CHAPTER 21

Electric Fields

BIGIDEA **Electric charges are surrounded by electric fields that exert a force on other charged objects.**

SECTIONS

1 Measuring Electric Fields

2 Applications of Electric Fields

LaunchLAB

iLab Station

CHARGED OBJECTS AND DISTANCE

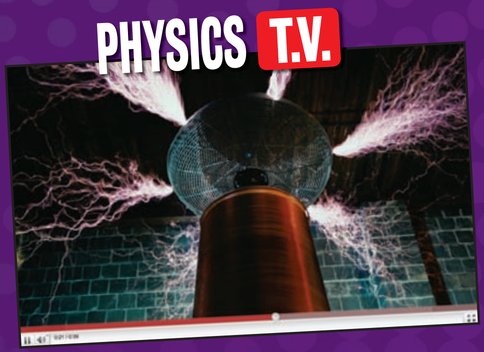
How do charged objects interact at a distance?

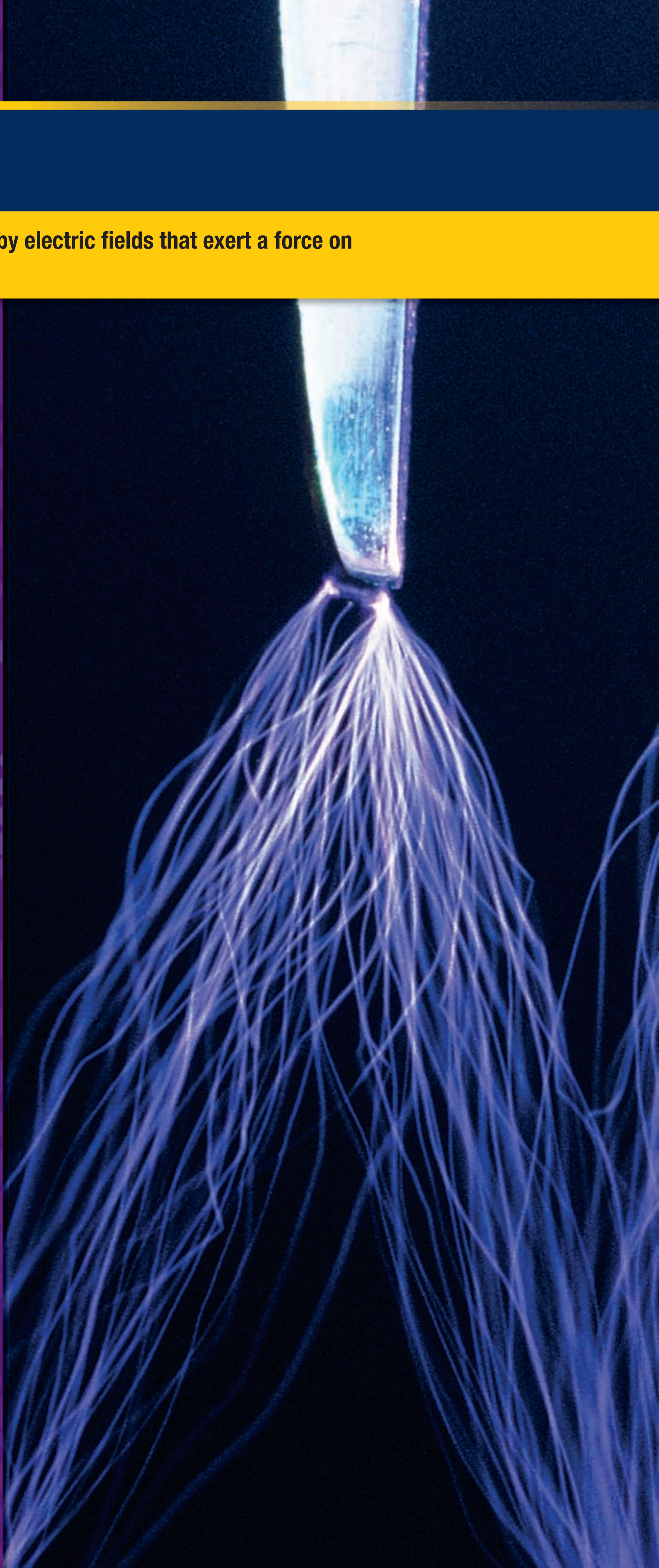
WATCH THIS!

Video

ELECTRIC SPARKS

Have you ever had an electric spark jump from a doorknob to your hand? What was surrounding the doorknob to produce that spark? Take a trip to your local science museum to find out.





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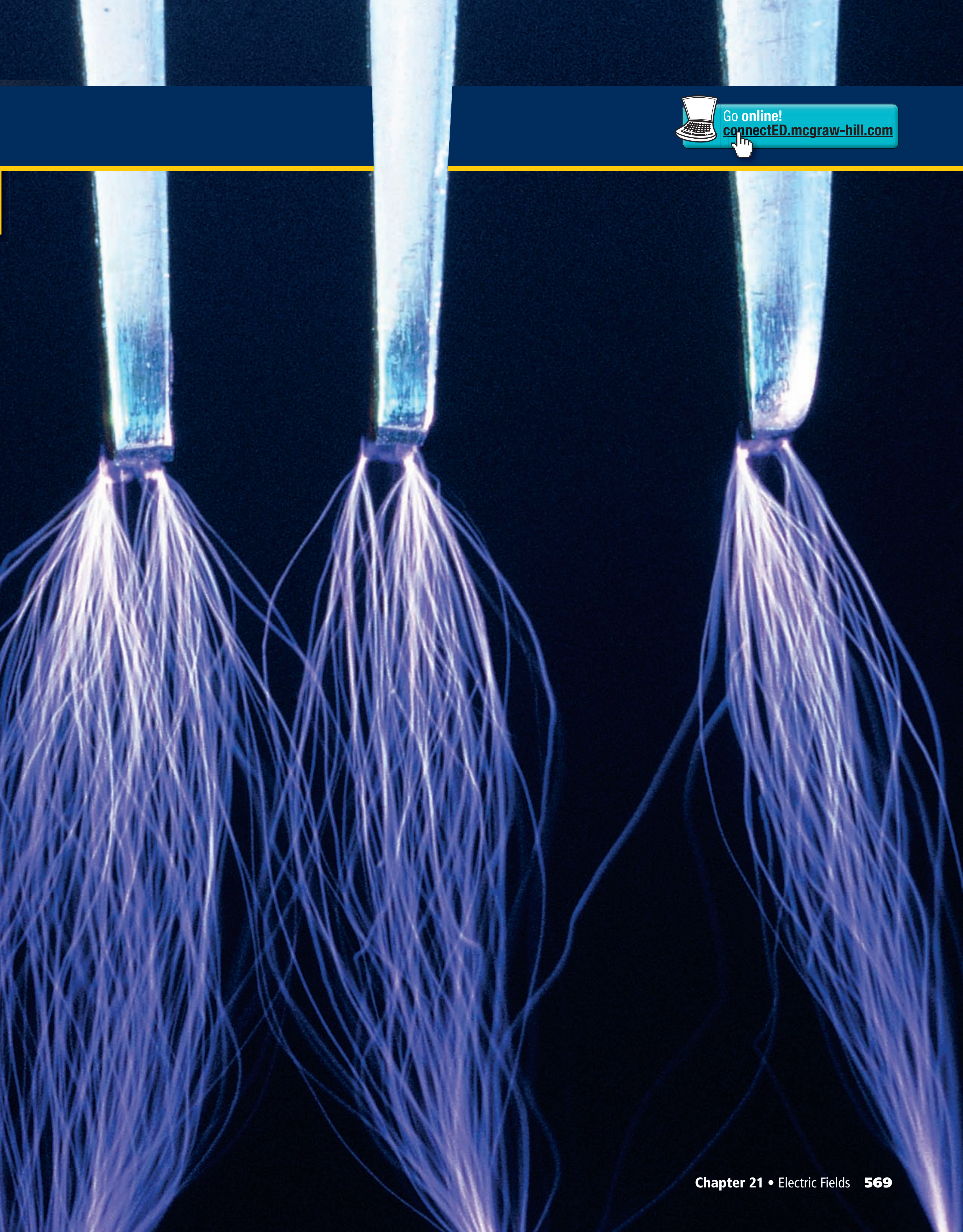

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SECTION 1

Measuring Electric Fields

PHYSICS 4 YOU

What image do you imagine when you hear the term electric field? If you have seen a Van de Graaff generator in operation, you might imagine someone's hair sticking up. What do a Van de Graaff generator, hair, and an electric field have in common?

MAINIDEA

An electric field is a property of the space around a charged object that exerts forces on other charged objects.

Essential Questions

- What is an electric field?
- How are charge, electric field, and forces on charged objects related?
- How can you represent electric fields in diagrams and other models?

Review Vocabulary

Coulomb's law states that the force between two point charges varies directly with the product of their charges and inversely with the square of the distance between them

New Vocabulary

electric field

electric field line

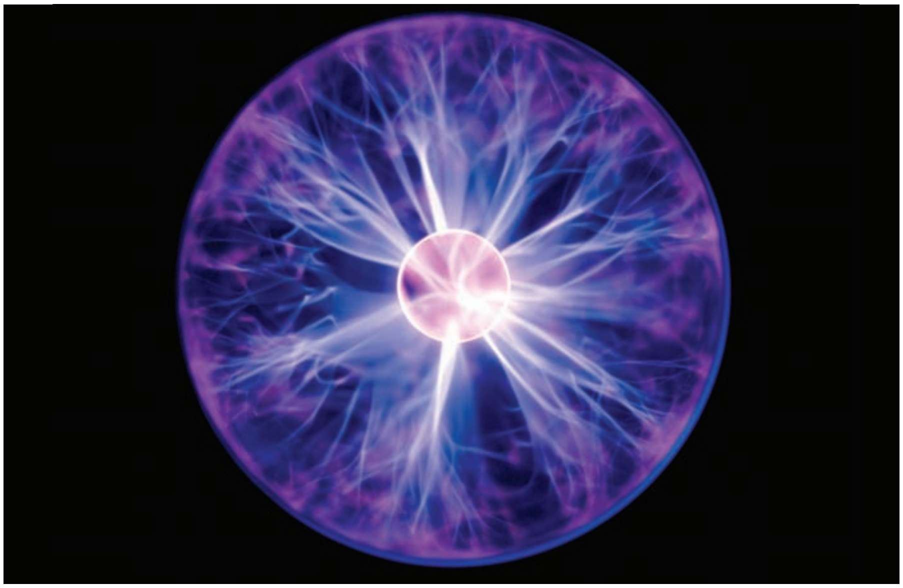
Defining the Electric Field

The idea of a force field is probably not new to you if you have watched science-fiction television shows or movies or have read science-fiction books. In these fictional applications, characters use force fields to create invisible barriers to stop invading armies, and to hold prisoners in a cell. As it turns out, force fields really exist but they are not quite like the ones in science fiction.

