CHAPTER 18
Static Electricity

Figure 18.1 This child’s hair contains an imbalance of electrical charge (commonly called *static electricity*), which causes it to stand on end. The sliding motion stripped electrons away from the child’s body, leaving him with an excess of positive charges, which repel each other along each strand of hair. (credit: Ken Bosma, Wikimedia Commons)

Chapter Outline

18.1 Electrical Charges, Conservation of Charge, and Transfer of Charge

18.2 Coulomb's law

18.3 Electric Field

18.4 Electric Potential

18.5 Capacitors and Dielectrics

INTRODUCTION You may have been introduced to static electricity like the child sliding down the slide in the opening photograph (Figure 18.1). The *zap* that he is likely to receive if he touches a playmate or parent tends to bring home the lesson. But static electricity is more than just fun and games—it is put to use in many industries. The forces between electrically charged particles are used in technologies such as printers, pollution filters, and spray guns used for painting cars and trucks. Static *electricity* is the study of phenomena that involve an imbalance of electrical charge. Although creating this imbalance typically requires moving charge around, once the imbalance is created, it often remains static for a long time. The study of charge in motion is called *electromagnetism* and will be covered in a later chapter. What is electrical charge, how is it associated with objects, and what forces does it create? These are just some of the questions that this chapter addresses.

18.1 Electrical Charges, Conservation of Charge, and Transfer of Charge

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe positive and negative electric charges
- Use conservation of charge to calculate quantities of charge transferred between objects
- Characterize materials as conductors or insulators based on their electrical properties
- Describe electric polarization and charging by induction

Section Key Terms

conduction	conductor	electron	induction
insulator	law of conservation of charge	polarization	proton

Electric Charge

You may know someone who has an *electric* personality, which usually means that other people are attracted to this person. This saying is based on electric charge, which is a property of matter that causes objects to attract or repel each other. Electric charge comes in two varieties, which we call *positive* and *negative.* Like charges repel each other, and unlike charges attract each other. Thus, two positive charges repel each other, as do two negative charges. A positive charge and a negative charge attract each other.

How do we know there are two types of electric charge? When various materials are rubbed together in controlled ways, certain combinations of materials always result in a net charge of one type on one material and a net charge of the opposite type on the other material. By convention, we call one type of charge positive and the other type negative. For example, when glass is rubbed with silk, the glass becomes positively charged and the silk negatively charged. Because the glass and silk have opposite charges, they attract one another like clothes that have rubbed together in a dryer. Two glass rods rubbed with silk in this manner will repel one another, because each rod has positive charge on it. Similarly, two silk cloths rubbed in this manner will repel each other, because both cloths have negative charge. Figure 18.2 shows how these simple materials can be used to explore the nature of the force between charges.

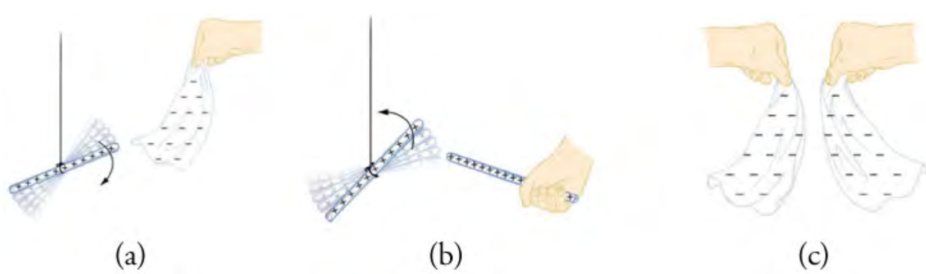

Figure 18.2 A glass rod becomes positively charged when rubbed with silk, whereas the silk becomes negatively charged. (a) The glass rod is attracted to the silk, because their charges are opposite. (b) Two similarly charged glass rods repel. (c) Two similarly charged silk cloths repel.

