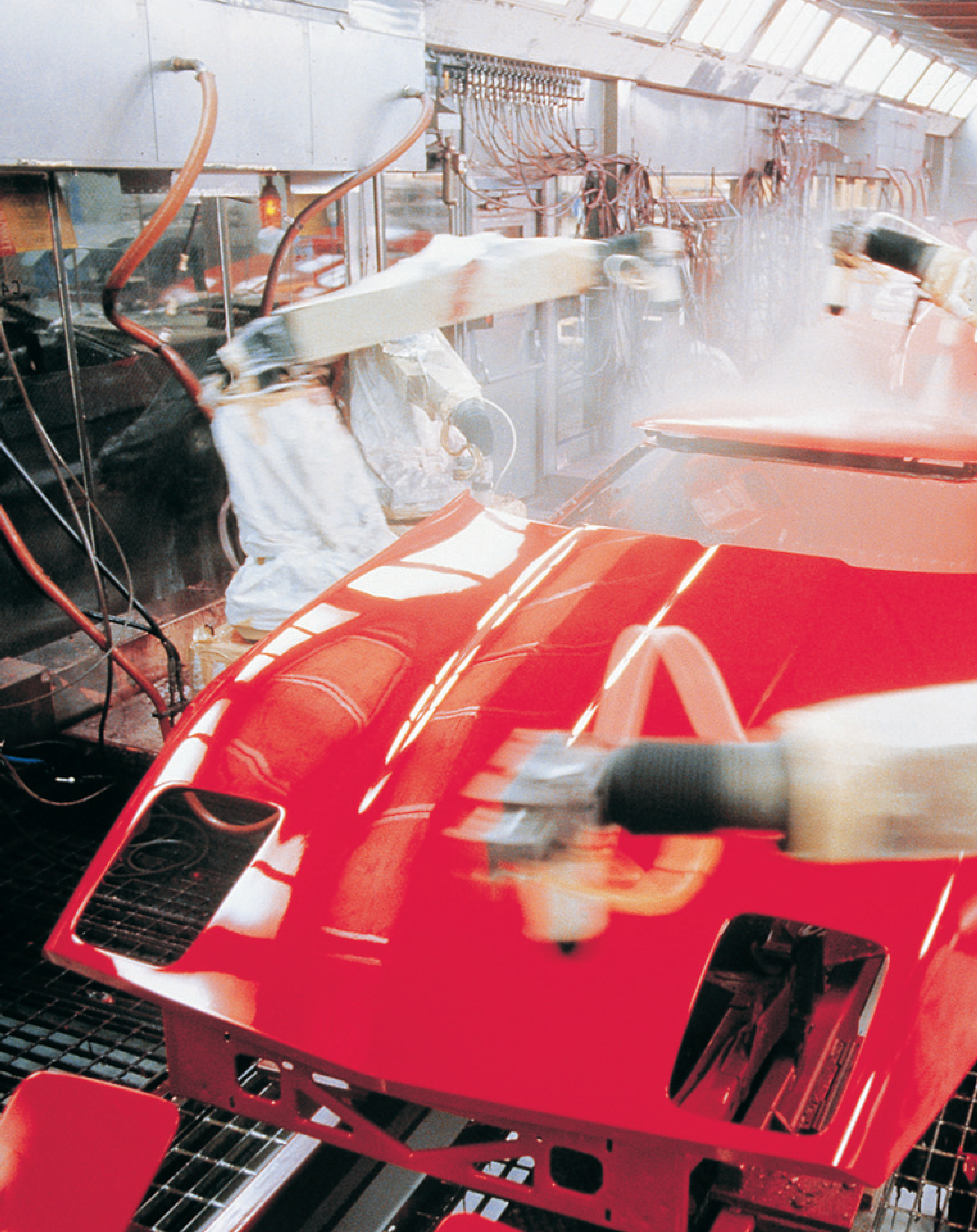

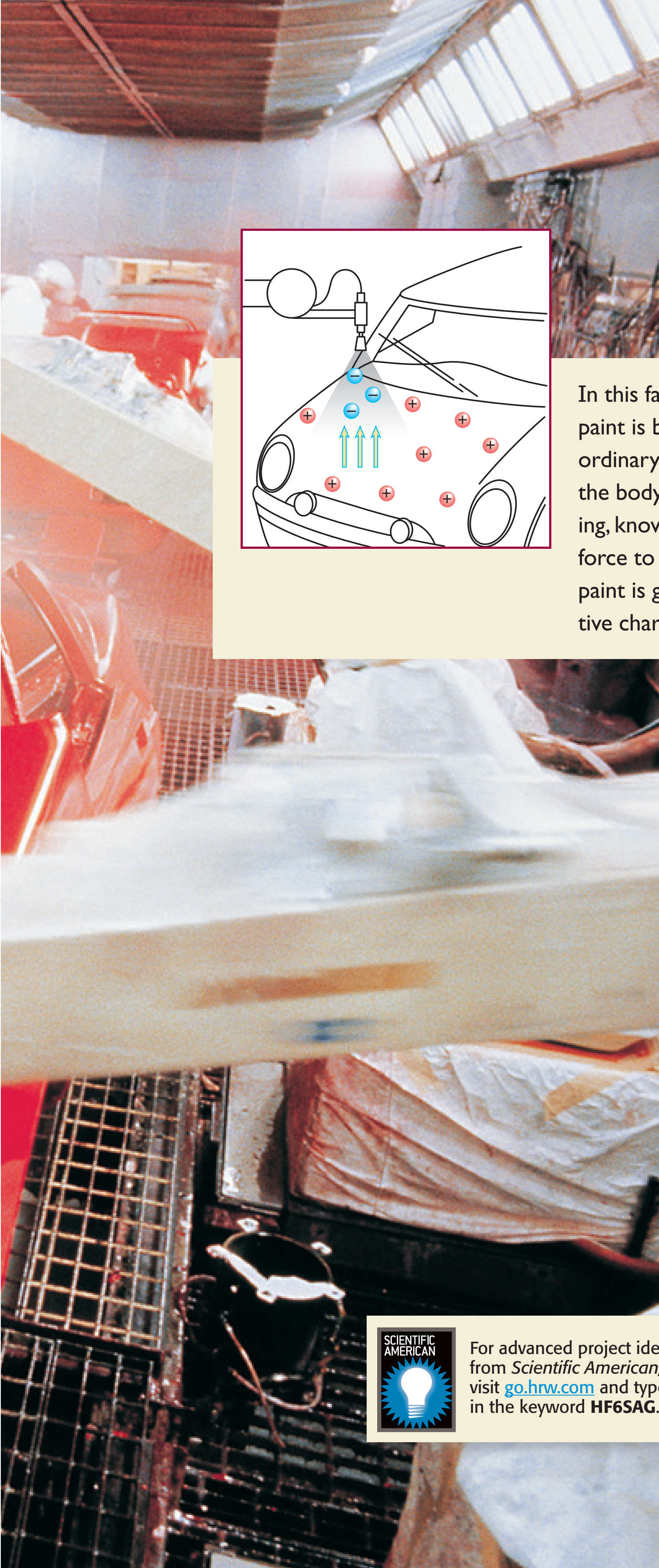

CHAPTER 16

Electric Forces and Fields

In this factory in Bowling Green, Kentucky, a fresh coat of paint is being applied to an automobile by spray guns. With ordinary spray guns, any paint that does not happen to hit the body of the car is wasted. A special type of spray painting, known as *electrostatic spray painting,* utilizes electric force to minimize the amount of paint that is wasted. The paint is given a negative charge and the car is given a positive charge. Thus, the paint is attracted to the car.

WHAT TO EXPECT

In this chapter, you will learn about the basic properties of electric charges. You will learn to calculate the electric force produced by point charges and will learn to interpret electric field lines.

WHY IT MATTERS

According to one estimate, electrostatic spray painting saves industries in the United States as much as $50 million each year. You will study how electric force is used in electrostatic spray painting.

CHAPTER PREVIEW

1 Electric Charge
- Properties of Electric Charge
- Transfer of Electric Charge

2 Electric Force
- Coulomb's Law

3 The Electric Field
- Electric Field Strength
- Electric Field Lines
- Conductors in Electrostatic Equilibrium

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SECTION 1

Electric Charge

SECTION OBJECTIVES

- Understand the basic properties of electric charge.
- Differentiate between conductors and insulators.
- Distinguish between charging by contact, charging by induction, and charging by polarization.

PROPERTIES OF ELECTRIC CHARGE

You have probably noticed that after running a plastic comb through your hair on a dry day, the comb attracts strands of your hair or small pieces of paper. A simple experiment you might try is to rub an inflated balloon back and forth across your hair. You may find that the balloon is attracted to your hair, as shown in **Figure 1(a).** On a dry day, a rubbed balloon will stick to the wall of a room, often for hours. When materials behave this way, they are said to be *electrically charged.* Experiments such as these work best on a dry day because excessive moisture can provide a pathway for charge to leak off a charged object.

You can give your body an electric charge by vigorously rubbing your shoes on a wool rug or by sliding across a car seat. You can then remove the charge on your body by lightly touching another person. Under the right conditions, you will see a spark just before you touch, and both of you will feel a slight tingle.

Another way to observe static electricity is to rub two balloons across your hair and then hold them near one another, as shown in **Figure 1(b).** In this case, you will see the two balloons pushing each other apart. Why is a rubbed balloon attracted to your hair but repelled by another rubbed balloon?

There are two kinds of electric charge

The two balloons must have the same kind of charge because each became charged in the same way. Because the two charged balloons repel one another, we see that *like charges repel.* Conversely, a rubbed balloon and your hair, which do not have the same kind of charge, are attracted to one another. Thus, *unlike charges attract.*

Table 1 Conventions for Representing Charges and Electric Field Vectors

Positive charge	$+q$
Negative charge	$-q$
Electric field vector	**E**
Electric field lines	

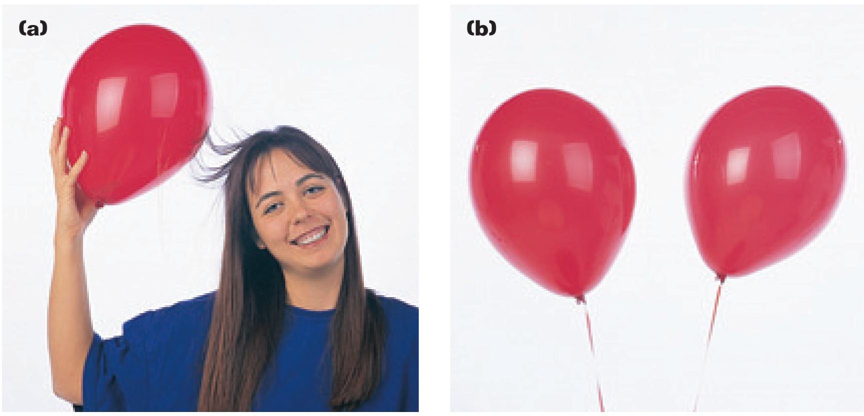


Figure 1
(a) If you rub a balloon across your hair on a dry day, the balloon and your hair become charged and attract each other. **(b)** Two charged balloons, on the other hand, repel each other.

Benjamin Franklin (1706–1790) named the two different kinds of charge *positive* and *negative.* By convention, when you rub a balloon across your hair, the charge on your hair is referred to as *positive* and that on the balloon is referred to as *negative,* as shown in **Figure 2.** Positive and negative charges are said to be *opposite* because an object with an equal amount of positive and negative charge has no net charge.

Electrostatic spray painting utilizes the principle of attraction between unlike charges. Paint droplets are given a negative charge, and the object to be painted is given a positive charge. In ordinary spray painting, many paint droplets drift past the object being painted. But in electrostatic spray painting, the negatively charged paint droplets are attracted to the positively charged target object, so more of the paint droplets hit the object being painted and less paint is wasted.

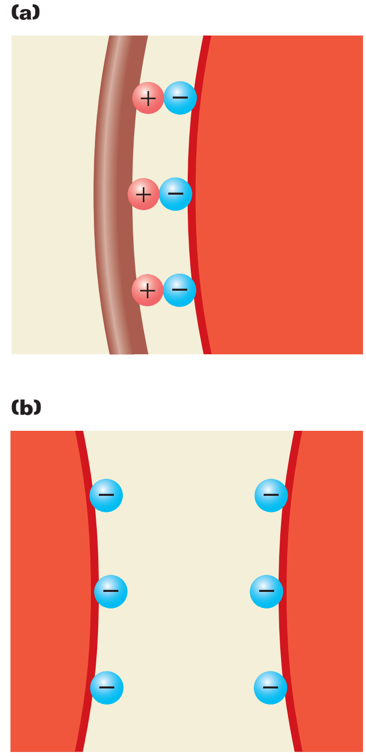


Figure 2
(a) This negatively charged balloon is attracted to positively charged hair because the two have opposite charges. **(b)** Two negatively charged balloons repel one another because they have the same charge.