Recall that according to Coulomb's law, the force between two point charges varies inversely as the distance between those charges changes. How can one object exert a force on another object across empty space? Michael Faraday suggested the idea of a force field. The electric field is one example of a force field. An **electric field** is a property of the space around a charged object that exerts forces on other charged objects. You cannot see an electric field, but there are ways to detect that an electric field is present.

For example, the streams in the plasma sphere shown in **Figure 1** show the effects of the electric field around that plasma sphere's central electrode. A plasma sphere's central electrode is a charged object whose net charge alternates rapidly (120 times per second) between positive net charge and negative net charge. The glass globe contains ions, which are charged particles. The electric field from the central electrode accelerates the ions in the globe. The resulting streams illustrate the paths that the ions travel along and represent the electric field inside the plasma sphere.

Figure 1 The plasma sphere shows how an electric field can interact with matter.



(t)JENS SCHLUETER/AFP/Getty Images, (b)Lawrence Lawry/Getty Images

The strength of an electric field You might wonder how you can detect an electric field if you cannot see it. You can envision the force from an electric field by modeling its effects on a small, charged object—a test charge (q')—at some location. If there is an electrostatic force on the object, then there is an electric field at that point. **Figure 2** illustrates a charged object with a net charge of q. Suppose you place the positive test charge at point (A) and measure a force ($\mathbf{F}_A$). According to Coulomb's law, the force is directly proportional to the strength of the test charge (q'). That is, if the charge on the test charge is doubled, so is the force $\left(\frac{2\mathbf{F}}{2q'} = \frac{\mathbf{F}}{q'}\right)$. Therefore, the ratio of the force to the strength of the test charge is a constant. When you divide force ($\mathbf{F}$) by the strength of the test charge (q'), you obtain a vector quantity $\left(\frac{\mathbf{F}}{q'}\right)$. The electric field at point A, the location of q', is represented by the following equation.

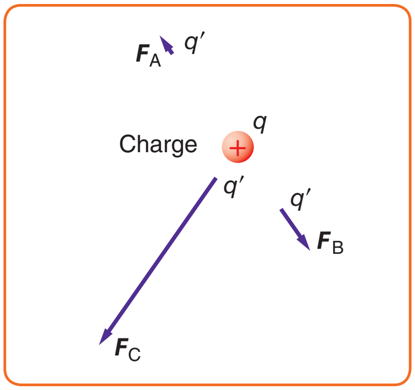


Figure 2 An electric field surrounds particle q. The forces exerted on a positively charged test particle (q') at locations A, B, and C are represented by force vectors. The vectors represent the magnitude and direction of the force from the electric field on the test particle at that point.

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

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

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

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

READING CHECK **Explain** why some of the variables are bold type in the text and in the equation.

Field vectors You can make a model of an electric field by using arrows to represent the field vectors at various locations, as shown in **Figure 2.** The length of the arrow represents the field strength. The direction of the arrow represents the field direction. To find the field from two charges, add the fields from the individual charges through vector addition. Some typical electric field strengths are shown in **Table 1.**

You also can use a test charge to map the electric field resulting from any collection of test charges. A test charge should be small enough so that its effect on the charge you are testing (q) is negligible. Remember that, according to Newton's third law, the test charge exerts forces back on the charges that produce the electric field. It is important that these forces do not redistribute the charges that you are trying to measure, thereby affecting the electric field that you are trying to map.

Table 1 Typical Electric Field Strengths (Approximate)

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

Coulomb's law and electric fields If, and only if, the charge q is a point charge or a uniformly charged sphere, you can calculate its electric field from Coulomb's law. Use Coulomb's law in the electric field equation above to find the magnitude of the force exerted on the test charge ($F_{\text{on } q'}$) as shown below.

$$E = \frac{F_{\text{on } q'}}{q'} = F_{\text{on } q'} \times \frac{1}{q'} = \frac{Kqq'}{r^2} \times \frac{1}{q'} = \frac{Kq}{r^2}$$

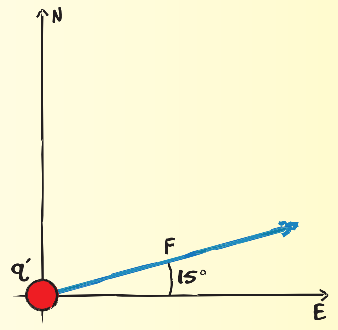
EXAMPLE PROBLEM 1

Find help with **operations with significant digits.** Math Handbook

ELECTRIC FIELD STRENGTH Suppose that you are measuring an electric field 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

$q' = 3.0\times10^{-6}$ C

$\boldsymbol{F} = 0.12$ N at 15° N of E

UNKNOWN

$\boldsymbol{E} = ?$

2 SOLVE FOR THE UNKNOWN

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

$$= \frac{0.12\text{ N}}{3.0\times10^{-6}\text{ C}}$$ ◀ 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.

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

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 similar to those in **Table 1.**

PRACTICE PROBLEMS

Do additional problems. Online Practice

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. Suppose that you place a 2.1×10^{-3}-N pith ball in a 6.5×10^{4} N/C downward electric field. What net charge (magnitude and sign) must you place on the pith ball so that the electrostatic force acting on that pith ball will suspend it against the gravitational force?

4. Complete **Table 2** using your understanding of electric fields.

Table 2 Sample Data

Test Charge Strength (C)	Force Exerted on Test Charge (N)	Electric Field Intensity (N/C)
1.0×10^{-6}	0.30	
2.0×10^{-6}		3.3×10^{5}
	0.45	1.5×10^{5}

5. 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?

6. A negative test charge is placed in an electric field as shown in **Figure 3.** It experiences the force shown. What is the magnitude of the electric field at the location of the charge?

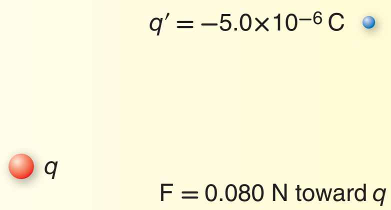


Figure 3

7. CHALLENGE 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

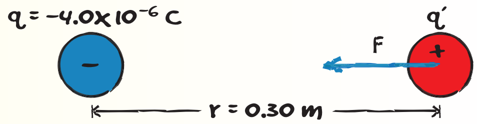
Find help with **operations with scientific notation.** Math Handbook

ELECTRIC FIELD STRENGTH AND COULOMB'S LAW What is the magnitude of the electric field at a point that is 0.30 m to the right of a small sphere with a net charge of -4.0×10^{-6} C?

1 ANALYZE AND SKETCH THE PROBLEM

- Draw and label the sphere with its net charge (q) as well as the test charge (q'), 0.30 m away.
- Show and label the distance between the charges.
- Diagram and label the force vector acting on q'.

Recall that a test charge is usually positive.



KNOWN	**UNKNOWN**
$q = -4.0\times10^{-6}$ C	$\mathbf{E} = ?$
$r = 0.30$ m	

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 equation.

$$E = \frac{Kq}{r^2}$$

$$= \frac{(9.0\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(-4.0\times10^{-6}\ \text{C})}{(0.30\ \text{m})^2}$$

◀ Substitue $K = 9.0\times10^9$ N•m²/C², $q = -4.0\times10^{-6}$ C, $r = 0.30$ m.

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

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

3 EVALUATE THE ANSWER

- **Are the units correct?** $\frac{(\text{N}\cdot\text{m}^2/\text{C}^2)(\text{C})}{\text{m}^2} = \text{N/C}$. 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 negative charge attracts the positive test charge.
- **Is the magnitude realistic?** This field strength is similar to those in **Table 1.**

PRACTICE PROBLEMS

Do additional problems. Online Practice

8. What is the magnitude of the electric field at a position that is 1.2 m from a 4.2×10^{-6}-C point charge?

9. What is the magnitude of the electric field at a distance twice as far from the point charge in the previous problem?

10. What is the electric field at a position that is 1.6 m east of a point charge of $+7.2\times10^{-6}$ C?

11. The electric field that is 0.25 m from a small sphere is 450 N/C toward the sphere. What is the net charge on the sphere?

12. How far from a point charge of $+2.4\times10^{-6}$ C must you place a test charge in order to measure a field magnitude of 360 N/C?

13. Explain why the strength of the electric field exerted on charge q' by the charged body q is independent of the charge on q'. *Hint: Use mathematics to prove your point.*

14. What is the magnitude of the electric field exerted on the test charge shown in **Figure 4?**

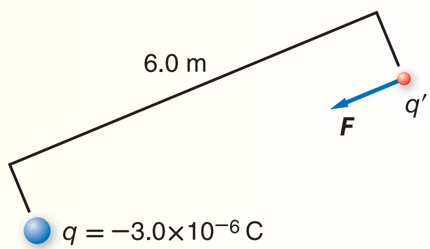


Figure 4

15. CHALLENGE You place a small sphere with a net charge of 5.0×10^{-6} C at one corner of a square that measures 5.0 m on each side. What is the magnitude of the electric field at the opposite corner of the square?

Modeling the Electric Field

An electric field is present even if there is no test charge to measure that field because a test charge is just an imaginary model. Any charge placed in an electric field experiences a force on it resulting from the electric field at that location. So far, you have measured an electric field at a single location. Now, imagine moving the test charge to another location. Measure the force on it again and calculate the electric field again. Repeat this process again and again until you assign to every location in a region a measurement of the electric field. The magnitude of the force depends on the magnitude of the field (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.

Electric field lines You have already seen how the streams in a plasma sphere represent an electric field. You also can represent electric fields with electric field lines, such as those shown in **Figure 5.** An **electric field line** indicates the direction of the force due to the electric field on a positive test charge. The spacing between the lines indicates the electric field's strength. The field is stronger where the lines are spaced more closely. The field is weaker where the lines are spaced farther apart.

Because electric field lines indicate the force on a positive test charge, they are directed toward negative charges and away from positive charges. The direction of the electric field ($\boldsymbol{E}$) at any point is the tangent drawn to a field line at that point, as shown in **Figure 6** on the next page.