It took scientists a long time to discover what lay behind these two types of charges. The word *electric* itself comes from the Greek word *elektron* for amber, because the ancient Greeks noticed that amber, when rubbed by fur, attracts dry straw. Almost 2,000 years later, the English physicist William Gilbert proposed a model that explained the effect of electric charge as being due to a mysterious electrical fluid that would pass from one object to another. This model was debated for several hundred years, but it was finally put to rest in 1897 by the work of the English physicist J. J. Thomson and French physicist Jean Perrin. Along with many others, Thomson and Perrin were studying the mysterious *cathode rays* that were known at the time to consist of particles smaller than the smallest atom. Perrin showed that cathode rays actually carried negative electrical charge. Later, Thomson's work led him to declare, "I can see no escape from the conclusion that [cathode rays] are charges of negative electricity carried by particles of matter."

It took several years of further experiments to confirm Thomson's interpretation of the experiments, but science had in fact discovered the particle that carries the fundamental unit of negative electrical charge. We now know this particle as the **electron**.

Atoms, however, were known to be electrically neutral, which means that they carry the same amount of positive and negative charge, so their net charge is zero. Because electrons are negative, some other part of the atom must contain positive charge. Thomson put forth what is called the *plum pudding model*, in which he described atoms as being made of thousands of electrons swimming around in a nebulous mass of positive charge, as shown by the left-side image of Figure 18.3. His student, Ernest Rutherford, originally believed that this model was correct and used it (along with other models) to try to understand the results of his experiments bombarding gold foils with *alpha* particles (i.e., helium atoms stripped of their electrons). The results, however, did not confirm Thomson's model but rather destroyed it! Rutherford found that most of the space occupied by the gold atoms was actually empty and that almost all of the matter of each atom was concentrated into a tiny, extremely dense nucleus, as shown by the right-side image of Figure 18.3. The atomic nucleus was later found to contain particles called **protons**, each of which carries a unit of positive electric charge.[1]

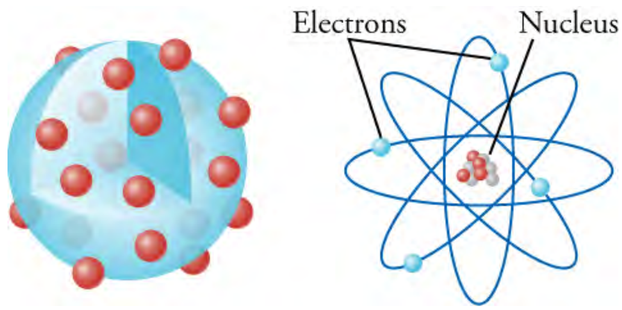

Figure 18.3 The left drawing shows Thompson's plum-pudding model, in which the electrons swim around in a nebulous mass of positive charge. The right drawing shows Rutherford's model, in which the electrons orbit around a tiny, massive nucleus. Note that the size of the nucleus is vastly exaggerated in this drawing. Were it drawn to scale with respect to the size of the electron orbits, the nucleus would not be visible to the naked eye in this drawing. Also, as far as science can currently detect, electrons are point particles, which means that they have no size at all!

Protons and electrons are thus the fundamental particles that carry electric charge. Each proton carries one unit of positive charge, and each electron carries one unit of negative charge. To the best precision that modern technology can provide, the charge carried by a proton is *exactly* the opposite of that carried by an electron. The SI unit for electric charge is the *coulomb* (abbreviated as "C"), which is named after the French physicist Charles Augustin de Coulomb, who studied the force between charged objects. The proton carries $+1.602 \times 10^{-19}\,\mathrm{C}$. and the electron carries $-1.602 \times 10^{-19}\,\mathrm{C}$, . The number *n* of protons required to make +1.00 C is

$$n = 1.00\ \mathrm{C} \times \frac{1\ \text{proton}}{1.602 \times 10^{-19}\,\mathrm{C}} = 6.25 \times 10^{18}\,\text{protons.} \tag{18.1}$$

The same number of electrons is required to make –1.00 C of electric charge. The fundamental unit of charge is often represented as *e*. Thus, the charge on a proton is *e*, and the charge on an electron is –*e*. Mathematically, $e = +1.602 \times 10^{-19}\,\mathrm{C}$.

