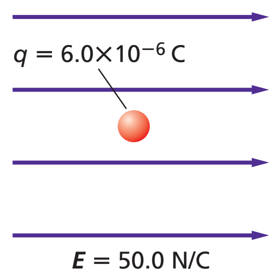


Figure 21-20

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

73. In a television picture tube, electrons are accelerated by an electric field having a value of 1.00×10^5 N/C.
a. Find the force on an electron.
b. If the field is constant, find the acceleration of the electron (mass = 9.11×10^{-31} kg).

74. What is the electric field strength 20.0 cm from a point charge of 8.0×10^{-7} C?

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

21.2 Applications of Electric Fields

76. If 120 J of work is performed to move 2.4 C of charge from the positive plate to the negative plate shown in **Figure 21-21,** what potential difference exists between the plates?

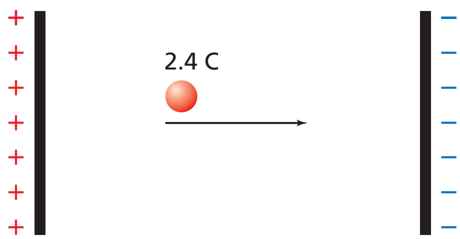


Figure 21-21

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

78. An electron is moved through an electric potential difference of 450 V. How much work is done on the electron?

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

80. The electric field intensity between two charged plates is 1.5×10^3 N/C. The plates are 0.060 m apart. What is the electric potential difference, in volts, between the plates?

81. A voltmeter indicates that the electric potential difference between two plates is 70.0 V. The plates are 0.020 m apart. What electric field intensity exists between them?

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

83. What electric potential difference exists across a 5.4-μF capacitor that has a charge of 8.1×10^{-4} C?

84. The oil drop shown in **Figure 21-22** is negatively charged and weighs 4.5×10^{-15} N. The drop is suspended in an electric field intensity of 5.6×10^3 N/C.
a. What is the charge on the drop?
b. How many excess electrons does it carry?

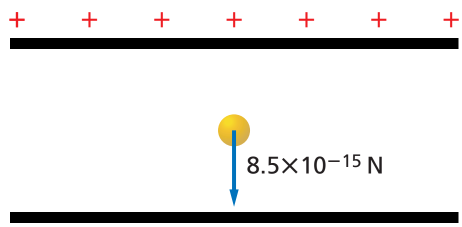


Figure 21-22

85. What is the charge on a 15.0-pF capacitor when it is connected across a 45.0-V source?

86. A force of 0.065 N is required to move a charge of 37 μC a distance of 25 cm in a uniform electric field, as in **Figure 21-23.** What is the size of the electric potential difference between the two points?

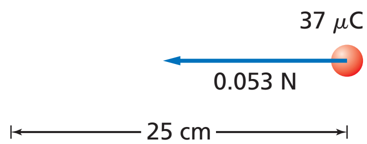


Figure 21-23

87. Photoflash The energy stored in a capacitor with capacitance C, and an electric potential difference, ΔV, is represented by $W = \frac{1}{2}C\Delta V^2$. One application of this is in the electronic photoflash of a strobe light, like the one in **Figure 21-24.** In such a unit, a capacitor of 10.0 μF is charged to 3.0×10^2 V. Find the energy stored.

Figure 21-24

88. Suppose it took 25 s to charge the capacitor in problem 87.
a. Find the average power required to charge the capacitor in this time.
b. When this capacitor is discharged through the strobe lamp, it transfers all its energy in 1.0×10^{-4} s. Find the power delivered to the lamp.
c. How is such a large amount of power possible?

 For more problems, go to Additional Problems, Appendix B.
Horizons Companies

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

a. Given that $W = \frac{1}{2}C\Delta V^2$, find the energy stored in the capacitors.

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

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

Mixed Review

90. How much work does it take to move 0.25 μC between two parallel plates that are 0.40 cm apart if the field between the plates is 6400 N/C?