Electric charge is conserved

When you rub a balloon across your hair, how do the balloon and your hair become electrically charged? To answer this question, you'll need to know a little about the atoms that make up the matter around you. Every atom contains even smaller particles. Positively charged particles, called *protons,* and uncharged particles, called *neutrons,* are located in the center of the atom, called the *nucleus.* Negatively charged particles, known as *electrons,* are located outside the nucleus and move around it. (You will study the structure of the atom and the particles within the atom in greater detail in later chapters on atomic and subatomic physics in this book.)

Protons and neutrons are relatively fixed in the nucleus of the atom, but electrons are easily transferred from one atom to another. When the electrons in an atom are balanced by an equal number of protons, the atom has no net charge. If an electron is transferred from one neutral atom to another, the second atom gains a negative charge and the first atom loses a negative charge, thereby becoming positive. Atoms that are positively or negatively charged are called *ions.*

Both a balloon and your hair contain a very large number of neutral atoms. Charge has a natural tendency to be transferred between unlike materials. Rubbing the two materials together serves to increase the area of contact and thus enhance the charge-transfer process. When a balloon is rubbed against your hair, some of your hair's electrons are transferred to the balloon. Thus, the balloon gains a certain amount of negative charge while your hair loses an equal amount of negative charge and hence is left with a positive charge. In this and similar experiments, only a small portion of the total available charge is transferred from one object to another.

The positive charge on your hair is equal in magnitude to the negative charge on the balloon. Electric charge is conserved in this process; no charge is created or destroyed. This principle of conservation of charge is one of the fundamental laws of nature.

Did you know?

Some cosmetic products contain an organic compound called *chitin,* which is found in crabs and lobsters, and in butterflies and other insects. Chitin is positively charged, so it helps cosmetic products stick to human hair and skin, which are usually slightly negatively charged.

Electric charge is quantized

In 1909, Robert Millikan (1886–1953) performed an experiment at the University of Chicago in which he observed the motion of tiny oil droplets between two parallel metal plates, as shown in **Figure 3.** The oil droplets were charged by friction in an atomizer and allowed to pass through a hole in the top plate. Initially, the droplets fell due to their weight. The top plate was given a positive charge as the droplets fell, and the droplets with a negative charge were attracted back upward toward the positively charged plate. By turning the charge on this plate on and off, Millikan was able to watch a single oil droplet for many hours as it alternately rose and fell.

Did you know?

In typical electrostatic experiments, in which an object is charged by rubbing, a net charge on the order of 10^{-6} C (= 1 μC) is obtained. This is a very small fraction of the total amount of charge within each object.

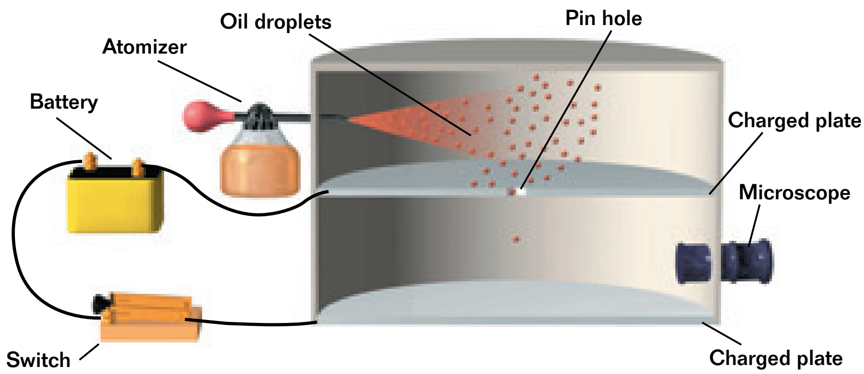


Figure 3
This is a schematic view of apparatus similar to that used by Millikan in his oil-drop experiment. In his experiment, Millikan found that there is a fundamental unit of charge.

After repeating this process for thousands of drops, Millikan found that when an object is charged, its charge is always a multiple of a fundamental unit of charge, symbolized by the letter e. In modern terms, charge is said to be *quantized.* This means that charge occurs as integer multiples of e in nature. Thus, an object may have a charge of $\pm e$, or $\pm 2e$, or $\pm 3e$, and so on.

Other experiments in Millikan's time demonstrated that the electron has a charge of $-e$ and the proton has an equal and opposite charge, $+e$. The value of e has since been determined to be $1.602\,176 \times 10^{-19}$ C, where the coulomb (C) is the SI unit of electric charge. For calculations, this book will use the approximate value given in **Table 2.** A total charge of -1.0 C contains 6.2×10^{18} electrons. Comparing this with the number of free electrons in 1 cm^3 of copper, which is on the order of 10^{23}, shows that 1.0 C is a substantial amount of charge.

Table 2 Charge and Mass of Atomic Particles

Particle	Charge (C)	Mass (kg)
electron	-1.60×10^{-19}	9.109×10^{-31}
proton	$+1.60 \times 10^{-19}$	1.673×10^{-27}
neutron	0	1.675×10^{-27}

TRANSFER OF ELECTRIC CHARGE

When a balloon and your hair are charged by rubbing, only the rubbed areas become charged, and there is no tendency for the charge to move into other regions of the material. In contrast, when materials such as copper, aluminum, and silver are charged in some small region, the charge readily distributes itself over the entire surface of the material. For this reason, it is convenient to classify substances in terms of their ability to transfer electric charge.

Materials in which electric charges move freely, such as copper and aluminum, are called **electrical conductors.** Most metals are conductors. Materials in which electric charges do not move freely, such as glass, rubber, silk, and plastic, are called **electrical insulators.**

Semiconductors are a third class of materials characterized by electrical properties that are somewhere between those of insulators and conductors. In their pure state, semiconductors are insulators. But the carefully controlled addition of specific atoms as impurities can dramatically increase a semiconductor's ability to conduct electric charge. Silicon and germanium are two well-known semiconductors that are used in a variety of electronic devices.

Certain metals and compounds belong to a fourth class of materials, called *superconductors.* Superconductors have zero electrical resistance when they are at or below a certain temperature. Thus, superconductors can conduct electricity indefinitely without heating.

Insulators and conductors can be charged by contact

In the experiments discussed above, a balloon and hair become charged when they are rubbed together. This process is known as *charging by contact.* Another example of charging by contact is a common experiment in which a glass rod is rubbed with silk and a rubber rod is rubbed with wool or fur. The two rods become oppositely charged and attract one another, as a balloon and your hair do. If two glass rods are charged, the rods have the same charge and repel each other, just as two charged balloons do. Likewise, two charged rubber rods repel one another. All of the materials used in these experiments—glass, rubber, silk, wool, and fur—are insulators. Can conductors also be charged by contact?

If you try a similar experiment with a copper rod, the rod does not attract or repel another charged rod. This result might suggest that a metal cannot be charged by contact. However, if you hold the copper rod with an insulating handle and then rub it with wool or fur, the rod attracts a charged glass rod and repels a charged rubber rod.

In the first case, the electric charges produced by rubbing readily move from the copper through your body and finally to Earth because copper and the human body are both conductors. The copper rod does become charged, but it soon becomes neutral again. In the second case, the insulating handle prevents the flow of charge to Earth, and the copper rod remains charged. Thus, both insulators and conductors can become charged by contact.

electrical conductor

a material in which charges can move freely

electrical insulator

a material in which charges cannot move freely

Conceptual Challenge

1. Plastic Wrap

Plastic wrap becomes electrically charged as it is pulled from its container, and, as a result, it is attracted to objects such as food containers. Explain why plastic is a good material for this purpose.

2. Charge Transfer

If a glass rod is rubbed with silk, the glass becomes positively charged and the silk becomes negatively charged. Compare the mass of the glass rod before and after it is charged.

3. Electrons

Many objects in the large-scale world have no net charge, even though they contain an extremely large number of electrons. How is this possible?

Conductors can be charged by induction

When a conductor is connected to Earth by means of a conducting wire or copper pipe, the conductor is said to be *grounded.* The Earth can be considered to be an infinite reservoir for electrons because it can accept an unlimited number of electrons. This fact is the key to understanding another method of charging a conductor.

Consider a negatively charged rubber rod brought near a neutral (uncharged) conducting sphere that is insulated so that there is no conducting path to ground. The repulsive force between the electrons in the rod and those in the sphere causes a redistribution of negative charge on the sphere, as shown in **Figure 4(a).** As a result, the region of the sphere nearest the negatively charged rod has an excess of positive charge.

If a grounded conducting wire is then connected to the sphere, as shown in **Figure 4(b),** some of the electrons leave the sphere and travel to Earth. If the wire to ground is then removed while the negatively charged rod is held in place, as shown in **Figure 4(c),** the conducting sphere is left with an excess of induced positive charge. Finally, when the rubber rod is removed from the vicinity of the sphere, as in **Figure 4(d),** the induced positive charge remains on the ungrounded sphere. The motion of negative charges on the sphere causes the charge to become uniformly distributed over the outside surface of the ungrounded sphere. This process is known as **induction,** and the charge is said to be *induced* on the sphere.

Notice that charging an object by induction requires no contact with the object inducing the charge but does require contact with a third object, which serves as either a *source* or a *sink* of electrons. A sink is a system which can absorb a large number of charges, such as Earth, without becoming locally charged itself. In the process of inducing a charge on the sphere, the charged rubber rod did not come in contact with the sphere and thus did not lose any of its negative charge. This is in contrast to charging an object by contact, in which charges are transferred directly from one object to another.

Quick Lab

Polarization

MATERIALS LIST

- plastic comb
- water faucet

Turn on a water faucet, and adjust the flow of water so that you have a small but steady stream. The stream should be as slow as possible without producing individual droplets. Comb your hair vigorously. Hold the charged end of the comb near the stream without letting the comb get wet. What happens to the stream of water? What might be causing this to happen?

induction

the process of charging a conductor by bringing it near another charged object and grounding the conductor

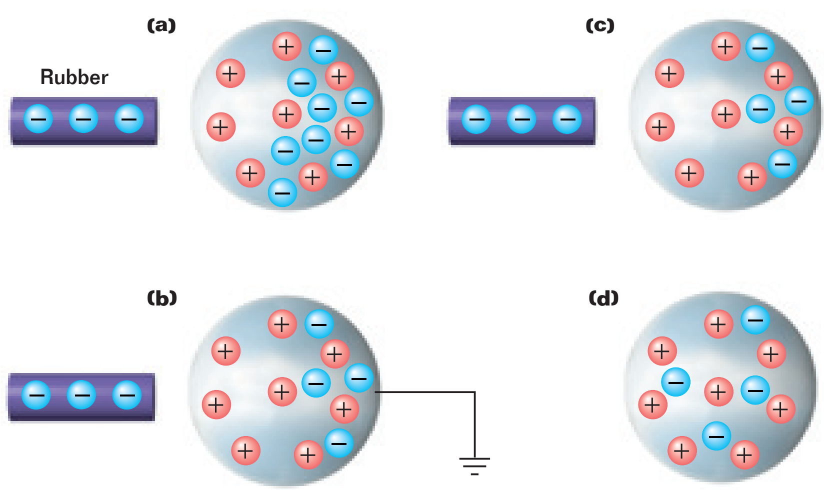


Figure 4
(a) When a charged rubber rod is brought near a metal sphere, the charge on the sphere becomes redistributed. **(b)** If the sphere is grounded, some of the electrons travel through the wire to the ground. **(c)** When this wire is removed, the sphere has an excess of positive charge. **(d)** The electrons become evenly distributed on the surface of the sphere when the rod is removed.

A surface charge can be induced on insulators by polarization

A process very similar to charging by induction in conductors takes place in insulators. In most neutral atoms or molecules, the center of positive charge coincides with the center of negative charge. In the presence of a charged object, these centers may shift slightly, resulting in more positive charge on one side of a molecule than on the other. This is known as *polarization.*

This realignment of charge within individual molecules produces an induced charge on the surface of the insulator, as shown in **Figure 5(a).** When an object becomes polarized, it has no net charge but is still able to attract or repel objects due to this realignment of charge. This explains why a plastic comb can attract small pieces of paper that have no net charge, as shown in **Figure 5(b).** As with induction, in polarization one object induces a charge on the surface of another object with no physical contact.