LINKS TO PHYSICS

Measuring the Fundamental Electric Charge

The American physicist Robert Millikan (1868–1953) and his student Harvey Fletcher (1884–1981) were the first to make a relatively accurate measurement of the fundamental unit of charge on the electron. They designed what is now a classic

1Protons were later found to contain sub particles called *quarks*, which have fractional electric charge. But that is another story that we leave for subsequent physics courses.

experiment performed by students. The Millikan oil-drop experiment is shown in Figure 18.4. The experiment involves some concepts that will be introduced later, but the basic idea is that a fine oil mist is sprayed between two plates that can be charged with a known amount of opposite charge. Some oil drops accumulate some excess negative charge when being sprayed and are attracted to the positive charge of the upper plate and repelled by the negative charge on the lower plate. By tuning the charge on these plates until the weight of the oil drop is balanced by the electric forces, the net charge on the oil drop can be determined quite precisely.

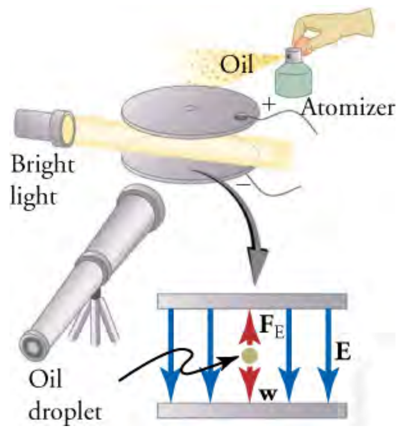

Figure 18.4 The oil-drop experiment involved spraying a fine mist of oil between two metal plates charged with opposite charges. By knowing the mass of the oil droplets and adjusting the electric charge on the plates, the charge on the oil drops can be determined with precision.

Millikan and Fletcher found that the drops would accumulate charge in discrete units of about $-1.59 \times 10^{-19}\,\mathrm{C}$, which is within 1 percent of the modern value of $-1.60 \times 10^{-19}\,\mathrm{C}$. Although this difference may seem quite small, it is actually five times greater than the possible error Millikan reported for his results!

Because the charge on the electron is a fundamental constant of nature, determining its precise value is very important for all of science. This created pressure on Millikan and others after him that reveals some equally important aspects of human nature.

First, Millikan took sole credit for the experiment and was awarded the 1923 Nobel Prize in physics for this work, although his student Harvey Fletcher apparently contributed in significant ways to the work. Just before his death in 1981, Fletcher divulged that Millikan coerced him to give Millikan sole credit for the work, in exchange for which Millikan promoted Fletcher's career at Bell Labs.

Another great scientist, Richard Feynman, points out that many scientists who measured the fundamental charge after Millikan were reluctant to report values that differed much from Millikan's value. History shows that later measurements slowly crept up from Millikan's value until settling on the modern value. Why did they not immediately find the error and correct the value, asks Feynman. Apparently, having found a value higher than the much-respected value found by Millikan, scientists would look for possible mistakes that might lower their value to make it agree better with Millikan's value. This reveals the important psychological weight carried by preconceived notions and shows how hard it is to refute them. Scientists, however devoted to logic and data they may be, are apparently just as vulnerable to this aspect of human nature as everyone else. The lesson here is that, although it is good to be skeptical of new results, you should not discount them just because they do not agree with conventional wisdom. If your reasoning is sound and your data are reliable, the conclusion demanded by the data must be seriously considered, even if that conclusion disagrees with the commonly accepted *truth*.

GRASP CHECK

Suppose that Millikan observed an oil drop carrying three fundamental units of charge. What would be the net charge on this oil drop?

a. -4.81×10^{-19} C
b. -1.602×10^{-19} C
c. 1.602×10^{-19} C
d. 4.81×10^{-19} C

Snap Lab

Like and Unlike Charges

This activity investigates the repulsion and attraction caused by static electrical charge.

- Adhesive tape
- Nonconducting surface, such as a plastic table or chair

Instructions

Procedure for Part (a)

1. Prepare two pieces of tape about 4 cm long. To make a handle, double over about 0.5 cm at one end so that the sticky side sticks together.
2. Attach the pieces of tape side by side onto a nonmetallic surface, such as a tabletop or the seat of a chair, as shown in Figure 18.5(a).
3. Peel off both pieces of tape and hang them downward, holding them by the handles, as shown in Figure 18.5(b). If the tape bends upward and sticks to your hand, try using a shorter piece of tape, or simply shake the tape so that it no longer sticks to your hand.
4. Now slowly bring the two pieces of tape together, as shown in Figure 18.5(c). What happens?