91. How much charge is stored on a 0.22-μF parallel plate capacitor if the plates are 1.2 cm apart and the electric field between them is 2400 N/C?

92. Two identical small spheres, 25 cm apart, carry equal but opposite charges of 0.060 μC, as in **Figure 21-25.** If the potential difference between them is 300 V, what is the capacitance of the system?

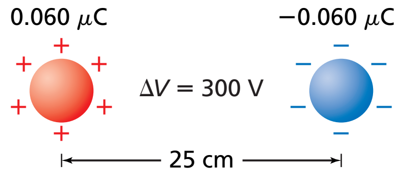


Figure 21-25

93. The plates of a 0.047 μF capacitor are 0.25 cm apart and are charged to a potential difference of 120 V. How much charge is stored on the capacitor?

94. What is the strength of the electric field between the plates of the capacitor in Problem 93 above?

95. An electron is placed between the plates of the capacitor in Problem 93 above, as in **Figure 21-26.** What force is exerted on that electron?

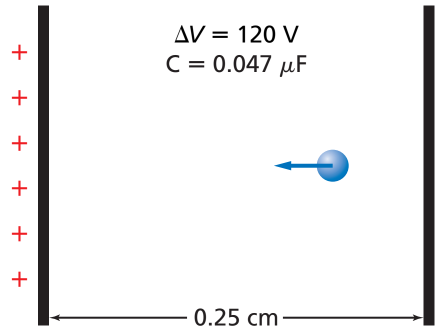


Figure 21-26

96. How much work would it take to move an additional 0.010 μC between the plates at 120 V in Problem 93?

97. The graph in **Figure 21-27** represents the charge stored in a capacitor as the charging potential increases. What does the slope of the line represent?

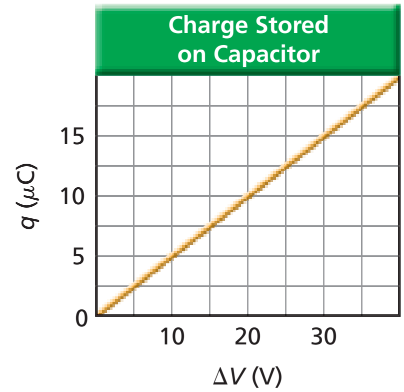


Figure 21-27

98. What is the capacitance of the capacitor represented by Figure 21-27?

99. What does the area under the graph line in Figure 21-27 represent?

100. How much work is required to charge the capacitor in problem 98 to a potential difference of 25 V?

101. The work found in Problem 100 above is not equal to $q\Delta V$. Why not?

102. Graph the electric field strength near a positive point charge as a function of distance from it.

103. Where is the field of a point charge equal to zero?

104. What is the electric field strength at a distance of zero meters from a point charge? Is there such a thing as a true point charge?

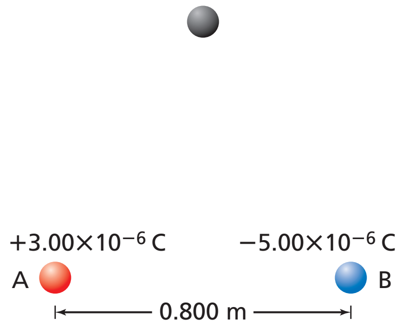
Thinking Critically

105. **Apply Concepts** Although a lightning rod is designed to carry charge safely to the ground, its primary purpose is to prevent lightning from striking in the first place. How does it do that?