Figure 6 shows two ways to represent various electric fields—with electric field lines and with grass seed suspended in oil. An electric field affects electric charges whether or not you represent that field with field lines and whether or not you try to visualize that field with grass seed suspended in oil.

Grass seed can be useful for visualizing electric fields in three dimensions. Both grass seed and electric field lines are only ways of *representing* electric fields, however. Neither is the same as the electric field itself.

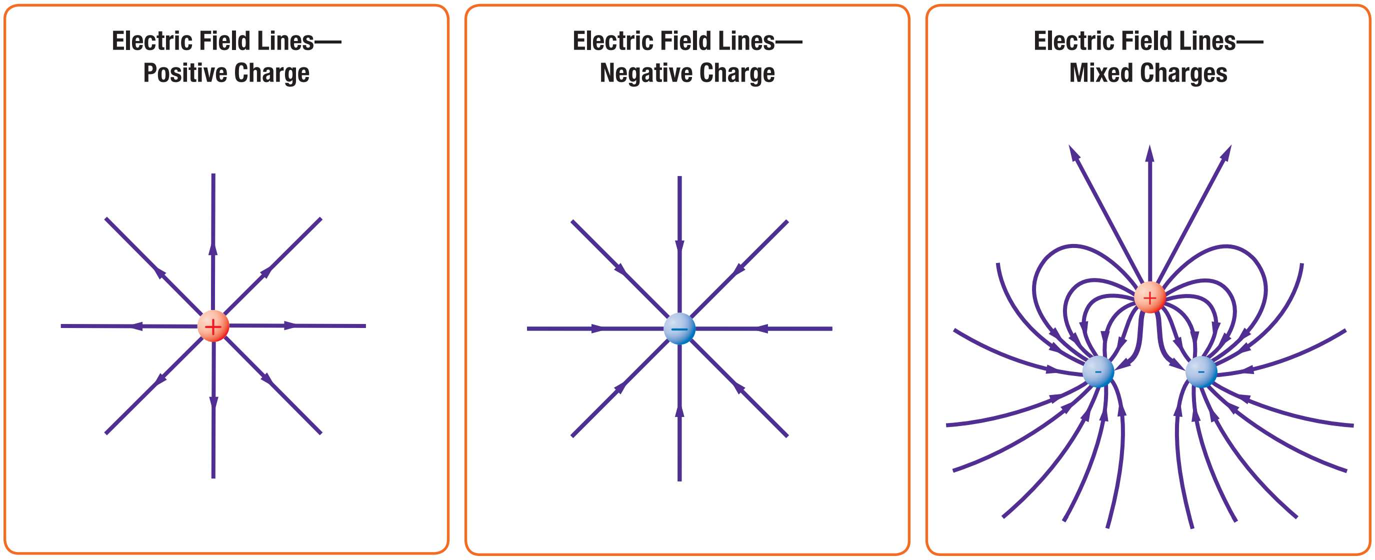


Figure 5 Two-dimensional models of electric fields are shown, but remember that electric fields exist in three dimensions.

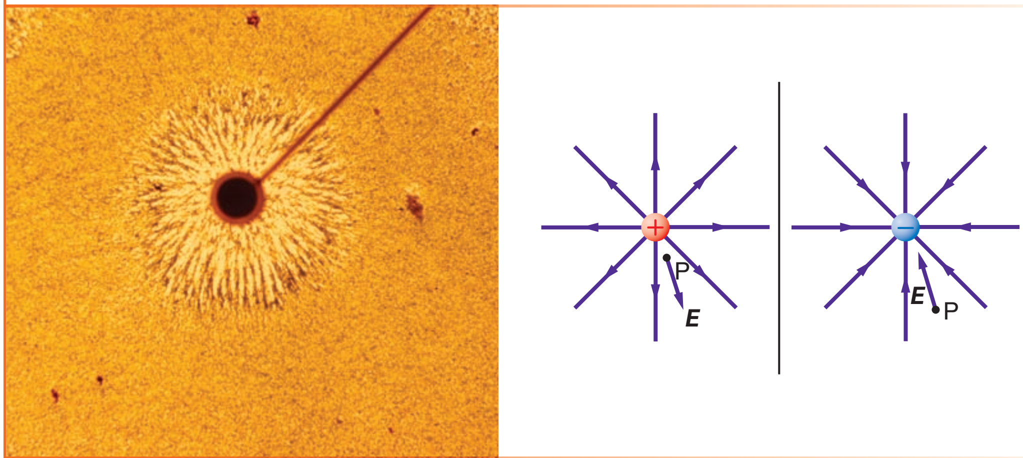
Explain how you should determine the direction of the arrows for electric field lines.

Figure 6 Models of electric fields around electric charges are shown. Electrostatic 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 lines and vectors drawn in the diagrams represent other ways to model electric fields.

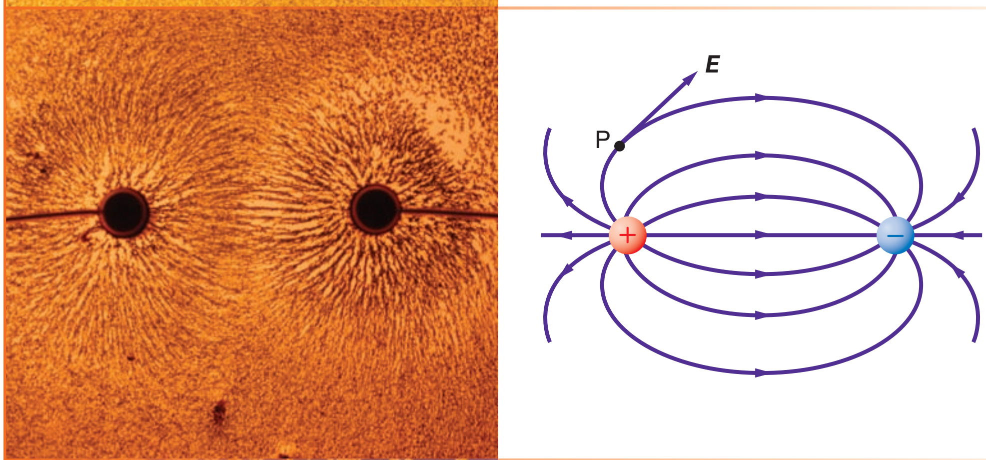
Identify the dark circles in each image.

View an animation and an interactive figure of **electric fields and force on a charge.**

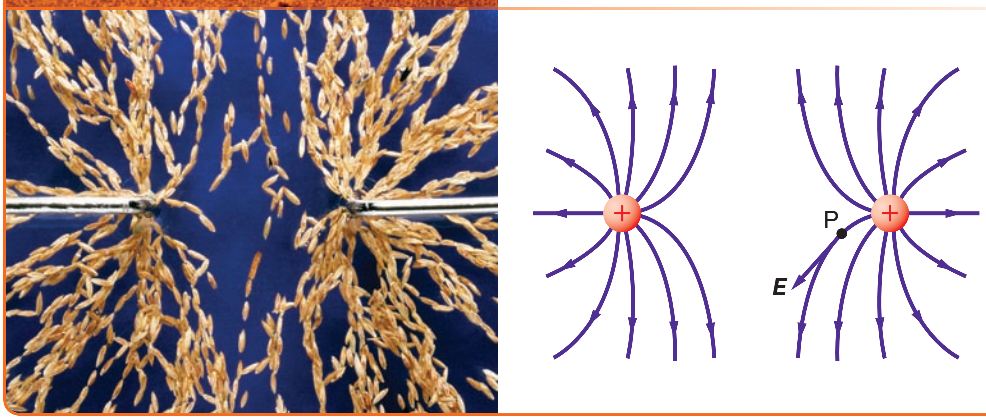
Concepts In Motion



Single Charge For a single charge, the electric field lines radiate from that charge. The field lines radiate out from a positive charge and they radiate inward toward a negative charge. The direction of the electric field (***E***) at any point is the tangent to the field line.



Two Equal and Unlike Charges The electric field lines of two equal and unlike charges form continuous lines from the positive charge to the negative charge. The vector at point P shows the direction of the electric field (***E***) at point P. Where the lines are closest, a charged particle would experience the most force.



Two Like Charges The electric field lines around two like charges never connect with each other. The vector at point P shows the direction of the electric field (***E***) at point P. A charge would experience no electrostatic force in the center where there are no electric field lines.

Figure 7 Robert Van de Graaff devised his generator in the 1930s to aid in the study of particle acceleration and the study of the structure of the atom. When a person touches the generator, the charges on the person's hairs repel each other, causing the hairs to align with the electric field of the metal dome.

View an animation on electric potential difference.

Concepts In Motion

Van de Graaff Generators

A Van de Graaff generator, shown in **Figure 7,** can build up a large amount of net charge on its metal dome. In a Van de Graaff generator, a belt is driven by two rollers or pulleys. One roller is attached to position A. The other roller is located in the metal dome at position B. When someone turns on the machine, the bottom roller rotates and moves the belt. The roller builds up a strong negative net charge, and the belt builds a weaker positive net charge.

The strong negative electric field on the roller repels electrons in the tips of a brush assembly near position A. The tips of the brushes become positively charged because the electrons move away from them. At the same time, the strong negative electric field of the roller strips electrons from nearby molecules in the air. The stripped electrons are repelled by the roller and are attracted to the positively charged tips of the brush. The positive ions from the air start to move to the negatively charged roller. The belt is between the positive ions and the negatively charged roller, however. The positive ions collect on the belt and are transported to the metal dome.

When a person touches the metal dome, the positively charged dome attracts the electrons in the person's body. The person's hair becomes positively charged, and the individual hairs repel each other. The hairs align with the electric field around the person's head.

SECTION 1 REVIEW

Section Self-Check Check your understanding.

16. MAINIDEA Suppose you are asked to measure the electric field at a point 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?

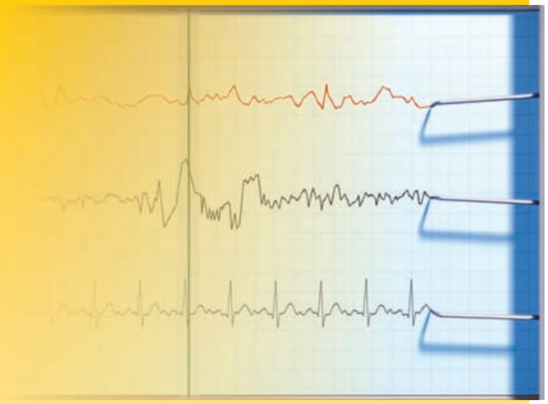
17. Field Strength and Direction A positive test charge of magnitude 2.40×10^{-8} C experiences a force of 1.50×10^{-3} N toward the east. What is the electric field at the position of the test charge?