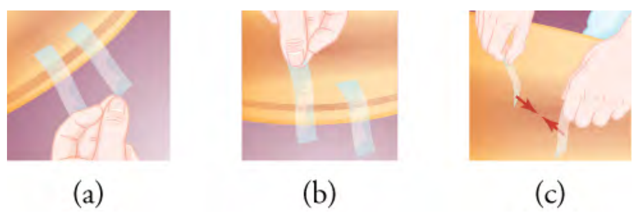

Figure 18.5

Procedure for Part (b)

5. Stick one piece of tape on the nonmetallic surface, and stick the second piece of tape on top of the first piece, as shown in Figure 18.6(a).
6. Slowly peel off the two pieces by pulling on the handle of the bottom piece.
7. Gently stroke your finger along the top of the second piece of tape (i.e., the nonsticky side), as shown in Figure 18.6(b).
8. Peel the two pieces of tape apart by pulling on their handles, as shown in Figure 18.6(c).
9. Slowly bring the two pieces of tape together. What happens?

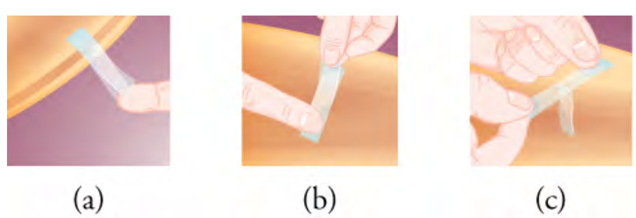

Figure 18.6

GRASP CHECK

In step 4, why did the two pieces of tape repel each other? In step 9, why did they attract each other?

a. Like charges attract, while unlike charges repel each other.
b. Like charges repel, while unlike charges attract each other.
c. Tapes having positive charge repel, while tapes having negative charge attract each other.
d. Tapes having negative charge repel, while tapes having positive charge attract each other.

Conservation of Charge

Because the fundamental positive and negative units of charge are carried on protons and electrons, we would expect that the total charge cannot change in any system that we define. In other words, although we might be able to move charge around, we cannot create or destroy it. This should be true provided that we do not create or destroy protons or electrons in our system. In the twentieth century, however, scientists learned how to create and destroy electrons and protons, but they found that charge is still conserved. Many experiments and solid theoretical arguments have elevated this idea to the status of a law. The **law of conservation of charge** says that electrical charge cannot be created or destroyed.

The law of conservation of charge is very useful. It tells us that the net charge in a system is the same before and after any interaction within the system. Of course, we must ensure that no external charge enters the system during the interaction and that no internal charge leaves the system. Mathematically, conservation of charge can be expressed as

$$q_{initial} = q_{final}. \tag{18.2}$$

where q_{initial} is the net charge of the system before the interaction, and q_{final}, is the net charge after the interaction.

WORKED EXAMPLE

What is the missing charge?

Figure 18.7 shows two spheres that initially have +4 C and +8 C of charge. After an interaction (which could simply be that they touch each other), the blue sphere has +10 C of charge, and the red sphere has an unknown quantity of charge. Use the law of conservation of charge to find the final charge on the red sphere.

Strategy

The net initial charge of the system is $q_{\text{initial}} = +4\text{ C} + 8\text{ C} = +12\text{ C}$. The net final charge of the system is $q_{\text{final}} = +10\text{ C} + q_{\text{red}}$, where q_{red} is the final charge on the red sphere. Conservation of charge tells us that $q_{\text{initial}} = q_{\text{final}}$, so we can solve for q_{red}.

Solution

Equating q_{initial} and q_{final} and solving for q_{red} gives

$$\begin{aligned} q_{\text{initial}} &= q_{\text{final}} \\ +12\text{ C} &= +10\text{ C} + q_{\text{red.}} \\ +2\text{ C} &= q_{\text{red.}} \end{aligned} \tag{18.3}$$

The red sphere has +2 C of charge.