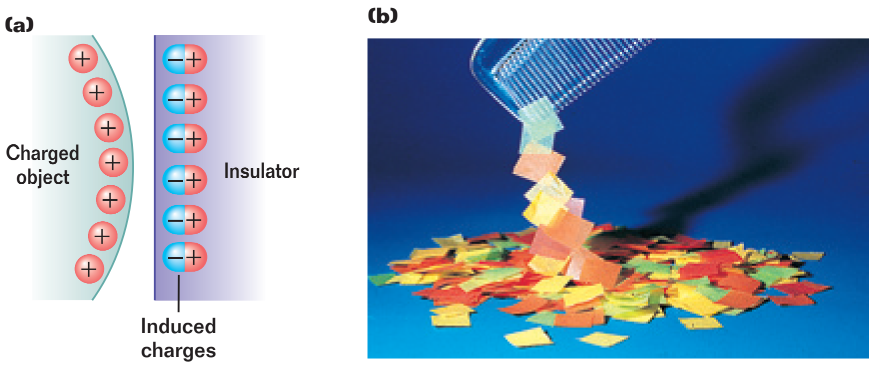


Figure 5
(a) The charged object on the left induces charges on the surface of an insulator, which is said to be *polarized.* **(b)** This charged comb induces a charge on the surface of small pieces of paper that have no net charge.

SECTION REVIEW

1. When a rubber rod is rubbed with wool, the rod becomes negatively charged. What can you conclude about the magnitude of the wool's charge after the rubbing process? Why?
2. What did Millikan's oil-drop experiment reveal about the nature of electric charge?
3. A typical lightning bolt has about 10.0 C of charge. How many excess electrons are in a typical lightning bolt?
4. If you stick a piece of transparent tape on your desk and then quickly pull it off, you will find that the tape is attracted to other areas of your desk that are not charged. Why does this happen?
5. **Critical Thinking** Metals, such as copper and silver, can become charged by induction, while plastic materials cannot. Explain why.
6. **Critical Thinking** Why is an electrostatic spray gun more efficient than an ordinary spray gun?

SECTION 2

Electric Force

SECTION OBJECTIVES

- Calculate electric force using Coulomb's law.
- Compare electric force with gravitational force.
- Apply the superposition principle to find the resultant force on a charge and to find the position at which the net force on a charge is zero.

Did you know?

The symbol k_C, called the *Coulomb constant,* has SI units of $N \bullet m^2/C^2$ because this gives N as the unit of electric force. The value of k_C depends on the choice of units. Experiments have determined that in SI units, k_C has the value 8.9875×10^9 $N \bullet m^2/C^2$.

COULOMB'S LAW

Two charged objects near one another may experience acceleration either toward or away from each other because each object exerts a force on the other object. This force is called the *electric force.* The two balloon experiments described in the first section demonstrate that the electric force is attractive between opposite charges and repulsive between like charges. What determines how small or large the electric force will be?

The closer two charges are, the greater is the force on them

It seems obvious that the distance between two objects affects the magnitude of the electric force between them. Further, it is reasonable that the amount of charge on the objects will also affect the magnitude of the electric force. What is the precise relationship between distance, charge, and the electric force?

In the 1780s, Charles Coulomb conducted a variety of experiments in an attempt to determine the magnitude of the electric force between two charged objects. Coulomb found that the electric force between two charges is proportional to the product of the two charges. Hence, if one charge is doubled, the electric force likewise doubles, and if both charges are doubled, the electric force increases by a factor of four. Coulomb also found that the electric force is inversely proportional to the square of the distance between the charges. Thus, when the distance between two charges is halved, the force between them increases by a factor of four. The following equation, known as Coulomb's law, expresses these conclusions mathematically for two charges separated by a distance, r.

COULOMB'S LAW

$$F_{electric} = k_C\left(\frac{q_1q_2}{r^2}\right)$$

$$\textbf{electric force} = \textbf{Coulomb constant} \times \frac{\textbf{(charge 1)(charge 2)}}{\textbf{(distance)}^2}$$

When dealing with Coulomb's law, remember that force is a vector quantity and must be treated accordingly. The electric force between two objects always acts along the line that connects their centers of charge. Also, note that Coulomb's law applies exactly only to point charges or particles and to spherical distributions of charge. When applying Coulomb's law to spherical distributions of charge, use the distance between the centers of the spheres as r.

SAMPLE PROBLEM A

Coulomb's Law

PROBLEM

The electron and proton of a hydrogen atom are separated, on average, by a distance of about 5.3×10^{-11} m. Find the magnitudes of the electric force and the gravitational force that each particle exerts on the other.

SOLUTION

1. DEFINE **Given:**

$r = 5.3 \times 10^{-11}$ m $q_e = -1.60 \times 10^{-19}$ C

$k_C = 8.99 \times 10^9$ N•m²/C² $q_p = +1.60 \times 10^{-19}$ C

$m_e = 9.109 \times 10^{-31}$ kg $G = 6.673 \times 10^{-11}$ N•m²/kg²

$m_p = 1.673 \times 10^{-27}$ kg

Unknown: $F_{electric} = ?$ $F_g = ?$

2. PLAN **Choose an equation or situation:**

Find the magnitude of the electric force using Coulomb's law and the magnitude of the gravitational force using Newton's law of gravitation (introduced in the chapter "Circular Motion and Gravitation" in this book).

$$F_{electric} = k_C \frac{q_1 q_2}{r^2} \qquad F_g = G\frac{m_e m_p}{r^2}$$

3. CALCULATE **Substitute the values into the equations and solve:**

Because we are finding the magnitude of the electric force, which is a scalar, we can disregard the sign of each charge in our calculation.

$$F_{electric} = k_C \frac{q_e q_p}{r^2} = \left(8.99 \times 10^9 \frac{\mathrm{N{\bullet}m^2}}{\mathrm{C^2}}\right)\left(\frac{(1.60 \times 10^{-19}\ \mathrm{C})^2}{(5.3 \times 10^{-11}\ \mathrm{m})^2}\right)$$

$$\boxed{F_{electric} = 8.2 \times 10^{-8}\ \mathrm{N}}$$

$$F_g = G\frac{m_e m_p}{r^2} =$$

$$\left(6.673 \times 10^{-11} \frac{\mathrm{N{\bullet}m^2}}{\mathrm{kg^2}}\right)\left(\frac{(9.109 \times 10^{-31}\ \mathrm{kg})(1.673 \times 10^{-27}\ \mathrm{kg})}{(5.3 \times 10^{-11}\ \mathrm{m})^2}\right)$$

$$\boxed{F_g = 3.6 \times 10^{-47}\ \mathrm{N}}$$

4. EVALUATE The electron and the proton have opposite signs, so the electric force between the two particles is attractive. The ratio $F_{electric}/F_g \approx 2 \times 10^{39}$; hence, the gravitational force between the particles is negligible compared with the electric force between them. Because each force is inversely proportional to distance squared, their ratio is independent of the distance between the two particles.

PRACTICE A

Coulomb's Law

1. A balloon rubbed against denim gains a charge of –8.0 μC. What is the electric force between the balloon and the denim when the two are separated by a distance of 5.0 cm? (Assume that the charges are located at a point.)

2. Two identical conducting spheres are placed with their centers 0.30 m apart. One is given a charge of $+12 \times 10^{-9}$ C and the other is given a charge of -18×10^{-9} C.

a. Find the electric force exerted on one sphere by the other.

b. The spheres are connected by a conducting wire. After equilibrium has occurred, find the electric force between the two spheres.

3. Two electrostatic point charges of +60.0 μC and +50.0 μC exert a repulsive force on each other of 175 N. What is the distance between the two charges?

Resultant force on a charge is the vector sum of the individual forces on that charge

Frequently, more than two charges are present, and it is necessary to find the net electric force on one of them. As demonstrated in Sample Problem A, Coulomb's law gives the electric force between any pair of charges. Coulomb's law also applies when more than two charges are present. Thus, the resultant force on any single charge equals the vector sum of the individual forces exerted on that charge by all of the other individual charges that are present. This is an example of the *principle of superposition.* Once the magnitudes of the individual electric forces are found, the vectors are added together exactly as you learned earlier. This process is demonstrated in Sample Problem B.

Conceptual Challenge

1. Electric Force

The electric force is significantly stronger than the gravitational force. However, although we feel our attraction to Earth by gravity, we do not usually feel the effects of the electric force. Explain why.

2. Electrons in a Coin

An ordinary nickel contains about 10^{24} electrons, all repelling one another. Why don't these electrons fly off the nickel?

3. Charged Balloons

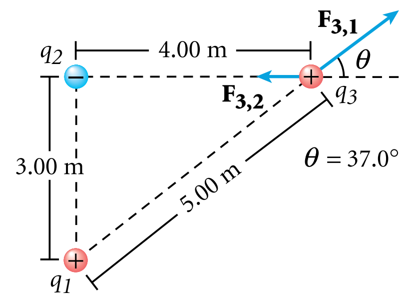
When the distance between two negatively charged balloons is doubled, by what factor does the repulsive force between them change?

SAMPLE PROBLEM B

STRATEGY The Superposition Principle

PROBLEM

Consider three point charges at the corners of a triangle, as shown at right, where $q_1 = 6.00 \times 10^{-9}$ C, $q_2 = -2.00 \times 10^{-9}$ C, and $q_3 = 5.00 \times 10^{-9}$ C. Find the magnitude and direction of the resultant force on q_3.



SOLUTION

1. Define the problem, and identify the known variables.

Given: $q_1 = +6.00 \times 10^{-9}$ C $\quad r_{2,1} = 3.00$ m

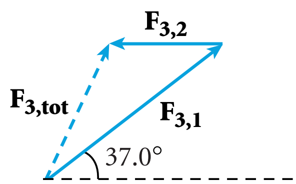
$q_2 = -2.00 \times 10^{-9}$ C $\quad r_{3,2} = 4.00$ m

$q_3 = +5.00 \times 10^{-9}$ C $\quad r_{3,1} = 5.00$ m

$\theta = 37.0°$

Unknown: $\mathbf{F_{3,tot}} = ?$

Diagram:



2. Determine the direction of the forces by analyzing the charges.

The force $\mathbf{F_{3,1}}$ is repulsive because q_1 and q_3 have the same sign.

The force $\mathbf{F_{3,2}}$ is attractive because q_2 and q_3 have opposite signs.

3. Calculate the magnitude of the forces with Coulomb's law.

$$F_{3,1} = k_C \frac{q_3 q_1}{(r_{3,1})^2} = (8.99 \times 10^9 \text{ N}\bullet\text{m}^2/\text{C}^2)\left(\frac{(5.00 \times 10^{-9}\text{ C})(6.00 \times 10^{-9}\text{ C})}{(5.00\text{ m})^2}\right)$$

$$F_{3,1} = 1.08 \times 10^{-8}\text{ N}$$

$$F_{3,2} = k_C \frac{q_3 q_2}{(r_{3,2})^2} = (8.99 \times 10^9 \text{ N}\bullet\text{m}^2/\text{C}^2)\left(\frac{(5.00 \times 10^{-9}\text{ C})(2.00 \times 10^{-9}\text{ C})}{(4.00\text{ m})^2}\right)$$

$$F_{3,2} = 5.62 \times 10^{-9}\text{ N}$$

4. Find the *x* and *y* components of each force.

At this point, the direction of each component must be taken into account.