18. Field Lines How can you tell which charges are positive and which are negative by examining the electric field lines?

19. Field Versus Force How does the electric field at a test charge differ from the force on that charge?

20. Critical Thinking Suppose the top charge in the field on the far right in **Figure 5** is a test charge measuring the field resulting from the two negative charges. Is it small enough to produce an accurate measurement? Explain.

SECTION 2 Applications of Electric Fields



Matthias Kulka/Bridge/CORBIS

PHYSICS 4 YOU Doctors use several medical procedures to monitor electrical activity in the human body. For example, electrocardiography (ECG or EKG) monitors the electrical activity in the heart, and electroencephalography (EEG) monitors the electrical activity of the brain.

MAIN IDEA

Electric potential (sometimes called voltage) is electric potential energy per unit charge.

Essential Questions

- What is an electric potential difference?
- How is potential difference related to the work required to move a charge?
- What are properties of capacitors?

Review Vocabulary

work the transfer of energy that occurs when a force is applied over a distance; is equal to the product of the object's displacement and the force applied to the object in the direction of displacement

New Vocabulary

electric potential difference
volt
equipotential
capacitor
capacitance

Energy and Electric Potential

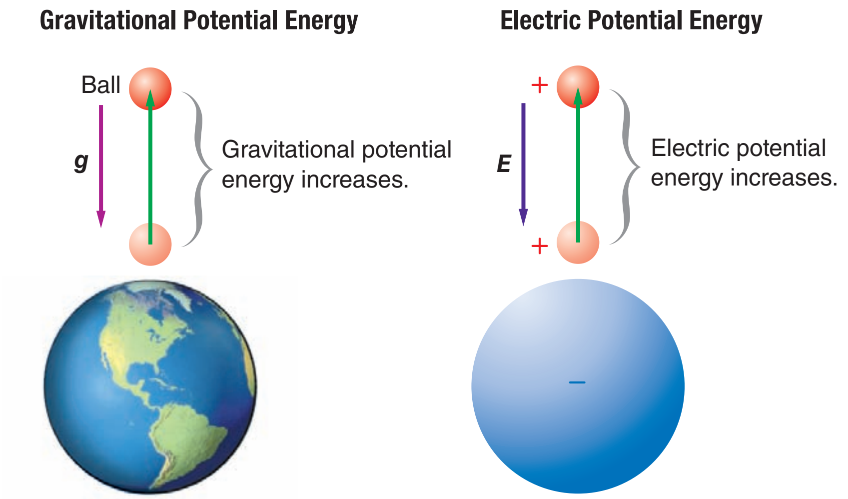
As you have read, the concept of energy is extremely useful in mechanics. The law of conservation of energy allows you to predict the motion of objects without knowing the forces in detail. Consider the change in gravitational potential energy of a ball when you lift it, as shown in **Figure 8.** Both the gravitational force (F_g) and the gravitational field $\left(g = \frac{F_g}{m}\right)$ point toward Earth. If you lift the ball against the gravitational force, you do work on the ball. The gravitational potential energy in the ball-Earth system increases.

The same is true in electrical interactions. The work performed moving a charged particle in an electric field can result in the particle gaining electric potential energy or kinetic energy, or both.

The situation is similar with two unlike charges. The charges attract each other, so you must do work to pull one charge away from the other. When you do this work, you increase the electric potential energy of the two-charge system. The larger the charge or the distance moved, the greater the increase in the electric potential energy (ΔPE). In this chapter, only charges at rest and changes in electric potential energy are considered and discussed.

Figure 8 When you lift the ball, you increase the gravitational potential energy of the ball-Earth system. When you separate two unlike charges, you increase the electric potential energy of the two-charge system.

Infer how you would increase the potential energy of a system that contains two like charges.



View an animation on **electric potential difference.**

Concepts In Motion

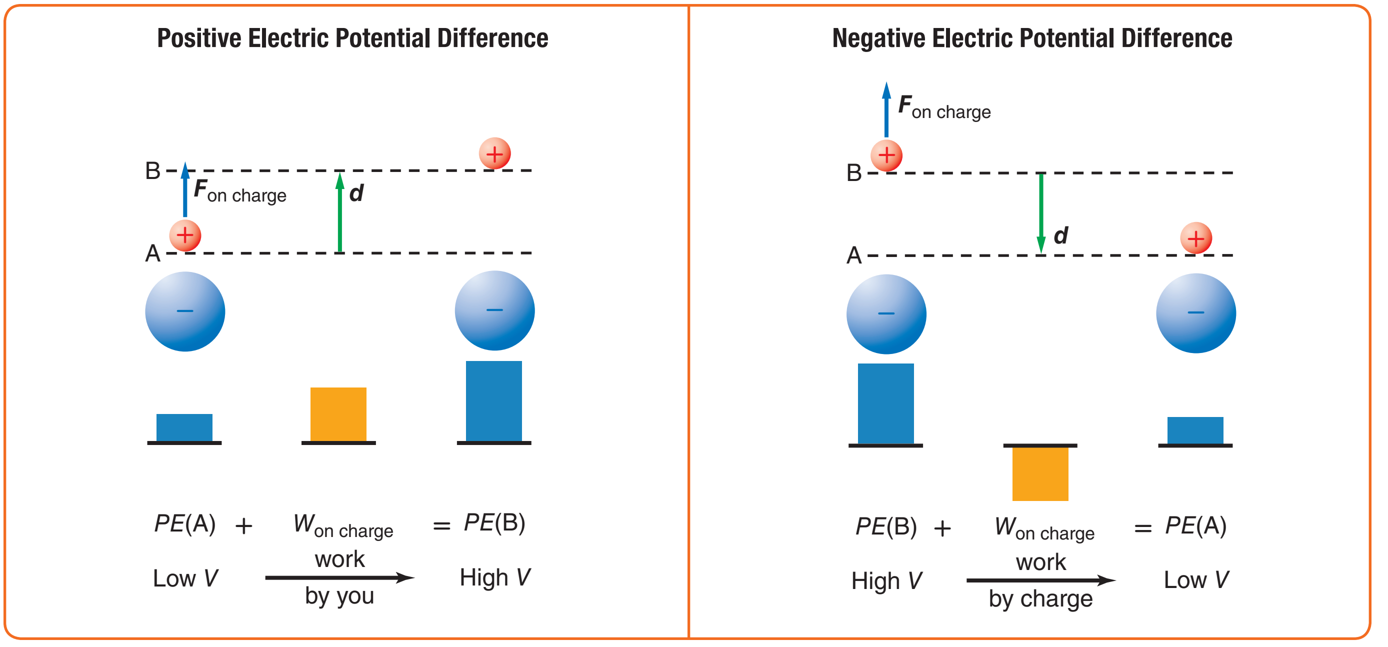


Figure 9 If you move unlike charges apart, then the electric potential difference is positive. If you move unlike charges closer together, then the electric potential difference is negative.

Explain how work and electric potential are related in regard to the test charge.

Electric potential difference You know from your study of mechanics that work done on an object is found using the relationship $W = Fd$. This same relationship is used to find work done to move a charge, $W_{\text{on } q'} = \boldsymbol{F}d$.

There are differences, however. The work done on a charge is expressed as work done per unit charge and it is called the electric potential difference. The **electric potential difference** (ΔV), which often is called potential difference, is the work ($W_{\text{on } q}$) needed to move a positive test charge from one point to another, divided by the magnitude of the test charge. You also can think of electric potential difference as the change in electric potential energy (ΔPE) per unit charge.

ELECTRIC POTENTIAL DIFFERENCE

Electric potential difference is the ratio of the work needed to move a charge to the magnitude of that charge.

$$\Delta V \equiv \frac{W_{\text{on } q'}}{q'}$$

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

READING CHECK **Define** electric potential difference in your own words, state the equation used to find it, and explain what the variables represent.

Positive electric potential difference The negative charge, in the left panel in **Figure 9,** produces an electric field toward itself. Suppose you place a small positive test charge in the field at position A. That test charge experiences a force in the direction of the field. If you now move the test charge away from the negative charge to position B, you will have to exert a force ($\boldsymbol{F}$) on that test charge. Because the force you exert is in the same direction as the displacement, the work you do on the test charge is positive, and the change in potential energy is positive, as represented by the bar diagram in the figure. Therefore, there is a positive electric potential difference from point A to point B. The potential difference between two points does not depend on the magnitude of the test charge. It depends only on the field and the displacement.

Negative electric potential difference Suppose you now move the test charge back to position A from position B, as in the right panel in **Figure 9.** The work you do on the test charge and the change in electric potential energy are now negative, also shown in the bar diagram in the figure. 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 depends only on the starting and final positions on that path.

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

Electric potential for like charges You have seen that electric potential difference increases as you pull a positive test charge away from a negative charge. What happens when you move a positive test charge away from another positive charge? There is a repulsive force between these two charges. Potential energy decreases as you move the two charges farther apart. Therefore, the electric potential around the positive charge decreases as you move away from that positive charge, as shown in **Figure 10.**

Reference point in a system Recall that the gravitational 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 you choose, the value of the electric potential difference from point A to point B always will be the same.

Voltage versus volts Only differences in gravitational 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).