106. **Analyze and Conclude** In an early set of experiments in 1911, Millikan observed that the following measured charges could appear on a single oil drop. What value of elementary charge can be deduced from these data?

a. 6.563×10^{-19} C
b. 8.204×10^{-19} C
c. 11.50×10^{-19} C
d. 13.13×10^{-19} C
e. 16.48×10^{-19} C
f. 18.08×10^{-19} C
g. 19.71×10^{-19} C
h. 22.89×10^{-19} C
i. 26.13×10^{-19} C

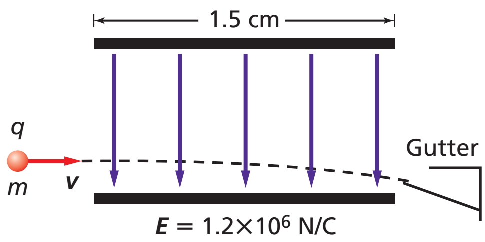
107. **Analyze and Conclude** Two small spheres, A and B, lie on the *x*-axis, as in **Figure 21-28.** Sphere A has a charge of $+3.00\times10^{-6}$ C. Sphere B is 0.800 m to the right of sphere A and has a charge of -5.00×10^{-6} C. Find the magnitude and direction of the electric field strength at a point above the *x*-axis that would form the apex of an equilateral triangle with spheres A and B.



■ **Figure 21-28**

108. **Analyze and Conclude** In an ink-jet printer, drops of ink are given a certain amount of charge before they move between two large, parallel plates. The purpose of the plates is to deflect the charges so that they are stopped by a gutter and do not reach the paper. This is shown in **Figure 21-29.** The plates are 1.5-cm long and have an electric field of $E = 1.2\times10^{6}$ N/C between them. Drops with a mass $m = 0.10$ ng, and a charge $q = 1.0\times10^{-16}$ C, are moving horizontally at a speed, $v = 15$ m/s, parallel to the plates. What is the vertical displacement of the drops when they leave the plates? To answer this question, complete the following steps.

a. What is the vertical force on the drops?
b. What is their vertical acceleration?
c. How long are they between the plates?
d. How far are they displaced?



■ **Figure 21-29**

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

Writing in Physics

110. Choose the name of an electric unit, such as coulomb, volt, or farad, and research the life and work of the scientist for whom it was named. Write a brief essay on this person and include a discussion of the work that justified the honor of having a unit named for him.

Cumulative Review

111. Michelson measured the speed of light by sending a beam of light to a mirror on a mountain 35 km away. (Chapter 16)

a. How long does it take light to travel the distance to the mountain and back?

b. Assume that Michelson used a rotating octagon with a mirror on each face of the octagon. Also assume that the light reflects from one mirror, travels to the other mountain, reflects off of a fixed mirror on that mountain, and returns to the rotating mirrors. If the rotating mirror has advanced so that when the light returns, it reflects off of the next mirror in the rotation, how fast is the mirror rotating?

c. If each mirror has a mass of 1.0×10^{1} g and rotates in a circle with an average radius of 1.0×10^{1} cm, what is the approximate centripetal force needed to hold the mirror while is it rotating?

112. **Mountain Scene** You can see an image of a distant mountain in a smooth lake just as you can see a mountain biker next to the lake because light from each strikes the surface of the lake at about the same angle of incidence and is reflected to your eyes. If the lake is about 100 m in diameter, the reflection of the top of the mountain is about in the middle of the lake, the mountain is about 50 km away from the lake, and you are about 2 m tall, then approximately how high above the lake does the top of the mountain reach? (Chapter 17)

113. A converging lens has a focal length of 38.0 cm. If it is placed 60.0 cm from an object, at what distance from the lens will the image be? (Chapter 18)

114. A force, F, is measured between two charges, Q and q, separated by a distance, r. What would the new force be for each of the following? (Chapter 20)

a. r is tripled
b. Q is tripled
c. both r and Q are tripled
d. both r and Q are doubled
e. all three, r, Q, and q, are tripled

 For more problems, go to Additional Problems, Appendix B.