For $\mathbf{F_{3,1}}$: $F_x = (F_{3,1})(\cos 37.0°) = (1.08 \times 10^{-8}\text{ N})(\cos 37.0°) = 8.63 \times 10^{-9}\text{ N}$

$F_y = (F_{3,1})(\sin 37.0°) = (1.08 \times 10^{-8}\text{ N})(\sin 37.0°) = 6.50 \times 10^{-9}\text{ N}$

For $\mathbf{F_{3,2}}$: $F_x = -F_{3,2} = -5.62 \times 10^{-9}\text{ N}$

$F_y = 0\text{ N}$

5. Calculate the magnitude of the total force acting in both directions.

$F_{x,tot} = 8.63 \times 10^{-9}\text{ N} - 5.62 \times 10^{-9}\text{ N} = 3.01 \times 10^{-9}\text{ N}$

$F_{y,tot} = 6.50 \times 10^{-9}\text{ N} + 0\text{ N} = 6.50 \times 10^{-9}\text{ N}$

TIP *According to the superposition principle, the resultant force on the charge q_3 is the vector sum of the forces exerted by q_1 and q_2 on q_3. First, find the force exerted on q_3 by each, and then add these two forces together vectorially to get the resultant force on q_3.*

continued on next page

6. Use the Pythagorean theorem to find the magnitude of the resultant force.

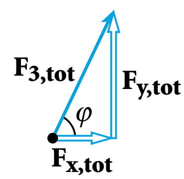
$$F_{3,tot} = \sqrt{(F_{x,tot})^2 + (F_{y,tot})^2} = \sqrt{(3.01 \times 10^{-9}\ \text{N})^2 + (6.50 \times 10^{-9}\ \text{N})^2}$$

$$\boxed{F_{3,tot} = 7.16 \times 10^{-9}\ \text{N}}$$

7. Use a suitable trigonometric function to find the direction of the resultant force.

In this case, you can use the inverse tangent function:

$$\tan \varphi = \frac{F_{y,tot}}{F_{x,tot}} = \frac{6.50 \times 10^{-9}\ \text{N}}{3.01 \times 10^{-9}\ \text{N}}$$



$$\boxed{\varphi = 65.2°}$$

PRACTICE B

The Superposition Principle

1. Three point charges, q_1, q_2, and q_3, lie along the x-axis at $x = 0$, $x = 3.0$ cm, and $x = 5.0$ cm, respectively. Calculate the magnitude and direction of the electric force on each of the three point charges when $q_1 = +6.0\ \mu C$, $q_2 = +1.5\ \mu C$, and $q_3 = -2.0\ \mu C$.

2. Four charged particles are placed so that each particle is at the corner of a square. The sides of the square are 15 cm. The charge at the upper left corner is $+3.0\ \mu C$, the charge at the upper right corner is $-6.0\ \mu C$, the charge at the lower left corner is $-2.4\ \mu C$, and the charge at the lower right corner is $-9.0\ \mu C$.

a. What is the net electric force on the $+3.0\ \mu C$ charge?
b. What is the net electric force on the $-6.0\ \mu C$ charge?
c. What is the net electric force on the $-9.0\ \mu C$ charge?

Consider an object that is in equilibrium. According to Newton's first law, the net external force acting on a body in equilibrium must equal zero. In electrostatic situations, the equilibrium position of a charge is the location at which the net electric force on the charge is zero. To find this location, you must find the position at which the electric force from one charge is equal and opposite the electric force from another charge. This can be done by setting the forces (found by Coulomb's law) equal and then solving for the distance between either charge and the equilibrium position. This is demonstrated in Sample Problem C.

SAMPLE PROBLEM C

Equilibrium

PROBLEM

Three charges lie along the *x*-axis. One positive charge, q_1 = 15 µC, is at *x* = 2.0 m, and another positive charge, q_2 = 6.0 µC, is at the origin. At what point on the *x*-axis must a negative charge, q_3, be placed so that the resultant force on it is zero?

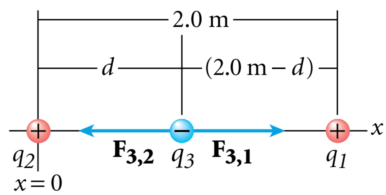
SOLUTION

Given: $q_1 = 15\ \mu C$ $\quad r_{3,1} = 2.0\ m - d$

$q_2 = 6.0\ \mu C$ $\quad r_{3,2} = d$

Unknown: the distance (d) between the negative charge q_3 and the positive charge q_2 such that the resultant force on q_3 is zero

Diagram:



Because we require that the resultant force on q_3 be zero, $F_{3,1}$ must equal $F_{3,2}$. Each force can be found by using Coulomb's law.

$$F_{3,1} = F_{3,2}$$

$$k_C\left(\frac{q_3 q_1}{(r_{3,1})^2}\right) = k_C\left(\frac{q_3 q_2}{(r_{3,2})^2}\right)$$

$$\frac{q_1}{(2.0\ m - d)^2} = \frac{q_2}{d^2}$$

TIP *Because k_C and q_3 are common terms, they can be canceled from both sides of the equation.*

Now, solve for d to find the location of q_3.

$$(d^2)(q_1) = (2.0\ m - d)^2(q_2)$$

Take the square root of both sides, and then isolate d.

$$d\sqrt{q_1} = (2.0\ m - d)\sqrt{q_2}$$

$$d\left(\sqrt{q_1} + \sqrt{q_2}\right) = \sqrt{q_2}(2.0\ m)$$

$$d = \frac{\sqrt{q_2}(2.0\ m)}{\sqrt{q_1} + \sqrt{q_2}} = \frac{\sqrt{6.0\ \mu C}\ (2.0\ m)}{\sqrt{15\ \mu C} + \sqrt{6.0\ \mu C}} = 0.77\ m$$

$$\boxed{d = 0.77\ m}$$

PRACTICE C

Equilibrium

1. A charge of $+2.00 \times 10^{-9}$ C is placed at the origin, and another charge of $+4.00 \times 10^{-9}$ C is placed at $x = 1.5$ m. Find the point between these two charges where a charge of $+3.00 \times 10^{-9}$ C should be placed so that the net electric force on it is zero.

2. A charge q_1 of -5.00×10^{-9} C and a charge q_2 of -2.00×10^{-9} C are separated by a distance of 40.0 cm. Find the equilibrium position for a third charge of $+15.0 \times 10^{-9}$ C.

3. An electron is released above the Earth's surface. A second electron directly below it exerts just enough of an electric force on the first electron to cancel the gravitational force on it. Find the distance between the two electrons.

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Topic: Van de Graaff Generator
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PHYSICS INTERACTIVE TUTOR

Module 16
"Force Between Charges"
provides an interactive lesson with guided problem-solving practice to teach you about the electric forces between all kinds of objects, including point charges.

Electric force is a field force

The Coulomb force is the second example we have studied of a force that is exerted by one object on another even though there is no physical contact between the two objects. Such a force is known as a *field force.* Recall that another example of a field force is gravitational attraction. Notice that the mathematical form of the Coulomb force is very similar to that of the gravitational force. Both forces are inversely proportional to the square of the distance of separation.

However, there are some important differences between electric and gravitational forces. First of all, as you have seen, electric forces can be either attractive or repulsive. Gravitational forces, on the other hand, are always attractive. The reason is that objects can have either a positive or a negative charge, while mass is always positive.

Another difference between the gravitational force and the electric force is their relative strength. As shown in Sample Problem A, the electric force is significantly stronger than the gravitational force. As a result, the electric force between charged atomic particles is much stronger than their gravitational attraction to Earth and between each other.

In the large-scale world, the relative strength of these two forces can be seen by noting that the amount of charge required to overcome the gravitational force is relatively small. For example, if you rub a balloon against your hair and hold the balloon directly above your hair, your hair will stand on end because it is attracted toward the balloon. Although only a small amount of charge is transferred from your hair to the balloon, the electric force between the two is nonetheless stronger than the gravitational force that pulls your hair toward the ground.

Coulomb quantified electric force with a torsion balance

Earlier in this chapter, you learned that Charles Coulomb was the first person to quantify the electric force and establish the inverse square law for electric charges. Coulomb measured electric forces between charged objects with a torsion balance, as shown in **Figure 6.** A torsion balance consists of two small spheres fixed to the ends of a light horizontal rod. The rod is made of an insulating material and is suspended by a silk thread.

In this experiment, one of the spheres is given a charge and another charged object is brought near the charged sphere. The attractive or repulsive force between the two causes the rod to rotate and to twist the suspension. The angle through which the rod rotates is measured by the deflection of a light beam reflected from a mirror attached to the suspension. The rod rotates through some angle against the restoring force of the twisted thread before reaching equilibrium. The value of the angle of rotation increases as the charge increases, thereby providing a quantitative measure of the electric force. With this experiment, Coulomb established the equation for electric force introduced at the beginning of this section. More recent experiments have verified these results to within a very small uncertainty.

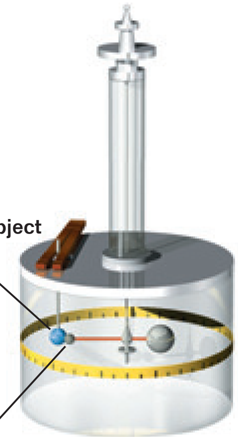

Figure 6
Coulomb's torsion balance was used to establish the inverse square law for the electric force between two charges.

SECTION REVIEW

1. A small glass ball rubbed with silk gains a charge of +2.0 μC. The glass ball is placed 12 cm from a small charged rubber ball that carries a charge of −3.5 μC.

a. What is the magnitude of the electric force between the two balls?

b. Is this force attractive or repulsive?

c. How many electrons has the glass ball lost in the rubbing process?

2. The electric force between a negatively charged paint droplet and a positively charged automobile body is increased by a factor of two, but the charges on each remain constant. How has the distance between the two changed? (Assume that the charge on the automobile is located at a single point.)

3. A $+2.2 \times 10^{-9}$ C charge is on the x-axis at $x = 1.5$ m, a $+5.4 \times 10^{-9}$ C charge is on the x-axis at $x = 2.0$ m, and a $+3.5 \times 10^{-9}$ C charge is at the origin. Find the net force on the charge at the origin.

4. A charge q_1 of -6.00×10^{-9} C and a charge q_2 of -3.00×10^{-9} C are separated by a distance of 60.0 cm. Where could a third charge be placed so that the net electric force on it is zero?

5. **Critical Thinking** What are some similarities between the electric force and the gravitational force? What are some differences between the two forces?

SECTION 3

The Electric Field

SECTION OBJECTIVES

- **Calculate electric field strength.**
- **Draw and interpret electric field lines.**
- **Identify the four properties associated with a conductor in electrostatic equilibrium.**

electric field

a region where an electric force on a test charge can be detected

ELECTRIC FIELD STRENGTH

As discussed earlier in this chapter, electric force, like gravitational force, is a field force. Unlike contact forces, which require physical contact between objects, field forces are capable of acting through space, producing an effect even when there is no physical contact between the objects involved. The concept of a field is a model that is frequently used to understand how two objects can exert forces on each other at a distance. For example, a charged object sets up an **electric field** in the space around it. When a second charged object enters this field, forces of an electrical nature arise. In other words, the second object interacts with the field of the first particle.

To define an electric field more precisely, consider **Figure 7(a),** which shows an object with a small positive charge, q_0, placed near a second object with a larger positive charge, Q. The strength of the electric field, E, at the location of q_0 is defined as the magnitude of the electric force acting on q_0 divided by the charge of q_0:

$$E = \frac{F_{electric}}{q_0}$$

Note that this is the electric field at the location of q_0 produced by the charge Q, and *not* the field produced by q_0.

Because electric field strength is a ratio of force to charge, the SI units of E are newtons per coulomb (N/C). The electric field is a vector quantity. By convention, the direction of **E** at a point is defined as the direction of the electric force that would be exerted on a small *positive* charge (called a test charge) placed at that point. Thus, in **Figure 7(a),** the direction of the electric field is horizontal and away from the sphere because a positive charge would be repelled by the positive sphere. In **Figure 7(b),** the direction of the electric field is toward the sphere because a positive charge would be attracted toward the negatively charged sphere. In other words, the direction of **E** depends on the sign of the charge producing the field.

Figure 7
(a) A small object with a positive charge q_0 placed in the field, **E,** of an object with a larger positive charge experiences an electric force away from the object. **(b)** A small object with a positive charge q_0 placed in the field, **E,** of a negatively charged object experiences an electric force toward the object.

Now, consider the positively charged conducting sphere in **Figure 8(a).** The field in the region surrounding the sphere could be explored by placing a positive test charge, q_0, in a variety of places near the sphere. To find the electric field at each point, you would first find the electric force on this charge, then divide this force by the magnitude of the test charge.

However, when the magnitude of the test charge is great enough to influence the charge on the conducting sphere, a difficulty with our definition arises. According to Coulomb's law, a strong test charge will cause a rearrangement of the charges on the sphere, as shown in **Figure 8(b).** As a result, the force exerted on the test charge is different from what the force would be if the movement of charge on the sphere had not taken place. Furthermore, the strength of the measured electric field is different from what it would be in the absence of the test charge. To eliminate this problem, we assume that the test charge is small enough to have a negligible effect on the location of the charges on the sphere, the situation shown in **Figure 8(a).**

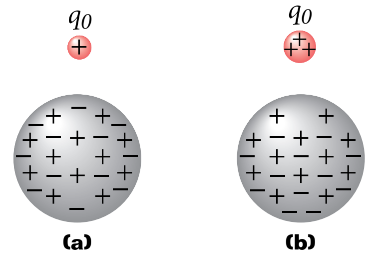

Figure 8
We must assume a small test charge, as in **(a),** because a larger test charge, as in **(b),** can cause a redistribution of the charge on the sphere, which changes the electric field strength.