Electric Potential

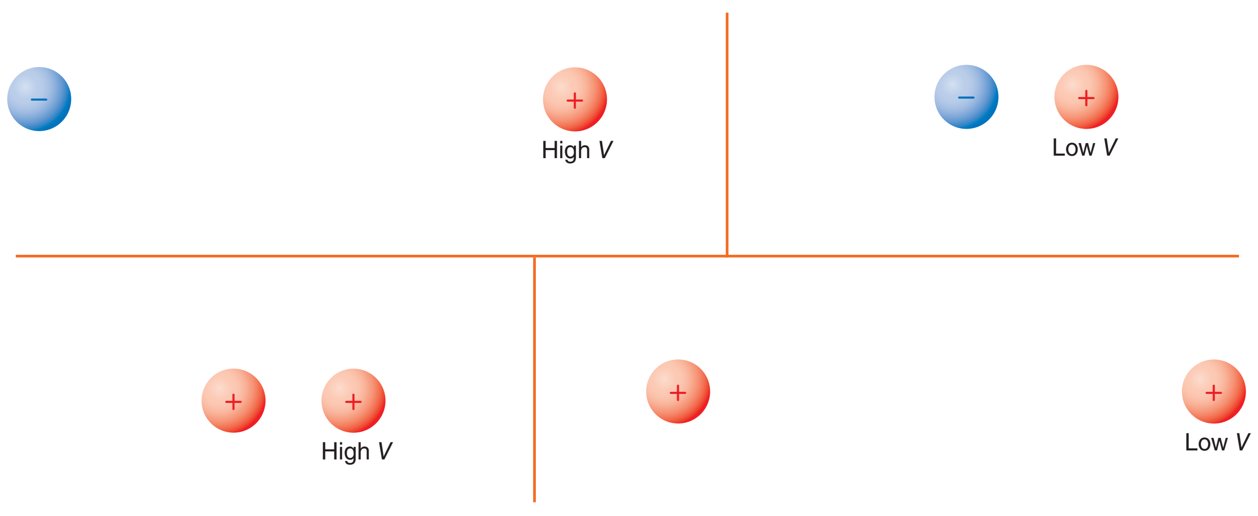


Figure 10 When you push two unlike charges farther apart, the electric potential increases. When you move two like charges farther apart, the electric potential decreases.

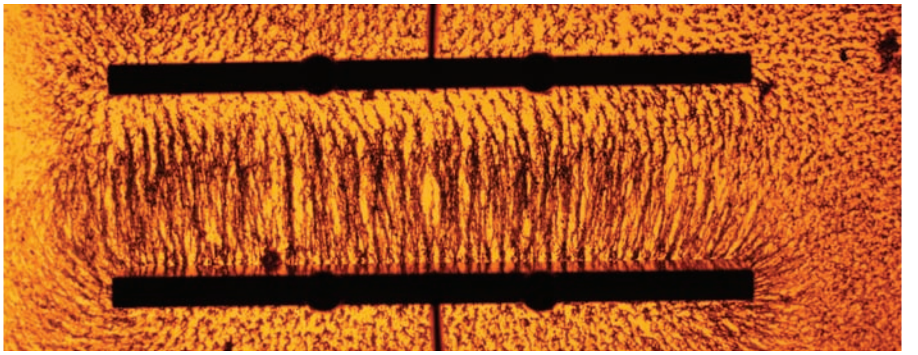


Figure 11 A model of an electric field between two oppositely charged parallel plates is shown. Grass seed is used to model the electric field lines.

PHOTOTAKE Inc./Alamy

Electric Potential in a Uniform Field

You can produce a uniform electric field by placing two large, flat conducting plates parallel to each other. One plate is charged positively, and the other plate is charged negatively. The magnitude and the direction of the electric field are the same at all points between the plates, except at the edges of the plates, and the electric field points from the positive plate to the negative plate. The pattern formed by the grass seeds pictured in **Figure 11** represents the electric field between parallel plates.

Imagine that you move a positive test charge (q') a distance (d) in the direction opposite the electric field direction. Because the field is uniform, the force from that field on the charge is constant. As a result, you can use the relationship $W_{\text{on } q'} = Fd$ to find the work done on the charge. Then, the electric potential difference, the work done per unit charge, is $\Delta V = \frac{Fd}{q'} = \left(\frac{F}{q'}\right)d$. Remember that electric field intensity is force per unit charge $\left(E = \frac{F}{q'}\right)$. Therefore, you can represent the electric potential difference (ΔV) between two points a distance (d) apart in a uniform field ($\boldsymbol{E}$) with the following equation.

ELECTRIC POTENTIAL DIFFERENCE IN A UNIFORM FIELD

The potential difference between two locations in a uniform electric field equals the product of electric field intensity and the distance between the locations parallel to the direction of the field.

$$\Delta V = Ed$$

The electric potential is higher near the positively charged plate and lower near the negatively charged plate.

PRACTICE PROBLEMS

Do additional problems. Online Practice

21. 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?

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

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

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

25. CHALLENGE You apply a potential difference of 275 V between two parallel plates that are 0.35 cm apart. How large is the electric field between the plates?

EXAMPLE PROBLEM 3

Find help with **operations with scientific notation.** Math Handbook

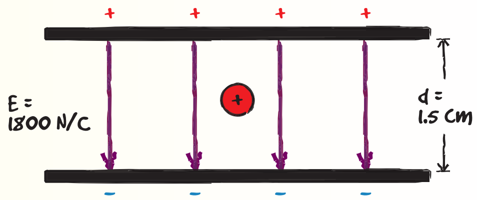
WORK REQUIRED TO MOVE A PROTON BETWEEN CHARGED PARALLEL PLATES Two charged parallel plates are 1.5 cm apart. The magnitude of the electric field between the plates is 1800 N/C.

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

b. How much 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	UNKNOWN
$E = 1800$ N/C	$\Delta V = ?$
$d = 1.5$ cm	$W = ?$
$q = 1.602\times10^{-19}$ C	

2 SOLVE FOR THE UNKNOWN

a. $\Delta V = Ed$

$= (1800 \text{ N/C})(0.015 \text{ m})$ ◀ Substitute $E = 1800$ N/C, $d = 0.015$ m.

$= 27$ V

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

$W = q\Delta V$

$= (1.602\times10^{-19} \text{ C})(27 \text{ V})$ ◀ Substitute $q = 1.602\times10^{-19}$ C, $\Delta V = 27$ V.

$= 4.3\times10^{-18}$ 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?** You must do positive work to move a positive charge toward a positive plate.
- **Is the magnitude realistic?** When you move such a small charge through a potential difference of less than 100 volts, the work done is small.

EXAMPLE PROBLEM

PRACTICE PROBLEMS

Do additional problems. Online Practice

26. What work is done on a 3.0-C charge when you move that charge through a 1.5-V electric potential difference?

27. What is the magnitude of the electric field between the two plates shown in **Figure 12?**

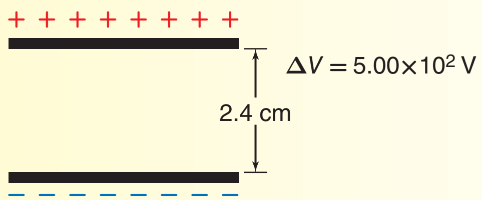


Figure 12

28. An electron in an old 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?

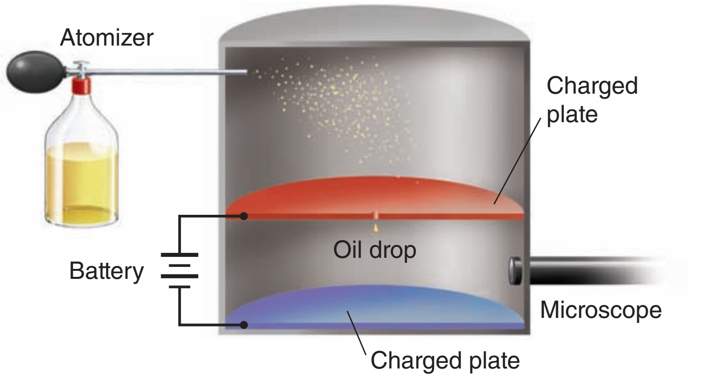
29. The electric field in a particle accelerator has a magnitude of 4.5×10^5 N/C. How much work is done to move a proton 25 cm through that field?

30. **CHALLENGE** A 12-V car battery has 1.44×10^6 C of usable charge on one plate when it is fully energized. How much work can this battery do before it needs to be energized again?

Figure 13 The American physicist Robert A. Millikan used an apparatus similar to this one to determine the charge of a single electron in 1909.

View an **animation of Millikan's oil-drop experiment.**

Concepts In Motion



Millikan's Oil-Drop Experiment

You have read that the magnitude of the elementary charge is $e = 1.602\times10^{-19}$ C. The net charge on an object must be some integer multiple of this value. In other words, the net charge on an object can be 2e, −5e, 7e, or even −3157e. The net charge cannot be a fractional charge, such as 0.5e, −23.7e, 6.2e, or −31,524.6e. How do we know?

In 1909, Robert Millikan performed an experiment to test whether charge exists in discrete amounts. Millikan was able to measure the magnitude of the elementary charge with his experiment. A diagram of Millikan's apparatus for this experiment is shown in **Figure 13.** Notice that Millikan used two parallel plates to produce a uniform electric field in his apparatus. How did Millikan perform his experiment?

First, Millikan sprayed fine oil drops from an atomizer into the air. These drops were charged by friction as they were sprayed from the atomizer. Earth's gravitational force pulled the drops downward, and a few of those drops entered the hole in the top plate of Millikan's apparatus. Millikan then adjusted the electric field between the plates until he had suspended a negatively charged drop. At this point, the downward force from Earth's gravitational field and the upward force from the electric field were equal in magnitude.

MiniLAB

ELECTRIC FIELDS

Can you observe the effects of an electric field?

iLab Station

READING CHECK **Explain** why the following net charges are impossible: 0.66e, 1.554e, and 3.504e.

Calculating charge Millikan calculated the magnitude of the electric field (E) from the electric potential difference between the plates $\left(E = \frac{\Delta V}{d}\right)$. Millikan had to make a second measurement to find the weight (mg) of the tiny drop. To find the weight of a drop, Millikan first suspended it. Then, he turned off the electric field and measured the rate of the fall of the drop. Because of friction with air molecules, the oil drop quickly reached terminal velocity, which was related to the weight of the drop by a complex equation. Millikan was then able to calculate the charge (q) on the drop from the weight of the drop (mg) and the electric field ($\boldsymbol{E}$). He found that the net charge on an oil drop was always some integer multiple of a number close to 1.6×10^{-19} C. In later experiments, others have refined this result to 1.60217653×10^{-19} C.