Standardized Test Practice

Multiple Choice

1. Why is an electric field measured only by a small test charge?

Ⓐ so the charge doesn't disturb the field
Ⓑ because small charges have small momentum
Ⓒ so its size doesn't nudge the charge to be measured aside
Ⓓ because an electron always is used as the test charge and electrons are small

2. A force of 14 N exists on charge *q*, which is 2.1×10^{-9} C. What is the magnitude of the electric field?

Ⓐ 0.15×10^{-9} N/C
Ⓑ 6.7×10^{-9} N/C
Ⓒ 29×10^{-9} N/C
Ⓓ 6.7×10^{9} N/C

3. A positive test charge of 8.7 μC experiences a force of 8.1×10^{-6} N at an angle of 24° N of E. What are the magnitude and direction of the electric field strength at the location of the test charge?

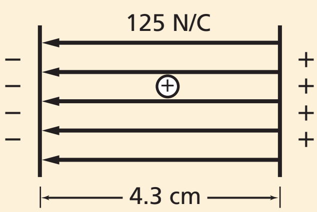
Ⓐ 7.0×10^{-8} N/C, 24° N of E
Ⓑ 1.7×10^{-6} N/C, 24° S of W
Ⓒ 1.1×10^{-3} N/C, 24° W of S
Ⓓ 9.3×10^{-1} N/C, 24° N of E

4. What is the potential difference between two plates that are 18 cm apart with a field of 4.8×10^{3} N/C?

Ⓐ 27 V
Ⓑ 86 V
Ⓒ 0.86 kV
Ⓓ 27 kV

5. How much work is done on a proton to move it from the negative plate to a positive plate 4.3 cm away if the field is 125 N/C?

Ⓐ 5.5×10^{-23} J
Ⓑ 8.6×10^{-19} J
Ⓒ 1.1×10^{-16} J
Ⓓ 5.4 J

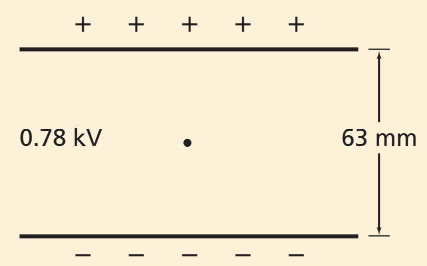


6. How was the magnitude of the field in Millikan's oil-drop experiment determined?

Ⓐ using a measurable electromagnet
Ⓑ from the electric potential between the plates
Ⓒ from the magnitude of the charge
Ⓓ by an electrometer

7. In an oil drop experiment, a drop with a weight of 1.9×10^{-14} N was suspended motionless when the potential difference between the plates that were 63 mm apart was 0.78 kV. What was the charge on the drop?

Ⓐ -1.5×10^{-18} C
Ⓑ -3.9×10^{-16} C
Ⓒ -1.2×10^{-15} C
Ⓓ -9.3×10^{-13} C



8. A capacitor has a capacitance of 0.093 μF. If the charge on the capacitor is 58 μC, what is the electrical potential difference?

Ⓐ 5.4×10^{-12} V
Ⓑ 1.6×10^{-6} V
Ⓒ 6.2×10^{2} V
Ⓓ 5.4×10^{3} V

Extended Answer

9. Assume 18 extra electrons are on an oil drop. Calculate the charge of the oil drop, and calculate the potential difference needed to suspend it if it has a weight of 6.12×10^{-14} N and the plates are 14.1 mm apart.

✓ Test-Taking TIP

Use the Buddy System

Study in a group. A small study group works well because it allows you to draw from a broader base of skills and content knowledge. Keep your group small, question each other, and stay on target.

Chapter 22

Current Electricity

What You'll Learn

- You will explain energy transfer in circuits.
- You will solve problems involving current, potential difference, and resistance.
- You will diagram simple electric circuits.

Why It's Important

The electric tools and appliances that you use are based upon the ability of electric circuits to transfer energy resulting from potential difference, and thus, perform work.

Power Transmission Lines Transmission lines crisscross our country to transfer energy to where it is needed. This transfer is accomplished at high potential differences, often as high as 500,000 V.

Think About This ▶

Transmission line voltages are too high to use safely in homes and businesses. Why are such high voltages used in transmission lines?

Physics Online

physicspp.com

Lester Lefkowitz/CORBIS