Electric field strength depends on charge and distance

To reformulate our equation for electric field strength from a point charge, consider a small test charge, q_0, located a distance, r, from a charge, q. According to Coulomb's law, the magnitude of the force on the test charge is given by the following equation:

$$F_{electric} = k_C \frac{q q_0}{r^2}$$

We can find the magnitude of the electric field due to the point charge q at the position of q_0 by substituting this value into our previous equation for electric field strength.

$$E = \frac{F_{electric}}{q_0} = k_C \frac{q \cancel{q_0}}{r^2 \cancel{q_0}}$$

Notice that q_0 cancels, and we have a new equation for electric field strength due to a point charge.

ELECTRIC FIELD STRENGTH DUE TO A POINT CHARGE

$$E = k_C \frac{q}{r^2}$$

$$\text{electric field strength} = \text{Coulomb constant} \times \frac{\text{charge producing the field}}{(\text{distance})^2}$$

As stated above, electric field, **E,** is a vector. If q is positive, the field due to this charge is directed outward radially from q. If q is negative, the field is directed toward q. As with electric force, the electric field due to more than one charge is calculated by applying the principle of superposition. A strategy for solving superposition problems is given in Sample Problem D.

extension

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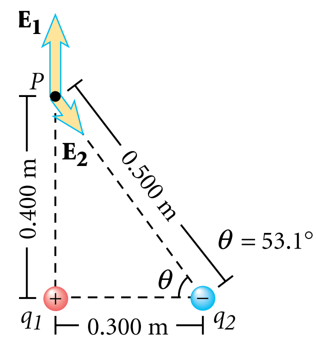
Table 3 Electric Fields	
Examples	***E*, N/C**
in a fluorescent lighting tube	10
in the atmosphere during fair weather	100
under a thundercloud or in a lightning bolt	10 000
at the electron in a hydrogen atom	5.1×10^{11}

Our new equation for electric field strength points out an important property of electric fields. As the equation indicates, an electric field at a given point depends only on the charge, q, of the object setting up the field and on the distance, r, from that object to a specific point in space. As a result, we can say that an electric field exists at any point near a charged body even when there is no test charge at that point. The examples in **Table 3** show the magnitudes of various electric fields.

SAMPLE PROBLEM D

STRATEGY Electric Field Strength



PROBLEM

A charge q_1 = +7.00 μC is at the origin, and a charge q_2 = −5.00 μC is on the x-axis 0.300 m from the origin, as shown at right. Find the electric field strength at point P, which is on the y-axis 0.400 m from the origin.

SOLUTION

1. Define the problem, and identify the known variables.

Given: $q_1 = +7.00\ \mu C = 7.00 \times 10^{-6}$ C $\quad r_1 = 0.400$ m

$q_2 = -5.00\ \mu C = -5.00 \times 10^{-6}$ C $\quad r_2 = 0.500$ m

$\theta = 53.1°$

Unknown: **E** at P ($y = 0.400$ m)

TIP *Apply the principle of superposition. You must first calculate the electric field produced by each charge individually at point P and then add these fields together as vectors.*

2. Calculate the electric field strength produced by each charge.

Because we are finding the magnitude of the electric field, we can neglect the sign of each charge.

$$E_1 = k_C \frac{q_1}{r_1^2} = (8.99 \times 10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)\left(\frac{7.00 \times 10^{-6}\ \text{C}}{(0.400\ \text{m})^2}\right) = 3.93 \times 10^5\ \text{N/C}$$

$$E_2 = k_C \frac{q_2}{r_2^2} = (8.99 \times 10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)\left(\frac{5.00 \times 10^{-6}\ \text{C}}{(0.500\ \text{m})^2}\right) = 1.80 \times 10^5\ \text{N/C}$$

3. Analyze the signs of the charges.

The field vector $\mathbf{E_1}$ at P due to q_1 is directed vertically upward, as shown in the figure above, because q_1 is positive. Likewise, the field vector $\mathbf{E_2}$ at P due to q_2 is directed toward q_2 because q_2 is negative.

4. Find the x and y components of each electric field vector.

For $\mathbf{E_1}$: $E_{x,1} = 0$ N/C

$E_{y,1} = 3.93 \times 10^5$ N/C

For $\mathbf{E_2}$: $E_{x,2} = (E_2)(\cos 53.1°) = (1.80 \times 10^5 \text{ N/C})(\cos 53.1°) = 1.08 \times 10^5 \text{ N/C}$

$E_{y,2} = -(E_2)(\sin 53.1°) = -(1.80 \times 10^5 \text{ N/C})(\sin 53.1°) = -1.44 \times 10^5 \text{ N/C}$

5. Calculate the total electric field strength in both directions.

$$E_{x,tot} = E_{x,1} + E_{x,2} = 0 \text{ N/C} + 1.08 \times 10^5 \text{ N/C} = 1.08 \times 10^5 \text{ N/C}$$

$$E_{y,tot} = E_{y,1} + E_{y,2} = 3.93 \times 10^5 \text{ N/C} - 1.44 \times 10^5 \text{ N/C} = 2.49 \times 10^5 \text{ N/C}$$

6. Use the Pythagorean theorem to find the magnitude of the resultant electric field strength vector.

$$E_{tot} = \sqrt{(E_{x,tot})^2 + (E_{y,tot})^2} = \sqrt{(1.08 \times 10^5 \text{ N/C})^2 + (2.49 \times 10^5 \text{ N/C})^2}$$

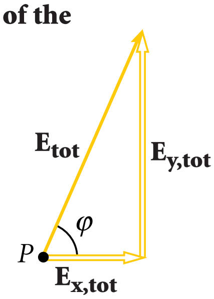
$$\boxed{E_{tot} = 2.71 \times 10^5 \text{ N/C}}$$

7. Use a suitable trigonometric function to find the direction of the resultant electric field strength vector.

In this case, you can use the inverse tangent function:

$$\tan \varphi = \frac{E_{y,tot}}{E_{x,tot}} = \frac{2.49 \times 10^5 \text{ N/C}}{1.08 \times 10^5 \text{ N/C}}$$

$$\boxed{\varphi = 66.6°}$$



8. Evaluate your answer.

The electric field at point P is pointing away from the charge q_1, as expected, because q_1, is a positive charge and is larger than the negative charge q_2.

PRACTICE D

Electric Field Strength

1. A charge, $q_1 = 5.00$ µC, is at the origin, and a second charge, $q_2 = -3.00$ µC, is on the x-axis 0.800 m from the origin. Find the electric field at a point on the y-axis 0.500 m from the origin.

2. A proton and an electron in a hydrogen atom are separated on the average by about 5.3×10^{-11} m. What is the magnitude and direction of the electric field set up by the proton at the position of the electron?

3. An electric field of 2.0×10^4 N/C is directed along the positive x-axis.

a. What is the electric force on an electron in this field?

b. What is the electric force on a proton in this field?

ELECTRIC FIELD LINES

A convenient aid for visualizing electric field patterns is to draw lines pointing in the direction of the electric field, called *electric field lines.* Although electric field lines do not really exist, they offer a useful means of analyzing fields by representing both the strength and the direction of the field at different points in space. This is useful because the field at each point is often the result of more than one charge, as seen in Sample Problem D. Field lines make it easier to visualize the net field at each point.

The number of field lines is proportional to the electric field strength

By convention, electric field lines are drawn so that the electric field vector, **E,** is tangent to the lines at each point. Further, the number of lines per unit area through a surface perpendicular to the lines is proportional to the strength of the electric field in a given region. Thus, E is stronger where the field lines are close together and weaker where they are far apart.

Figure 9(a) shows some representative electric field lines for a positive point charge. Note that this two-dimensional drawing contains only the field lines that lie in the plane containing the point charge. The lines are actually directed outward radially from the charge in all directions, somewhat like quills radiate from the body of a porcupine. Because a positive test charge placed in this field would be repelled by the positive charge q, the lines are directed away from the positive charge, extending to infinity. Similarly, the electric field lines for a single negative point charge, which begin at infinity, are directed inward toward the charge, as shown in **Figure 9(b).** Note that the lines are closer together as they get near the charge, indicating that the strength of the field is increasing. This is consistent with our equation for electric field strength, which is inversely proportional to distance squared. **Figure 9(c)** shows grass seeds in an insulating liquid. When a small charged conductor is placed in the center, these seeds align with the electric field produced by the charged body.

The rules for drawing electric field lines are summarized in **Table 4.** Note that no two field lines from the same field can cross one another. The reason is that at every point in space, the electric field vector points in a single direction and any field line at that point must also point in that direction.

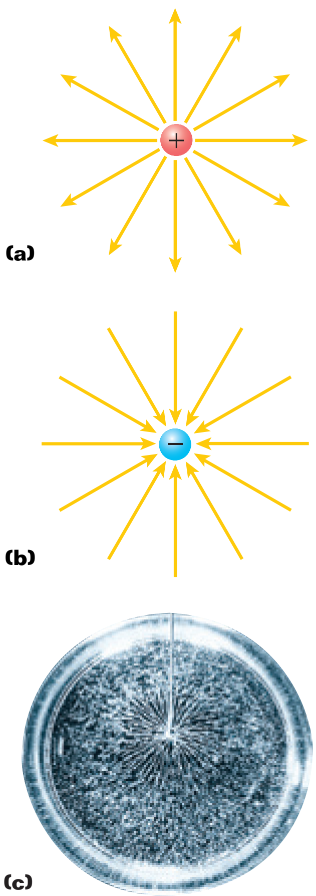


Figure 9
The diagrams **(a)** and **(b)** show some representative electric field lines for a positive and a negative point charge. In **(c),** grass seeds align with a similar field produced by a charged body.

Table 4 Rules for Drawing Electric Field Lines

The lines must begin on positive charges or at infinity and must terminate on negative charges or at infinity.
The number of lines drawn leaving a positive charge or approaching a negative charge is proportional to the magnitude of the charge.
No two field lines from the same field can cross each other.

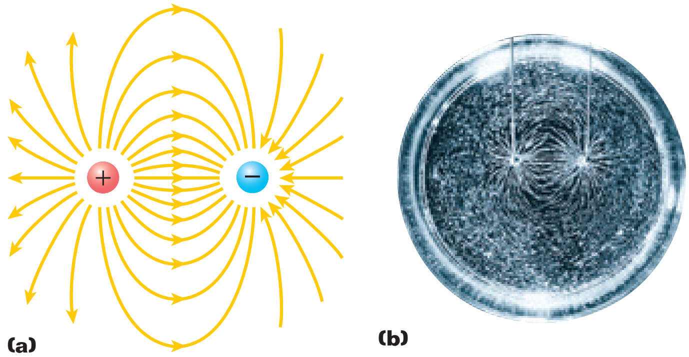


Figure 10
(a) This diagram shows the electric field lines for two equal and opposite point charges. Note that the number of lines leaving the positive charge equals the number of lines terminating on the negative charge. **(b)** In this photograph, grass seeds in an insulating liquid align with a similar electric field produced by two oppositely charged conductors.

Figure 10 shows the electric field lines for two point charges of equal magnitudes but opposite signs. This charge configuration is called an *electric dipole.* In this case, the number of lines that begin at the positive charge must equal the number of lines that terminate on the negative charge. At points very near the charges, the lines are nearly radial. The high density of lines between the charges indicates a strong electric field in this region.

In electrostatic spray painting, field lines between a negatively charged spray gun and a positively charged target object are similar to those shown in **Figure 10.** As you can see, the field lines suggest that paint droplets that narrowly miss the target object still experience a force directed toward the object, sometimes causing them to wrap around from behind and hit it. This does happen and increases the efficiency of an electrostatic spray gun.

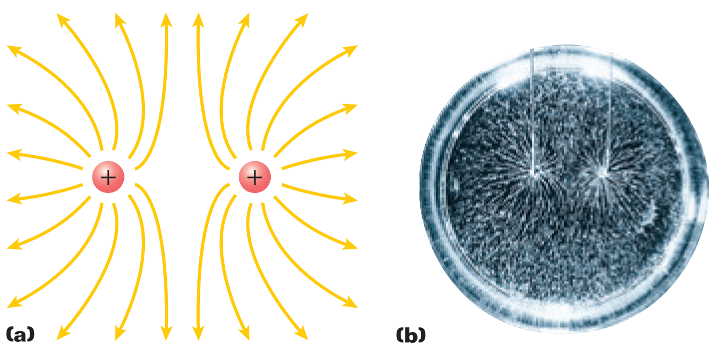


Figure 11
(a) This diagram shows the electric field lines for two positive point charges. **(b)** The photograph shows the analogous case for grass seeds in an insulating liquid around two conductors with the same charge.