EXAMPLE PROBLEM 4

Get help with **isolating variables.** Math Handbook

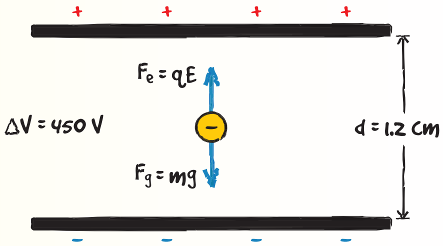
FINDING THE CHARGE ON AN OIL DROP In a Millikan oil-drop experiment, a particular oil drop weighs 2.4×10^{-14} N. The parallel plates are separated by a distance of 1.2 cm. When the potential difference between the plates is 450 V, the drop is suspended.

a. What is the net 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	UNKNOWN
$\Delta V = 450$ V	net charge on drop, q = ?
$F_g = 2.4\times10^{-14}$ N	number of electrons, n = ?
$d = 1.2$ cm	

2 SOLVE FOR THE UNKNOWN

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

$$F_e = F_g$$

$$qE = F_g$$ ◀ Substitute $F_e = qE$.

$$q\left(\frac{\Delta V}{d}\right) = F_g$$ ◀ Substitute $E = \frac{\Delta V}{d}$.

Solve for q.

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

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

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

Solve for the number of electrons on the drop.

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

$$= \frac{6.4\times10^{-19}\ \text{C}}{1.602\times10^{-19}\ \text{C}}$$ ◀ Substitute $q = 6.4\times10^{-19}$ C, $e = 1.602\times10^{-19}$ C.

$$= 4.0$$

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 oil drop. It makes sense that the drop would have a small charge and contain only a few electrons.

PRACTICE PROBLEMS

Do additional problems. Online Practice

31. 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.

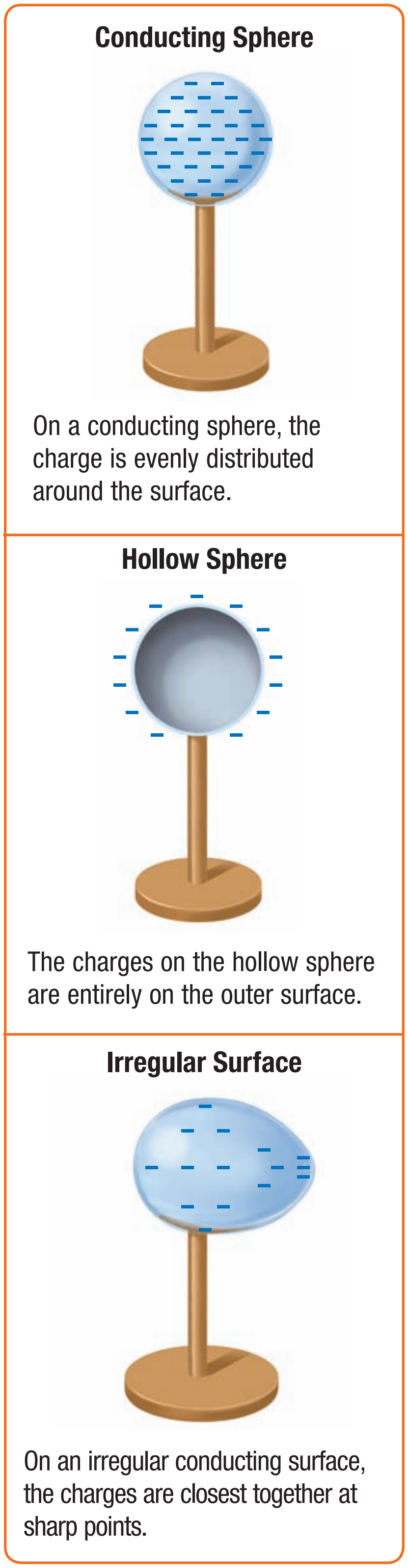
32. An oil drop weighs 1.9×10^{-15} N. You suspend it in an electric field of 6.0×10^{3} N/C. What is the net charge on the drop? How many excess electrons does it carry?

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

34. CHALLENGE You suspend a positively charged oil drop that weighs 1.2×10^{-14} N between two parallel plates that are 0.64 cm apart. The potential difference between the plates is 240 V. What is the net charge on the drop? How many electrons is the drop missing?

Figure 14 Charges on a conducting sphere spread far apart to minimize their potential energy.

Explain why the negative charges evenly distribute around the surface of a conductor using what you know about the interactions among negative charges.



Electric Fields Near Conductors

Recall that many of the electrons in a conductor are free to move. Consider the charges on the conducting sphere in **Figure 14.** Because these electrons have like charges, they repel each other. They spread far apart in a way that minimizes their potential energy. The result is these charges come to rest on the surface of the conductor. It does not matter if the conducting sphere is solid or hollow. The excess charges move to the outer surface of the conductor.

Closed metal containers What happens if a closed metal container, such as a box, is charged? You can use a voltmeter to measure the electric potential difference between any two points inside the container. You will find that this potential difference is zero no matter which two points you choose inside the container. What are the consequences of this measurement for the electric field inside of the closed, metal container? Recall that potential difference is equal to the product of the electrical field and distance, or $\Delta V = Ed$. Because the potential difference between any two points inside the container is zero, the equation implies that the field is zero everywhere inside a closed, charged metal container.

Cars are a good example of this scenario. A car is a closed metal box that protects passengers from electric fields generated by lightning. On the outside of the conductor, the electric field often is not zero. The field is always perpendicular to the surface of the conductor. This makes the surface an equipotential; the potential difference between any two locations on the surface is zero.

☑ READING CHECK **Summarize** why passengers are protected inside a car if it is struck by lightning.

Irregular surfaces The electric field at the surface does depend on the shape of the conductor, as well as on the electric potential difference between it and other objects. Free charges are closer together at the sharp points of a conductor, as indicated in **Figure 14.** 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, 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 produces the pink glow seen inside a gas-discharge sphere.

Lightning rods If an electric 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.

In order to protect buildings from lightning, builders install lightning rods. The electric field is strong near the pointed end of a lightning rod. As a result, charges in the clouds spark to the rod, rather than to another point on the building. From the rod, a conductor takes the charges to the ground. A lightning rod safely diverts lightning into the ground and away from the building.

☑ READING CHECK **Describe** how a lightning rod works.

Capacitors

When you lift a book, you increase the gravitational potential energy of the book-Earth system. You can interpret this 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 electrical energy. In honor of the city in which he worked, Musschenbroek called his device a Leyden jar. The modern, much smaller device for storing electrical energy is called a **capacitor.** Manufacturers make capacitors from two conducting plates separated by a thin insulator. They often roll these layers into a cylinder. Engineers design capacitors to have specific capacitances. Capacitors are key components in computers and other electronic devices. You can see an example of capacitors in **Figure 15.**

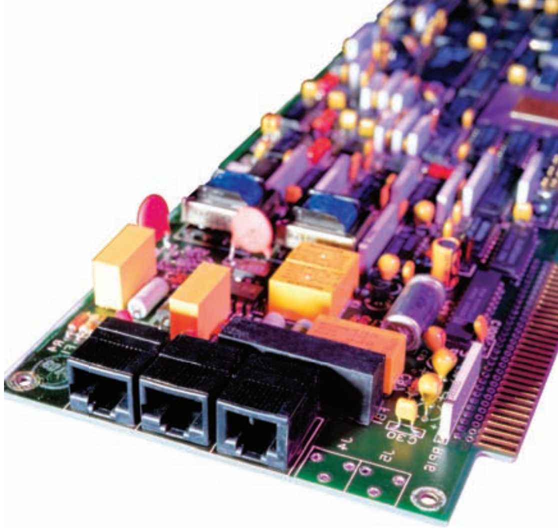


Figure 15 A computer circuit board uses many capacitors in its operation. The gray cylinders, the disk-shaped objects, and the tiny colored tear-drop shaped objects are all capacitors.

Capacitance Suppose you connect the positive terminal of a 1-V power source to one of the conducting plates of a capacitor and connect the negative terminal of that power source to the other plate of that capacitor. What happens? The power source would produce a potential difference (ΔV) of 1 V between the two plates. This would result in a net positive charge ($+q$) on one plate and a net negative charge of equal magnitude ($-q$) on the other plate.

Now suppose that you increase the voltage of the power source. What happens to the amount of net charge on each plate? **Figure 16** shows the results of an experiment in which the experimenter increases the potential difference across a capacitor's plates from 0 V to 12 V. Notice that the graph of q v. ΔV is a straight line. The slope of the line in a net charge versus potential difference graph is a constant and is called the **capacitance** (C) of the capacitor. You can measure the capacitance of a capacitor in farads (F), where 1 F = 1 C/V. The equation for capacitance is shown below.

MiniLAB

CONSTRUCT A CAPACITOR

Can you make an operational capacitor?

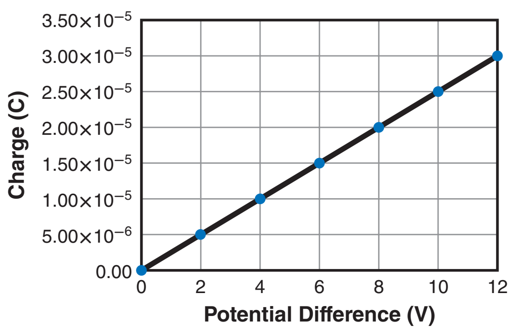
iLab Station

CAPACITANCE

Capacitance is the ratio of the magnitude of the net charge on one plate of the capacitor to the potential difference across the plates.

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

Figure 16 In an experiment, the potential difference results in a charge in each plate. A graph of the data shows the relationship is linear. The slope of this line is the capacitance of the capacitor.



Data Table

Potential Difference (V)	Charge on a Plate (C)
0.0	0.0
2.0	5.2×10^{-6}
4.0	9.7×10^{-6}
6.0	15.0×10^{-6}
8.0	20.3×10^{-6}
10.0	24.7×10^{-6}
12.0	30.1×10^{-6}

Arthur S. Aubry/Getty Images

PhysicsLAB

STORING CHARGE

How can large amounts of electrical energy be stored?

iLab Station

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 net 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, the 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 electric potential difference between the plates increases, the net amount of charge on each plate also increases.

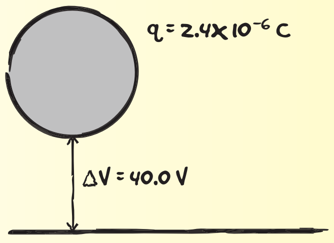
EXAMPLE PROBLEM 5

Find help with **operations with significant digits.** Math Handbook

FINDING CAPACITANCE A sphere was connected to the + pole of a 40-V battery while the − pole was connected to Earth. After a period of time, the sphere was charged to 2.4×10^{-6} C. What is the capacitance of the sphere-Earth system?

1 ANALYZE AND SKETCH THE PROBLEM

Draw a sphere above Earth, and label the net 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.

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

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

3 EVALUATE THE ANSWER

- **Are the units correct?** C/V = F. The units are farads.
- **Is the magnitude realistic?** The amount of net charge stored on the sphere equals the capacitance multiplied by 40.0 V.

PRACTICE PROBLEMS

Do additional problems. Online Practice

35. A 27-μF capacitor has an electric potential difference of 45 V across it. What is the amount the net charge on the positively charged plate of the capacitor?

36. Suppose you connect both a 3.3-μF and a 6.8-μF capacitor across a 24-V electric potential difference. Which capacitor has the greater net charge on its positively charged plate, and what is its magnitude?

37. You later find that the magnitude of net charge on each of the plates for each of the capacitors in the previous problem is 3.5×10^{-4} C. Which capacitor has the larger potential difference across it? What is that potential difference?

38. Suppose that you apply an electric potential difference of 6.0 V across a 2.2-μF capacitor. What does the magnitude of the net charge on one plate need to be to increase the electric potential difference to 15.0 V?

39. A sphere is charged by a 12 V battery and suspended above Earth as shown in **Figure 17.** What is the net charge on the sphere?

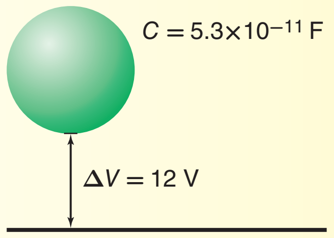
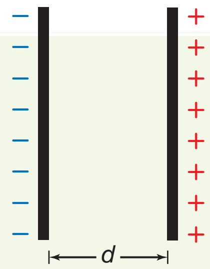


Figure 17

40. CHALLENGE You increase the potential difference across a capacitor from 12.0 V to 14.5 V. As a result, the magnitude of the net charge on each plate increases by 2.5×10^{-5} C. What is the capacitance of the capacitor?

PHYSICS CHALLENGE

The plates of a capacitor attract each other because they have equal and opposite net charge. 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 magnitude of net charge on one of the capacitor's plates is q.
2. The electrostatic force between the plates of a 22-μF capacitor is 2.0 N. What is the magnitude of the net charge on one plate if the separation between those plates is 1.5 mm?

Varieties of capacitors Capacitors have many shapes and sizes. Some are large enough to fill whole rooms and can store enough electrical energy to create artificial lightning or power giant lasers that release thousands of joules of energy in a few billionths of a second. Capacitors are also used in computers, televisions, and digital cameras. These capacitors store much less energy than those used to make artificial lightning, but they can still be dangerous. Charge can remain for hours after the device is turned off. This is why many electronic devices carry warnings not to open the case.

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

PhysicsLAB

ENERGIZING CAPACITORS

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

iLab Station

SECTION 2 REVIEW

Section Self-Check Check your understanding.

41. **MAIN**IDEA Suppose a friend asks you to explain how electric potential relates to potential energy. Write a brief explanation that you could use to explain this concept to a friend who does not understand the relationship between the two concepts.

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

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

44. **Millikan Experiment** When the net charge on an oil drop suspended in a Millikan apparatus is changed, the drop begins to fall. How should you adjust the potential difference between the conducting plates to bring the drop back into balance?

45. **Charge and Potential Difference** In the previous problem, if changing the potential difference between the conducting plates has no effect on the falling drop, what does this tell you about the new net charge on the drop?

46. **Capacitance** What is the magnitude of net charge on each conductor plate of a 0.47-μF capacitor when a potential difference of 12 V is applied across that capacitor?

47. **Charge Sharing** If you touch a large, positively charged, conducting sphere with a small, negatively charged, conducting sphere, what can be said about the
    a. potentials of the two spheres;
    b. charges on the two spheres?

48. **Critical Thinking** Explain how the charge in **Figure 18** 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?

Figure 18

courtesy of PASCO Scientific

HOW IT WORKS

Heart-Shaped Box

AEDs Did you know your heart is a pump that needs electric current to work? Cells in the heart muscle generate electric current that triggers the heart muscle to squeeze. If this electric current is disrupted, the heart stops beating—a serious condition called cardiac arrest. Automated external difibrillators (AED) can be used to help restart a heart in cardiac arrest.

1 Call 911 Before using an AED, have someone nearby call 911 for you.

2 Find the nearest AED Many public places have AEDs. Look for a sign that says "AED" or "emergency defibrillation."

3 Read the simple instructions Simple diagrams printed on the AED tell how and where to apply the electrodes on the unconscious person's body.

4 Apply the electrode pads Once placed, the self-stick electrode pads sense whether there is a heartbeat. The electrodes can detect the electric current generated by the heart through the person's skin.

5 Let the AED computer do its job By analyzing the signals from the sensors in the electrode pads, the AED determines whether the heart problem requires an electric shock.

6 Pay attention to the speaker or screen Simple instructions projected from a voice recording and displayed on a digital screen tell the user how and when to deliver the electric shock.

FIGURE 1 AEDs are designed to be used by trained responders as well as untrained bystanders. You can use an AED to deliver an electric shock that could "jumpstart" the pacemaker cells of someone who is suffering from cardiac arrest.

GOING FURTHER >>>

Research where AEDs are thought to be most useful in a community. Then, make a map of locations of AEDs in or around your school or other public locations.

CHAPTER 21

STUDY GUIDE

BIG IDEA Electric charges are surrounded by electric fields that exert a force on other charged objects.

SECTION 1 Measuring Electric Fields

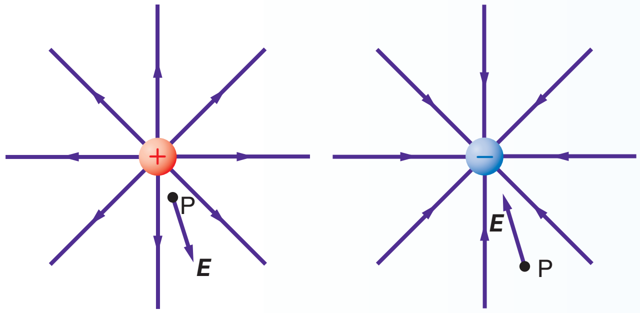
VOCABULARY
- **electric field** *(p. 570)*
- **electric field line** *(p. 574)*

MAIN IDEA An electric field is a property of the space around a charged object that exerts forces on other charged objects.

- An electric field exists around any charged object. The field produces forces on other charged objects.
- Quantities relating to charge, electric fields, and forces are related and can be calculated using these formulas:

$$E = \frac{F}{q'} \qquad E = \frac{Kqq'}{r^2 q'} = \frac{Kq}{r^2}$$

- Electric field lines provide a pictorial model 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. The direction of the electric field is the direction of the force on a tiny, positive test charge.



SECTION 2 Applications of Electric Fields

VOCABULARY
- **electric potential difference** *(p. 578)*
- **volt** *(p. 578)*
- **equipotential** *(p. 579)*
- **capacitor** *(p. 585)*
- **capacitance** *(p. 585)*

MAIN IDEA Electric potential (sometimes called voltage) is electric potential energy per unit charge.

- Electric potential difference is the change in potential energy per unit charge in an electric field. Electric potential differences are measured in volts.
- Potential difference is related to the work required to move a charge and is represented by the following equation:

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

- Capacitors are used to store electrical energy. A capacitor consists of two conducting plates separated by an insulator. The capacitance C depends only on the geometry of these plates and insulator. It can be calculated by the following equation.

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

Games and Multilingual eGlossary

Vocabulary Practice

CHAPTER 21 ASSESSMENT

Chapter Self-Check

SECTION 1 Measuring Electric Fields

Mastering Concepts

49. What are the two properties that a test charge must have?

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

51. BIGIDEA What are electric field lines?

52. How is the strength of an electric field indicated with electric field lines?

53. Draw some of the electric field lines between each of the following:

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

54. In **Figure 19,** where do the electric field lines that leave the positive charge end?

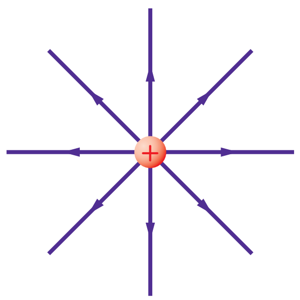


Figure 19

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

56. You are moving a constant positive charge through an increasing electric field. Does the amount of energy required to move it increase or decrease?

Mastering Problems

The charge of an electron is -1.602×10^{-19} *C.*

57. 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?

58. 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?

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

60. A positive charge of 1.0×10^{-5} C, shown in **Figure 20,** experiences a force of 0.30 N when it is located at a certain point. What is the electric field intensity at that point?

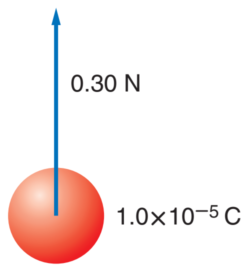


Figure 20

61. 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 -1.602×10^{-19} C.

c. Compare the force in part b with the force of gravity on the same electron (mass = 9.1×10^{-31} kg).

62. 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.)

63. 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.** What is the strength of the force exerted on the test charge?

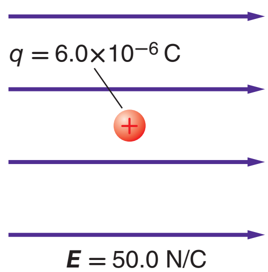


Figure 21

64. A force of 14.005 N exists on a positive test charge (q') that has a charge of 4.005×10^{-19} C. What is the magnitude of the electric field?

Chapter Self-Check

65. 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. 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.

66. In an old 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).

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

SECTION 2
Applications of Electric Fields
Mastering Concepts

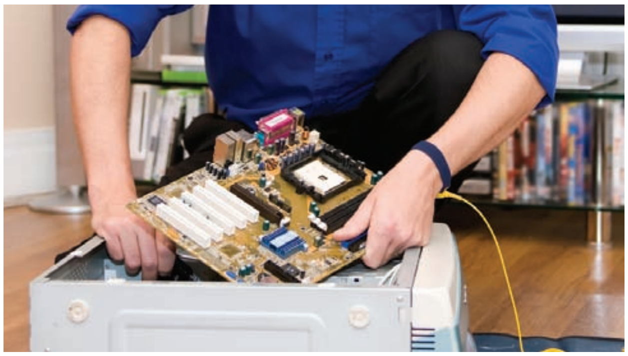
68. What SI unit is used to measure electric potential energy? What SI unit is used to measure electric potential difference?