Figure 11 shows the electric field lines in the vicinity of two equal positive point charges. Again, close to either charge, the lines are nearly radial. The same number of lines emerges from each charge because the charges are equal in magnitude. At great distances from the charges, the field approximately equals that of a single point charge of magnitude $2q$.

Finally, **Figure 12** is a sketch of the electric field lines associated with a positive charge $+2q$ and a negative charge $-q$. In this case, the number of lines leaving the charge $+2q$ is twice the number terminating on the charge $-q$. Hence, only half the lines that leave the positive charge end at the negative charge. The remaining half terminate at infinity. At distances that are great compared with the separation between the charges, the pattern of electric field lines is equivalent to that of a single charge, $+q$.

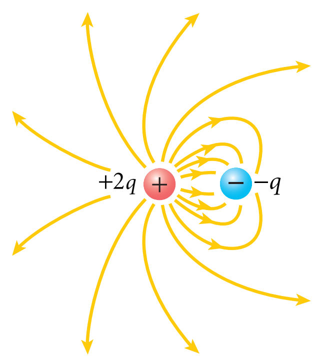


Figure 12
In this case, only half the lines originating from the positive charge terminate on the negative charge because the positive charge is twice as great as the negative charge.

CONDUCTORS IN ELECTROSTATIC EQUILIBRIUM

A good electric conductor, such as copper, contains charges (electrons) that are only weakly bound to the atoms in the material and are free to move about within the material. When no net motion of charge is occurring within a conductor, the conductor is said to be in *electrostatic equilibrium.* As we shall see, such a conductor that is isolated has the four properties summarized in **Table 5.**

The first property, which states that the electric field is zero inside a conductor in electrostatic equilibrium, can be understood by examining what would happen if this were not true. If there were an electric field inside a conductor, the free charges would move and a flow of charge, or current, would be created. However, if there were a net movement of charge, the conductor would no longer be in electrostatic equilibrium.

Table 5 Conductors in Electrostatic Equilibrium

The electric field is zero everywhere inside the conductor.
Any excess charge on an isolated conductor resides entirely on the conductor's outer surface.
The electric field just outside a charged conductor is perpendicular to the conductor's surface.
On an irregularly shaped conductor, charge tends to accumulate where the radius of curvature of the surface is smallest, that is, at sharp points.

The fact that any excess charge resides on the outer surface of the conductor is a direct result of the repulsion between like charges described by Coulomb's law. If an excess of charge is placed inside a conductor, the repulsive forces arising between the charges force them as far apart as possible, causing them to quickly migrate to the surface.

We can understand why the electric field just outside a conductor must be perpendicular to the conductor's surface by considering what would happen if this were not true. If the electric field were *not* perpendicular to the surface, the field would have a component along the surface. This would cause the free negative charges within the conductor to move on the surface of the conductor. But if the charges moved, a current would be created, and there would no longer be electrostatic equilibrium. Hence, **E** must be perpendicular to the surface.

To see why charge tends to accumulate at sharp points, consider a conductor that is fairly flat at one end and relatively pointed at the other. Any excess charge placed on the object moves to its surface. **Figure 13** shows the forces between two charges at each end of such an object. At the flatter end, these forces are predominantly directed parallel to the surface. Thus, the charges move apart until repulsive forces from other nearby charges create a state of equilibrium.

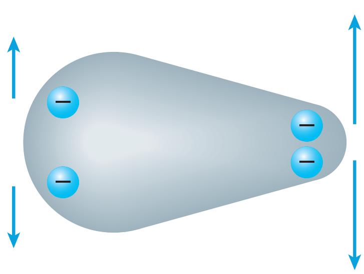
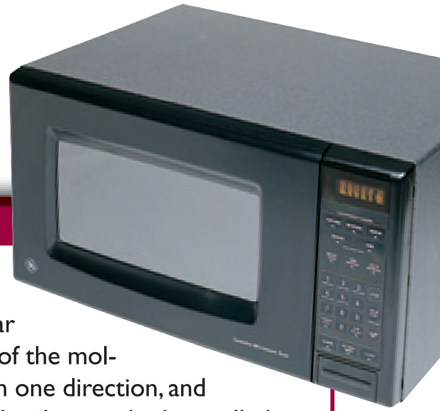


Figure 13
When one end of a conductor is more pointed than the other, excess charge tends to accumulate at the sharper end, resulting in a larger charge per unit area and therefore a larger repulsive electric force between charges at this end.

At the sharp end, however, the forces of repulsion between two charges are directed predominantly perpendicular to the surface. As a result, there is less tendency for the charges to move apart along the surface and the amount of charge per unit area is greater than at the flat end. The cumulative effect of many such outward forces from nearby charges at the sharp end produces a large electric field directed away from the surface.

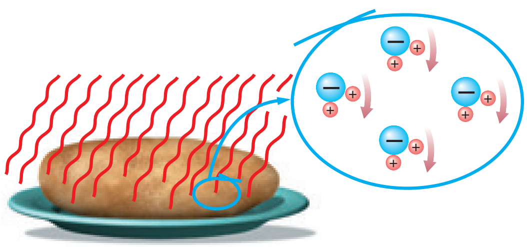
THE INSIDE STORY ON MICROWAVE OVENS



It would be hard to find a town in America that does not have a microwave oven. Most homes, convenience stores, and restaurants have this marvelous invention that somehow heats only the soft parts of the food and leaves the inorganic and hard materials, like ceramic and the surfaces of bone, at approximately the same temperature. A neat trick, indeed, but how is it done?

Microwave ovens take advantage of a property of water molecules called *bipolarity.* Water molecules are considered bipolar because each molecule has a positive and a negative end. In other words, more of the electrons in these molecules are at one end of the molecule than the other.

Because microwaves are a high-frequency form of electromagnetic radiation, they supply an electric field that changes polarity billions of times a second. As this electric field passes a bipolar molecule, the positive side of the molecule experiences a force in one direction, and the negative side of the molecule is pushed or pulled in the other direction. When the field changes polarity, the directions of these forces are reversed. Instead of tearing apart, the molecules swing around and line up with the electric field.



As the bipolar molecules swing around, they rub against one another, producing friction. This friction in turn increases the internal energy of the food. Energy is transferred to the food by radiation (the microwaves) as opposed to conduction from hot air, as in a conventional oven.

Depending on the microwave oven's power and design, this rotational motion can generate up to about 3 J of internal energy each second in 1 g of water. At this rate, a top-power microwave oven can boil a cup (250 mL) of water in 2 min using about 0.033 kW•h of electricity.

Items such as dry plates and the air in the oven are unaffected by the fluctuating electric field because they are not polarized. Because energy is not wasted on heating these nonpolar items, the microwave oven cooks food faster and more efficiently than other ovens.

SECTION REVIEW

1. Find the electric field at a point midway between two charges of $+40.0 \times 10^{-9}$ C and $+60.0 \times 10^{-9}$ C separated by a distance of 30.0 cm.

2. Two point charges are a small distance apart.

a. Sketch the electric field lines for the two if one has a charge four times that of the other and if both charges are positive.

b. Repeat **(a),** but assume both charges are negative.

3. Interpreting Graphics **Figure 14** shows the electric field lines for two point charges separated by a small distance.

a. Determine the ratio q_1/q_2.

b. What are the signs of q_1 and q_2?

4. Critical Thinking Explain why you're more likely to get a shock from static electricity by touching a metal object with your finger instead of with your entire hand.

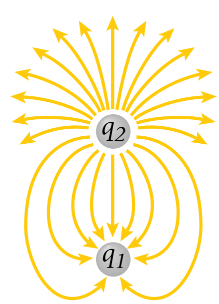


Figure 14

CHAPTER 16 Highlights

KEY TERMS

electrical conductor (p. 561)

electrical insulator (p. 561)

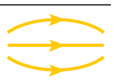
induction (p. 562)

electric field (p. 572)

PROBLEM SOLVING

See **Appendix D: Equations** for a summary of the equations introduced in this chapter. If you need more problem-solving practice, see **Appendix I: Additional Problems.**

Diagram Symbols

Positive charge	$+q$
Negative charge	$-q$
Electric field vector	 **E**
Electric field lines	

KEY IDEAS

Section 1 Electric Charge

- There are two kinds of electric charge: positive and negative. Like charges repel, and unlike charges attract.
- Electric charge is conserved.
- The fundamental unit of charge, *e*, is the magnitude of the charge of a single electron or proton.
- Conductors and insulators can be charged by contact. Conductors can also be charged by induction. A surface charge can be induced on an insulator by polarization.

Section 2 Electric Force

- According to Coulomb's law, the electric force between two charges is proportional to the magnitude of each of the charges and inversely proportional to the square of the distance between them.
- The electric force is a field force.
- The resultant electric force on any charge is the vector sum of the individual electric forces on that charge.

Section 3 The Electric Field

- An electric field exists in the region around a charged object.
- Electric field strength depends on the magnitude of the charge producing the field and the distance between that charge and a point in the field.
- The direction of the electric field vector, **E,** is the direction in which an electric force would act on a positive test charge.
- Field lines are tangent to the electric field vector at any point, and the number of lines is proportional to the magnitude of the field strength.

Variable Symbols

Quantities		Units		Conversions
$F_{electric}$	electric force	N	newtons	$= kg \bullet m/s^2$
q	charge	C e	coulomb (SI unit of charge) fundamental unit of charge	$= 6.3 \times 10^{18}\ e$ $= 1.60 \times 10^{-19}$ C
k_C	Coulomb constant	$N \bullet \frac{m^2}{C^2}$	newtons $\times \frac{\text{meters}^2}{\text{coulombs}^2}$	$= 8.99 \times 10^9\ N \bullet m^2$
E	electric field strength	N/C	newtons/coulomb	

CHAPTER 16 Review

ELECTRIC CHARGE

Review Questions

1. How are conductors different from insulators?

2. When a conductor is charged by induction, is the induced surface charge on the conductor the same or opposite the charge of the object inducing the surface charge?

3. A negatively charged balloon has 3.5 μC of charge. How many excess electrons are on this balloon?

Conceptual Questions

4. Would life be different if the electron were positively charged and the proton were negatively charged? Explain your answer.

5. Explain from an atomic viewpoint why charge is usually transferred by electrons.

6. Because of a higher moisture content, air is a better conductor of charge in the summer than in the winter. Would you expect the shocks from static electricity to be more severe in summer or winter? Explain your answer.

7. A balloon is negatively charged by rubbing and then clings to a wall. Does this mean that the wall is positively charged?

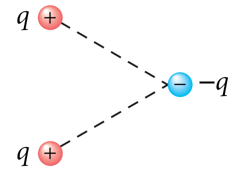
8. Which effect proves more conclusively that an object is charged, attraction to or repulsion from another object? Explain.

ELECTRIC FORCE

Review Questions

9. What determines the direction of the electric force between two charges?

10. In which direction will the electric force from the two equal positive charges move the negative charge shown below?



11. The gravitational force is always attractive, while the electric force is both attractive and repulsive. What accounts for this difference?

12. When more than one charged object is present in an area, how can the total electric force on one of the charged objects be predicted?

13. Identify examples of electric forces in everyday life.

Conceptual Questions

14. According to Newton's third law, every action has an equal and opposite reaction. When a comb is charged and held near small pieces of paper, the comb exerts an electric force on the paper pieces and pulls them toward it. Why don't you observe the comb moving toward the paper pieces as well?

Practice Problems

For problems 15–17, see Sample Problem A.

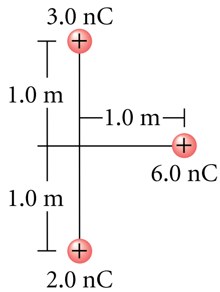
15. At the point of fission, a nucleus of ^{235}U that has 92 protons is divided into two smaller spheres, each of which has 46 protons and a radius of 5.90×10^{-15} m. What is the magnitude of the repulsive force pushing these two spheres apart?

16. What is the electric force between a glass ball that has +2.5 μC of charge and a rubber ball that has −5.0 μC of charge when they are separated by a distance of 5.0 cm?

17. An alpha particle (charge = $+2.0e$) is sent at high speed toward a gold nucleus (charge = $+79e$). What is the electric force acting on the alpha particle when the alpha particle is 2.0×10^{-14} m from the gold nucleus?

For problems 18–19, see Sample Problem B.

18. Three positive point charges of 3.0 nC, 6.0 nC, and 2.0 nC, respectively, are arranged in a triangular pattern, as shown at right. Find the magnitude and direction of the electric force acting on the 6.0 nC charge.



19. Two positive point charges, each of which has a charge of 2.5×10^{-9} C, are located at $y = +0.50$ m and $y = -0.50$ m. Find the magnitude and direction of the resultant electric force acting on a charge of 3.0×10^{-9} C located at $x = 0.70$ m.

For problems 20–21, see Sample Problem C.

20. Three point charges lie in a straight line along the y-axis. A charge of $q_1 = -9.0\ \mu C$ is at $y = 6.0$ m, and a charge of $q_2 = -8.0\ \mu C$ is at $y = -4.0$ m. The net electric force on the third point charge is zero. Where is this charge located?

21. A charge of +3.5 nC and a charge of +5.0 nC are separated by 40.0 cm. Find the equilibrium position for a −6.0 nC charge.

THE ELECTRIC FIELD

Review Questions

22. What is an electric field?

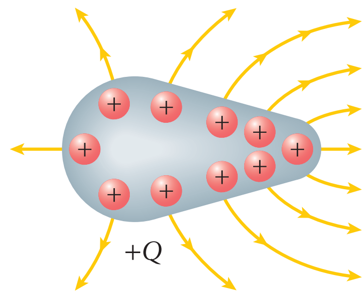
23. Show that the definition of electric field strength ($E = F_{electric}/q_0$) is equivalent to the equation $E = k_C q/r^2$ for point charges.

24. As you increase the potential on an irregularly shaped conductor, a bluish purple glow called a *corona* forms around a sharp end sooner than around a smoother end. Explain why.

25. Draw some representative electric field lines for two charges of $+q$ and $-3q$ separated by a small distance.

26. When electric field lines are being drawn, what determines the number of lines originating from a charge? What determines whether the lines originate from or terminate on a charge?

27. Consider the electric field lines in the figure below.
   a. Where is charge density the highest? Where is it the lowest?
   b. If an opposite charge were brought into the vicinity, where would charge on the pear-shaped object "leak off" most readily?



28. Do electric field lines actually exist?

Conceptual Questions

29. When defining the electric field, why must the magnitude of the test charge be very small?

30. Why can't two field lines from the same field cross one another?

31. A "free" electron and "free" proton are placed in an identical electric field. Compare the electric force on each particle. How do their accelerations compare?

Practice Problems

For problems 32–33, see Sample Problem D.

32. Find the electric field at a point midway between two charges of $+30.0 \times 10^{-9}$ C and $+60.0 \times 10^{-9}$ C separated by a distance of 30.0 cm.

33. A $+5.7\ \mu C$ point charge is on the x-axis at $x = -3.0$ m, and a $+2.0\ \mu C$ point charge is on the x-axis at $x = +1.0$ m. Determine the net electric field (magnitude and direction) on the y-axis at $y = +2.0$ m.

MIXED REVIEW

34. Calculate the net charge on a substance consisting of a combination of 7.0×10^{13} protons and 4.0×10^{13} electrons.

35. An electron moving through an electric field experiences an acceleration of 6.3×10^3 m/s^2.

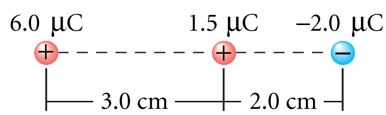
a. Find the electric force acting on the electron.
b. What is the strength of the electric field?

36. One gram of copper has 9.48×10^{21} atoms, and each copper atom has 29 electrons.

a. How many electrons are contained in 1.00 g of copper?
b. What is the total charge of these electrons?

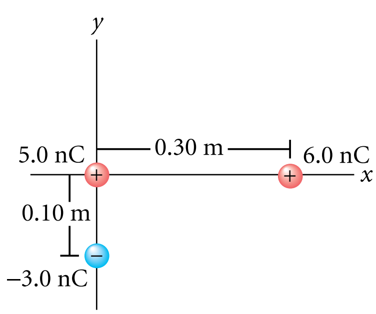
37. Consider three charges arranged as shown below.

a. What is the electric field strength at a point 1.0 cm to the left of the middle charge?
b. What is the magnitude of the force on a −2.0 µC charge placed at this point?



38. Consider three charges arranged in a triangle as shown below.

a. What is the net electric force acting on the charge at the origin?
b. What is the net electric field at the position of the charge at the origin?



39. Sketch the electric field pattern set up by a positively charged hollow conducting sphere. Include regions both inside and outside the sphere.

40. The moon ($m = 7.36 \times 10^{22}$ kg) is bound to Earth ($m = 5.98 \times 10^{24}$ kg) by gravity. If, instead, the force of attraction were the result of each having a charge of the same magnitude but opposite in sign, find the quantity of charge that would have to be placed on each to produce the required force.

41. Two small metallic spheres, each with a mass of 0.20 g, are suspended as pendulums by light strings from a common point. They are given the same electric charge, and the two come to equilibrium when each string is at an angle of 5.0° with the vertical. If the string is 30.0 cm long, what is the magnitude of the charge on each sphere?

42. What are the magnitude and the direction of the electric field that will balance the weight of an electron? What are the magnitude and direction of the electric field that will balance the weight of a proton?

43. An electron and a proton are each placed at rest in an external uniform electric field of magnitude 520 N/C. Calculate the speed of each particle after 48 ns.

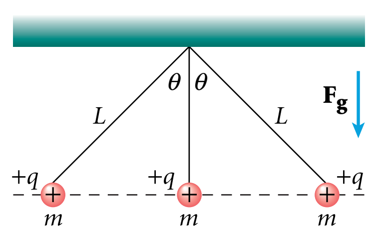
44. A Van de Graaff generator is charged so that the magnitude of the electric field at its surface is 3.0×10^4 N/C.

a. What is the magnitude of the electric force on a proton released at the surface of the generator?
b. Find the proton's acceleration at this instant.

45. Thunderstorms can have an electric field of up to 3.4×10^5 N/C. What is the magnitude of the electric force on an electron in such a field?

46. An object with a net charge of 24 µC is placed in a uniform electric field of 610 N/C, directed vertically. What is the mass of this object if it floats in this electric field?

47. Three identical point charges, with mass $m = 0.10$ kg, hang from three strings, as shown below. If $L = 30.0$ cm and $\theta = 45°$, what is the value of q?



48. In a laboratory experiment, five equal negative point charges are placed symmetrically around the circumference of a circle of radius *r*. Calculate the electric field at the center of the circle.

49. An electron and a proton both start from rest and from the same point in a uniform electric field of 370.0 N/C. How far apart are they 1.00 μs after they are released? Ignore the attraction between the electron and the proton. (Hint: Imagine the experiment performed with the proton only, and then repeat with the electron only.)

50. An electron is accelerated by a constant electric field of magnitude 300.0 N/C.

a. Find the acceleration of the electron.

b. Find the electron's speed after 1.00×10^{-8} s, assuming it starts from rest.

51. If the electric field strength is increased to about 3.0×10^6 N/C, air "breaks down" and loses its insulating quality. Under these conditions, sparking results.

a. What acceleration does an electron experience when the electron is placed in such an electric field?

b. If the electron starts from rest when it is placed in an electric field under these conditions, in what distance does it acquire a speed equal to 10.0 percent of the speed of light?

c. What acceleration does a proton experience when the proton is placed in such an electric field?

52. Each of the protons in a particle beam has a kinetic energy of 3.25×10^{-15} J. What are the magnitude and direction of the electric field that will stop these protons in a distance of 1.25 m?

Graphing Calculator Practice

Coulomb's Law

One of the most important and fundamental laws of physics—and of all science—is Coulomb's law. As you learned earlier in this chapter, this law states that the electric force, $F_{electric}$, between two charges, q_1 and q_2, which are separated by a distance, *r*, is given by the following equation.

$$F_{electric} = k_C\left(\frac{q_1q_2}{r^2}\right)$$

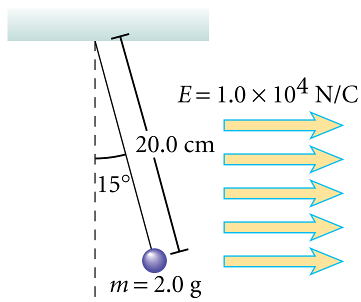
In this graphing calculator activity, you will enter the charges and will observe a graph of electric force versus distance. By analyzing graphs for various sets of charges (positive with positive, negative with negative, and positive with negative), you will better understand Coulomb's law and how charge and distance affect electric force.

Visit go.hrw.com and enter the keyword **HF6ELFX** to find this graphing calculator activity. Refer to **Appendix B** for instructions on downloading the program for this activity.

53. A small 2.0 g plastic ball is suspended by a 20.0 cm string in a uniform electric field of 1.0×10^4 N/C, as shown below.

a. Is the ball's charge positive or negative?

b. If the ball is in equilibrium when the string makes a 15° angle with the vertical as indicated, what is the net charge on the ball?



54. A constant electric field directed along the positive x-axis has a strength of 2.0×10^3 N/C.

a. Find the electric force exerted on a proton by the field.

b. Find the acceleration of the proton.

c. Find the time required for the proton to reach a speed of 1.00×10^6 m/s, assuming it starts from rest.

55. Consider an electron that is released from rest in a uniform electric field.

a. If the electron is accelerated to 1.0 percent of the speed of light after traveling 2.0 mm, what is the strength of the electric field?

b. What speed does the electron have after traveling 4.0 mm from rest?

56. A DNA molecule (deoxyribonucleic acid) is 2.17 µm long. The ends of the molecule become singly ionized so that there is -1.60×10^{-19} C on one end and $+1.60 \times 10^{-19}$ C on the other. The helical molecule acts as a spring and compresses 1.00 percent upon becoming charged. Find the effective spring constant of the molecule.

Alternative Assessment

1. A metal can is placed on a wooden table. If a positively charged ball suspended by a thread is brought close to the can, the ball will swing toward the can, make contact, then move away. Explain why this happens and predict whether the ball is likely to make contact a second time. Sketch diagrams showing the charges on the ball and on the can at each phase. How can you test whether your explanation is correct? If your teacher approves of your plan, try testing your explanation.

2. The common copying machine was designed in the 1960s, after the American inventor Chester Carlson developed a practical device for attracting carbon-black to paper using localized electrostatic action. Research how this process works and determine why the last copy made when several hundred copies are made can be noticeably less sharp than the first copy. Create a report, poster, or brochure for office workers containing tips for using copiers.

3. Research how an electrostatic precipitator works to remove smoke and dust particles from the polluting emissions of fuel-burning industries. Find out what industries in your community use precipitators. What are their advantages and costs? What alternatives are available? Summarize your findings in a brochure, poster, or chart.

4. Imagine you are a member of a research team interested in lightning and you are preparing a grant proposal. Research information about the frequency, location, and effects of thunderstorms. Write a proposal that includes background information, research questions, a description of necessary equipment, and recommended locations for data collection.

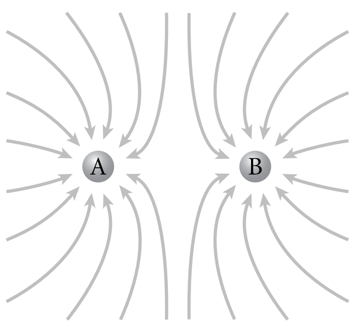
5. Electric force is also known as the *Coulomb force.* Research the historical development of the concept of electric force. Describe the work of Coulomb and other scientists such as Priestley, Cavendish, Benjamin Franklin, and Michael Faraday.

Standardized Test Prep

MULTIPLE CHOICE

1. In which way is the electric force similar to the gravitational force?
   - **A.** Electric force is proportional to the mass of the object.
   - **B.** Electric force is similar in strength to gravitational force.
   - **C.** Electric force is both attractive and repulsive.
   - **D.** Electric force decreases in strength as the distance between the charges increases.

2. What must the charges be for A and B in the figure below so that they produce the electric field lines shown?
   - **F.** A and B must both be positive.
   - **G.** A and B must both be negative.
   - **H.** A must be negative, and B must be positive.
   - **J.** A must be positive, and B must be negative.



3. Which activity does not produce the same results as the other three?
   - **A.** sliding over a plastic-covered automobile seat
   - **B.** walking across a woolen carpet
   - **C.** scraping food from a metal bowl with a metal spoon
   - **D.** brushing dry hair with a plastic comb

4. By how much does the electric force between two charges change when the distance between them is doubled?
   - **F.** 4
   - **G.** 2
   - **H.** $\frac{1}{2}$
   - **J.** $\frac{1}{4}$

Use the passage below to answer questions 5–6.

A negatively charged object is brought close to the surface of a conductor, whose opposite side is then grounded.