69. Define volt in terms of the change in potential energy of a charge moving in an electric field.

70. Why does a charged object lose its charge when it is touched to the ground?

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

72. **Computers** Delicate parts in electronic equipment, such as those pictured in **Figure 22,** are contained within a metal box inside a plastic case. Why?



Andrew Howe/Photodisc/Getty Images

Figure 22

Mastering Problems

73. 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 23,** what potential difference exists between the plates?

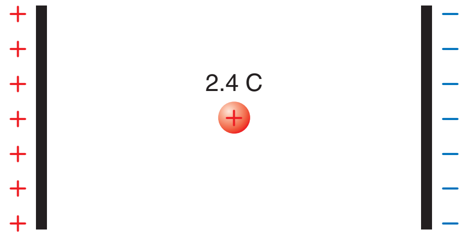


Figure 23

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

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

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

77. 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?

78. 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?

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

80. The oil drop shown in **Figure 24** 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?

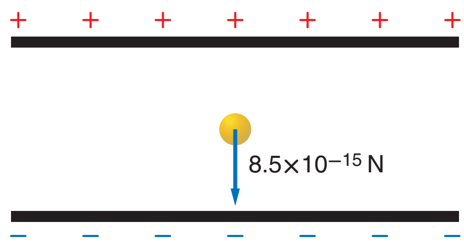


Figure 24

Chapter Self-Check

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

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

83. 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 25.** What is the size of the electric potential difference between the two points?

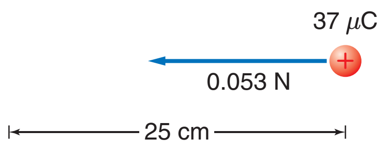


Figure 25

84. Photoflash The potential energy of a capacitor with capacitance (C) and an electric potential difference (ΔV) is represented by $PE = \frac{1}{2}C\Delta V^2$. One application of this is in the electronic photoflash of a strobe light, such the one in **Figure 26.** In such a unit, a capacitor of 10.0 μF has a charge of 3.0×10^2 V. Find the electrical energy stored.

Figure 26

85. Suppose it took 25 s to energize the capacitor in the previous problem.

a. Find the average power required to energize the capacitor in this time.

b. When the plates are 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?

86. 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 on one plate of the capacitor?

87. 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 6.1×10^{-2} F and is energized to a potential difference of 10.0 kV.

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

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

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

Applying Concepts

88. 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?

89. Figure 27 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. Which path will sphere x begin to follow? Assume that no other forces act on the spheres.

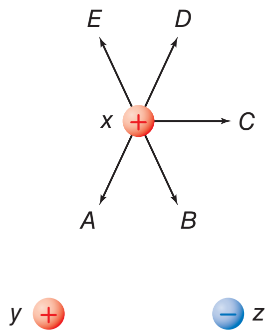


Figure 27

90. Ranking Task Rank the following point charges according to the magnitude of the electric force experienced, from greatest to least. Specifically indicate any ties.

A. a charge of 3 nC at a point where the electric field is 70 N/C

B. a charge of 5 nC at a point where the electric field is 600 N/C

C. a charge of 3 nC at a point where the electric field is 20 N/C

D. a charge of 6 nC at a point where the electric field is 35 N/C

E. a charge of 8 nC at a point where the electric field is 10 N/C

91. Two unlike-charged oil drops are held motionless in a Millikan oil-drop experiment at the same time.

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?

92. José and Sue are standing on an insulating platform and holding hands when they are given a charge, as in **Figure 28.** José is larger than Sue. Who has the larger amount of charge from the machine, or do they both have the same amount?

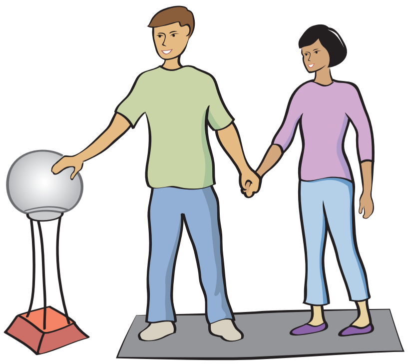


Figure 28

93. Reverse Problem Write a physics problem for which the following equation would be part of the solution:

$$E = \frac{(9\ \text{V} - 0\ \text{V})}{0.85\ \text{cm}}$$

94. How can you store different amounts of electrical energy in a capacitor?

Mixed Review

95. 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?

96. How much charge is 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?

97. Two identical small spheres 25 cm apart carry equal but opposite charges of 0.060 μC, as in **Figure 29.** If the potential difference between them is 300 V, what is the capacitance of the system?

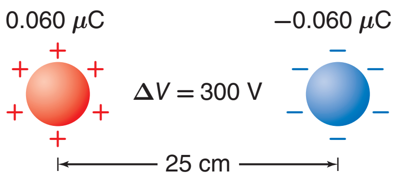


Figure 29

98. Problem Posing Complete this problem so that it must be solved using the concept indicated: " A point charge of 4.0 mC is at rest …."

a. electric field

b. electric potential difference

99. The plates of a 0.047-μF capacitor are 0.25 cm apart and are charged to a potential difference of 120 V.

a. How much charge is on the capacitor?

b. What is the strength of the electric field between the plates of the capacitor?

c. An electron is placed between the plates of the capacitor, as in **Figure 30.** What force is exerted on that electron?

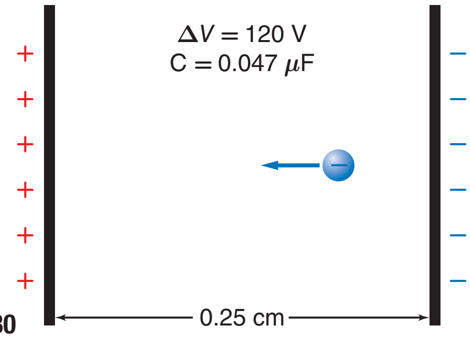


Figure 30

100. How much work would it take to move an additional 0.010 μC between the plates at 120 V in the previous problem?

101. The graph in **Figure 31** represents the amount of charge stored on one plate of a capacitor as a function of the charging potential.

a. What does the slope of the line represent?

b. What is the capacitance of the capacitor?

c. What does the area under the graph line represent?

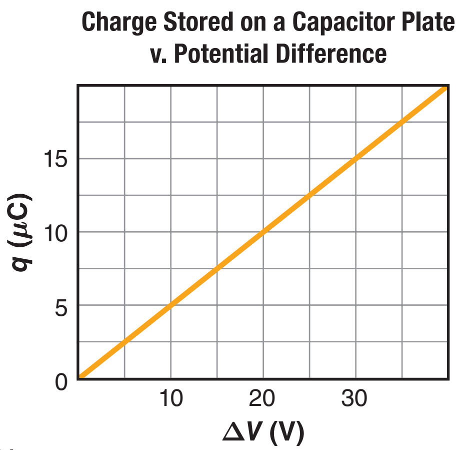


Figure 31

Chapter Self-Check

Thinking Critically

102. Analyze and Conclude Two small spheres, A and B, lie on the *x*-axis, as in **Figure 32.** 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 the 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.

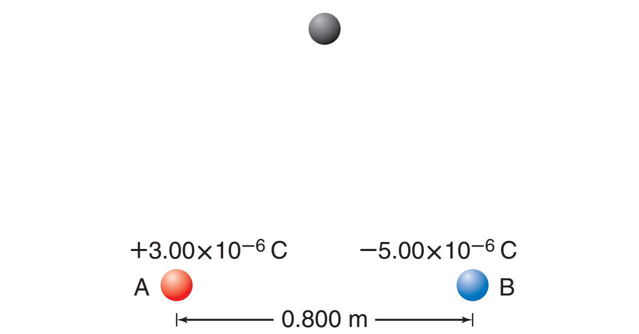


Figure 32

103. 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 plates deflect the charged ink particles as shown in **Figure 33.** The plates have an electric field of $E = 1.2\times10^{6}$ N/C between them and are 1.5 cm long. 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?

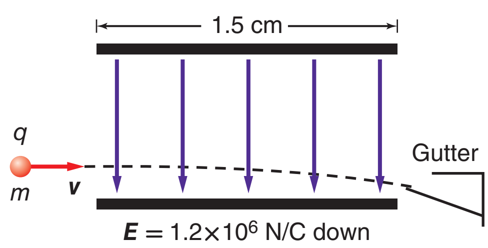


Figure 33

Writing in Physics

104. 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

105. Michelson measured the speed of light by sending a beam of light to a mirror on a mountain 35 km away.

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

b. Assume Michelson used a rotating octagon with a mirror on each face of the octagon. Also assume 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 it is rotating?

106. 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?

107. 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?

108. A force (F) is measured between two charges (Q and q) separated by a distance (r). What would the new force be for the following?

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

STANDARDIZED TEST PRACTICE

MULTIPLE CHOICE

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

A. so the charge doesn't disturb the field

B. because small charges have small momentum

C. so its size doesn't nudge the charge to be measured aside

D. because an electron always is used as the test charge and electrons are small

2. 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?

A. 7.0×10^{-8} N/C, 24° N of E

B. 1.7×10^{-6} N/C, 24° S of W

C. 1.1×10^{-3} N/C, 24° W of S

D. 9.3×10^{-1} N/C, 24° N of E

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

A. 27 V

B. 86 V

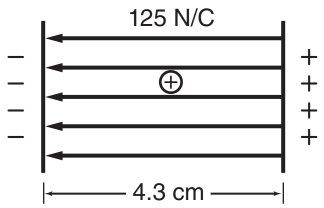
C. 0.86 kV

D. 27 kV

4. 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?

A. 5.5×10^{-23} J **C.** 1.1×10^{-16} J

B. 8.6×10^{-19} J **D.** 5.4 J



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

A. using a measurable electromagnet

B. from the electric potential between the plates

C. from the magnitude of the charge

D. by an electrometer

6. In an oil drop experiment, a drop with a weight of 2.0×10^{-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 of the drop?

A. -1.6×10^{-18} C **C.** -1.2×10^{-15} C

B. -4.0×10^{-16} C **D.** -9.3×10^{-13} C

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

A. 5.4×10^{-12} V

B. 1.6×10^{-6} V

C. 6.2×10^{2} V

D. 5.4×10^{3} V

FREE RESPONSE

8. 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.

NEED EXTRA HELP?

If you Missed Question	1	2	3	4	5	6	7	8
Review Section	1	1	2	2	2	2	2	2

Online Test Practice