5. What is this process of charging called?
   - **A.** charging by contact
   - **B.** charging by induction
   - **C.** charging by conduction
   - **D.** charging by polarization

6. What kind of charge is left on the conductor's surface?
   - **F.** neutral
   - **G.** negative
   - **H.** positive
   - **J.** both positive and negative

Use the graph on the next page to answer questions 7–10. The graph shows the electric field strength at different distances from the center of the charged conducting sphere of a Van de Graaff generator.

7. What is the electric field strength 2.0 m from the center of the conducting sphere?
   - **A.** 0 N/C
   - **B.** 5.0×10^2 N/C
   - **C.** 5.0×10^3 N/C
   - **D.** 7.2×10^3 N/C

8. What is the strength of the electric field at the surface of the conducting sphere?

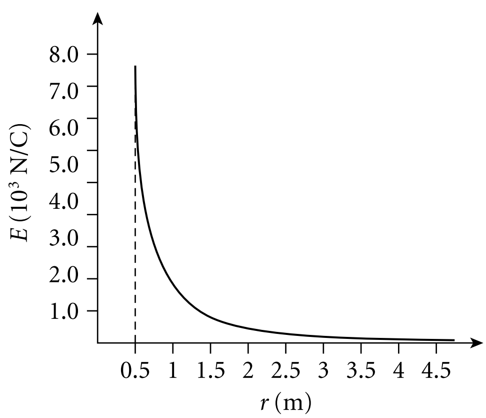
F. 0 N/C
G. 1.5×10^2 N/C
H. 2.0×10^2 N/C
J. 7.2×10^3 N/C

9. What is the strength of the electric field inside the conducting sphere?

A. 0 N/C
B. 1.5×10^2 N/C
C. 2.0×10^2 N/C
D. 7.2×10^3 N/C

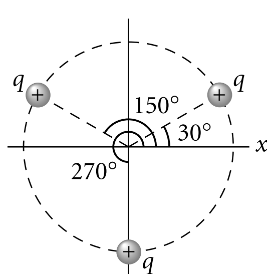
10. What is the radius of the conducting sphere?

F. 0.5 m
G. 1.0 m
H. 1.5 m
J. 2.0 m



SHORT RESPONSE

11. Three identical charges ($q = +5.0$ mC) are along a circle with a radius of 2.0 m at angles of 30°, 150°, and 270°, as shown in the figure below. What is the resultant electric field at the center?



12. If a suspended object is attracted to another object that is charged, can you conclude that the suspended object is charged? Briefly explain your answer.

13. One gram of hydrogen contains 6.02×10^{23} atoms, each with one electron and one proton. Suppose that 1.00 g of hydrogen is separated into protons and electrons, that the protons are placed at Earth's north pole, and that the electrons are placed at Earth's south pole. Assuming the radius of Earth to be 6.38×10^6 m, what is the magnitude of the resulting compressional force on Earth?

14. Air becomes a conductor when the electric field strength exceeds 3.0×10^6 N/C. Determine the maximum amount of charge that can be carried by a metal sphere 2.0 m in radius.

EXTENDED RESPONSE

Use the information below to answer questions 15–18.

A proton, which has a mass of 1.673×10^{-27} kg, accelerates from rest in a uniform electric field of 640 N/C. At some time later, its speed is 1.2×10^6 m/s.

15. What is the magnitude of the acceleration of the proton?

16. How long does it take the proton to reach this speed?

17. How far has it moved in this time interval?

18. What is its kinetic energy at the later time?

19. A student standing on a piece of insulating material places her hand on a Van de Graaff generator. She then turns on the generator. Shortly thereafter, her hairs stand on end. Explain how charge is or is not transferred in this situation, why the student is not shocked, and what causes her hairs to stand up after the generator is started.

Test TIP In problems for which resultant forces are asked, the solution can be made much easier by drawing a sketch of the situation described and seeing if a symmetrical arrangement of components, and thus a canceling of forces, exists.

CHAPTER 16

Skills Practice Lab Electrostatics

OBJECTIVES

- **Investigate** the use of an electroscope.
- **Use** an electroscope and other materials to analyze properties of static electricity.
- **Determine** the number of the kinds of electric charge.

MATERIALS LIST

- roll of cellophane tape
- wool pad
- 2 polystyrene rods
- 2 PVC rods
- demonstration capacitor
- electroscope
- flint glass rod
- insulated copper wire
- insulated wire with 2 alligator clips
- meterstick
- nylon cord
- silk cloth
- silk thread
- support stand with clamp
- suspension support for rod

When objects made of two different materials are rubbed together, electric charges accumulate on both objects. This phenomenon is known as *static electricity.* When an object has an electric charge, it attracts some things and repels others. The charges can also be transferred to some objects and not to others. In this experiment, you will develop charges on different objects and distinguish between the types of charges. You will also use an electroscope to examine the transfer of charges and the conductivity of different materials.

SAFETY

- **Put on goggles.**
- **Never put broken glass or ceramics in a regular waste container. Use a dustpan, brush, and heavy gloves to carefully pick up broken pieces and dispose of them in a container specifically provided for this purpose.**

PROCEDURE

Preparation

1. Read the entire lab, and plan what steps you will take.
2. If you are not using a datasheet provided by your teacher, prepare an observation table in your lab notebook with two wide columns. Label the columns *Experiment* and *Observation.* For each part of the lab, you will write a brief description of what you do in each step under *Experiment.* In the *Observation* column, record your observations of what happens.

Electric Charge

3. Cut four strips of cellophane tape 20 cm long. Fold over a tab at the end of each tape. Tape strips to the lab table, and label the strips *A, B, C,* and *D* with a pencil.
4. Vigorously rub tapes A and B with a wool pad. Grasp the tabbed ends of A and B and carefully remove the tapes from the table. Slowly bring the tapes close together, but do not allow them to touch. Observe how they affect one another. Record your observations in your lab notebook. Carefully place tapes A and B back on the lab table.

5. Carefully remove tape C from the lab table. Tape it firmly down on top of tape D. Carefully remove tapes C and D together from the lab table. Quickly separate them, being careful not to tangle the tapes. Bring the tapes close together—but not touching—and observe how they affect one another. Record your observations in your lab notebook. Place tape D back on the lab table, and place tape C down on top of tape D.

6. Vigorously rub tape A with a wool pad again. Grasp tape A by the tab and carefully remove it from the table. Remove C and D together from the table. Quickly pull C and D apart. Bring C close to tape A, but do not let them touch. Observe how they affect each other. Move C away, and bring D close to tape A. Record your observations in your lab notebook. Throw the four tapes away.

7. Tape a meterstick flat on the surface of the table so that the end of the meterstick extends over the edge of the table. Take another 20 cm long piece of tape, fold a tab on one end, and tape it down on the table. Vigorously rub the tape with a wool pad. Grasp the tab, and carefully remove the tape. Attach the tape to the end of the meterstick so that the tape freely hangs straight down.

8. Rub a polystyrene rod with the wool pad. Bring the rod near the end of the tape that is hanging down, and observe the effect on the tape. Record your observations in your lab notebook. Throw away the tape, and remove the meterstick from the tabletop.

9. Tie the suspension support securely to a string, and suspend the string from the support stand and clamp. Attach a polystyrene rod to the support, and rub the rod with the wool pad. Rub a second polystyrene rod with wool, and bring this rod near one end of the suspended rod. Observe what happens, and record your observations in your lab notebook.

10. Rub the PVC rod with the wool pad, and bring the rod near one end of the suspended polystyrene rod, as you see in **Figure 1.** Observe what happens, and record your observations.

11. Suspend a glass rod on the support, and rub the rod with silk. Rub the PVC rod with the wool pad, and bring the rod near one end of the glass rod. Observe what happens, and record your observations.

12. Suspend a PVC rod on the support, and rub the rod with the wool pad. Rub another PVC rod with wool, and bring the rod near one end of the suspended PVC rod. Observe what happens, and record your observations.

Figure 1
Step 9: Suspend the rod securely so that it hangs freely.
Step 10: Charge the rod by rubbing it vigorously with the wool pad. Bring the charged rod near one end of the suspended rod.

Charging an Electroscope by Conduction and Induction

13. Charge a polystyrene rod with a wool cloth, and touch it briefly against the knob of the electroscope. Record your observations.

14. Touch the knob of the electroscope with your hand. Observe what happens.

15. Bring a charged polystyrene rod near, but not touching, the electroscope knob. Observe what happens.

16. Continue holding the polystyrene rod near the electroscope knob. Briefly touch the knob of the electroscope with your finger. Observe what happens. Remove the rod, and observe what happens.

17. Discharge the electroscope by connecting a wire from it to a grounded object. Your teacher will tell you where to connect the wire.

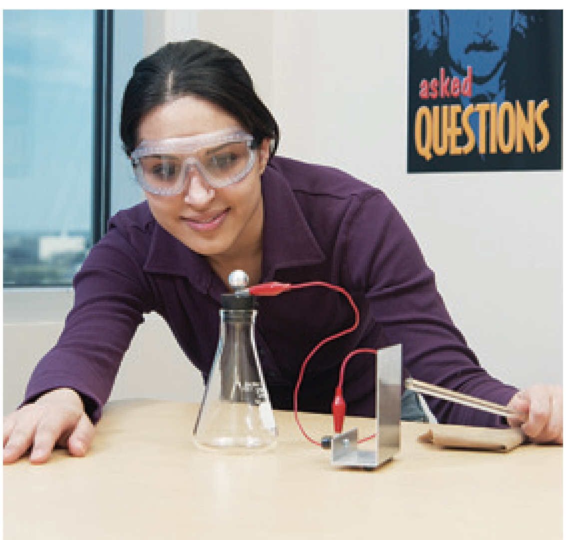
18. Charge a glass rod with a silk cloth, and repeat the procedure in steps 13–17 using the glass rod instead of the polystyrene rod.

Conductors, Insulators, and Capacitors

19. Set up the apparatus as shown in **Figure 2.** (You will not use the second capacitor plate until step 22.) The insulated wire has an alligator clip at each end. One alligator clip connects to the rod beneath the ball on the electroscope. Run the insulated copper wire from the other alligator clip to one of the plates of the demonstration capacitor.

20. Follow the procedure in steps 13–17, but this time bring the rod near the capacitor plate. Observe what happens to the leaves of the electroscope when the rod is brought near the capacitor plate. Record your observations.

Figure 2
Step 20: Use insulated wire to connect the electroscope to one plate of the capacitor. Touch the charged rod to the plate.



21. Replace the copper wire with a piece of thread. Follow the procedure in steps 13–17, but this time bring the rod near the capacitor plate. Observe what happens to the leaves of the electroscope when the rod is brought near the capacitor plate. Record your observations.

22. Connect the rod beneath the knob of the electroscope to one plate of the demonstration capacitor with a short piece of copper wire. Touch the charged polystyrene rod to the plate, and observe what happens to the leaves of the electroscope. Bring the second plate of the capacitor near, but not touching, the first. Observe what happens, and record your observations in your notebook.

23. Remove the second capacitor plate. Observe what happens. Record your observations in your notebook.

24. Bring the second plate near the first again. Using both capacitor plates, try to cause the same result as you obtained using only one plate.

25. Clean up your work area. Put equipment away safely so that it is ready to be used again. Recycle or dispose of used materials as directed by your teacher.

ANALYSIS

1. Classifying Use examples from your observations to explain your answers to the following questions. Assume that the polystyrene rod takes a negative charge when it is rubbed with wool. To answer these questions, assume that like charges repel one another and unlike charges attract one another.

a. What type of charge is on tape A?

b. What type of charge is on tape B?

c. Are the charges on C and D the same?

d. Are the charges on C or D the same as the charges on A or B?

e. What type of charge is on the charged suspended glass rod? Is the charge on the suspended glass rod the same as or different from the charge on tape A?

f. What type of charge is on the charged suspended polystyrene rod?

g. What type of charge is on the second charged polystyrene rod?

h. What type of charge is on the charged suspended PVC rod?

2. Describing Events Use your observations to answer the following:

a. After you touch the knob of the electroscope with your hand, what type of charge is on the electroscope? Explain how your observations support this conclusion.

b. When the charged polystyrene rod is used to charge an electroscope by induction, what type of charge is on the electroscope?

c. What type of charge is on the electroscope when it is charged by induction using the charged glass rod?

3. Classifying Is copper a conductor or an insulator? Is silk a conductor or an insulator? Use your observations to support your answers.

CONCLUSIONS

4. Drawing Conclusions Based on your observations, how many types of charge are there? Explain how your observations support this conclusion.

5. Applying Conclusions Use your results to explain what a capacitor does.