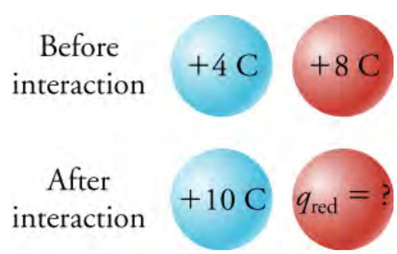

Figure 18.7 Two spheres, one blue and one red, initially have +4 C and +8 C of charge, respectively. After the two spheres interact, the blue sphere has a charge of +10 C. The law of conservation of charge allows us to find the final charge q_{red} on the red sphere.

Discussion

Like all conservation laws, conservation of charge is an accounting scheme that helps us keep track of electric charge.

Practice Problems

1. Which equation describes conservation of charge?
   a. $q_{\text{initial}} = q_{\text{final}} = \text{constant}$
   b. $q_{\text{initial}} = q_{\text{final}} = 0$
   c. $q_{\text{initial}} - q_{\text{final}} = 0$

d. $q_{\text{initial}}/q_{\text{final}} = \text{constant}$

2. An isolated system contains two objects with charges q_1 and q_2. If object 1 loses half of its charge, what is the final charge on object 2?

a. $\frac{q_2}{2}$
b. $\frac{3q_2}{2}$
c. $q_2 - \frac{q_1}{2}$
d. $q_2 + \frac{q_1}{2}$

Conductors and Insulators

Materials can be classified depending on whether they allow charge to move. If charge can easily move through a material, such as metals, then these materials are called **conductors**. This means that charge can be conducted (i.e., move) through the material rather easily. If charge cannot move through a material, such as rubber, then this material is called an **insulator**.

Most materials are insulators. Their atoms and molecules hold on more tightly to their electrons, so it is difficult for electrons to move between atoms. However, it is not impossible. With enough energy, it is possible to force electrons to move through an insulator. However, the insulator is often physically destroyed in the process. In metals, the outer electrons are loosely bound to their atoms, so not much energy is required to make electrons move through metal. Such metals as copper, silver, and aluminum are good conductors. Insulating materials include plastics, glass, ceramics, and wood.

The conductivity of some materials is intermediate between conductors and insulators. These are called *semiconductors*. They can be made conductive under the right conditions, which can involve temperature, the purity of the material, and the force applied to push electrons through them. Because we can control whether semiconductors are conductors or insulators, these materials are used extensively in computer chips. The most commonly used semiconductor is silicon. Figure 18.8 shows various materials arranged according to their ability to conduct electrons.

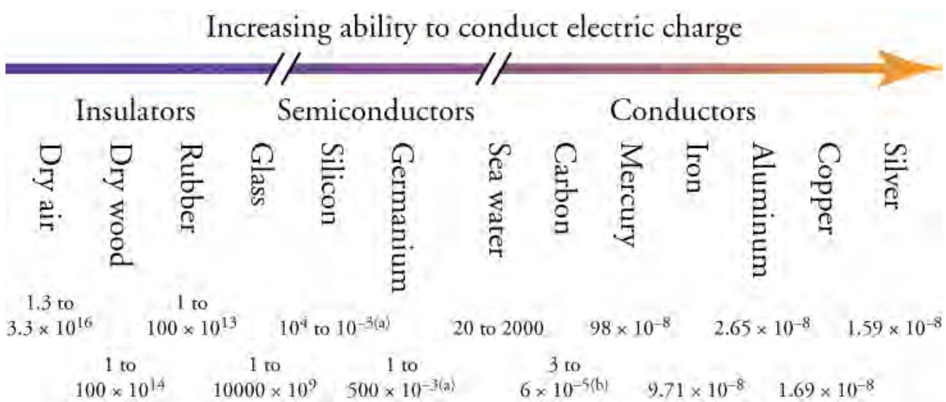

Figure 18.8 Materials can be arranged according to their ability to conduct electric charge. The slashes on the arrow mean that there is a very large gap in conducting ability between conductors, semiconductors, and insulators, but the drawing is compressed to fit on the page. The numbers below the materials give their *resistivity* in Ω•m (which you will learn about below). The resistivity is a measure of how hard it is to make charge move through a given material.

What happens if an excess negative charge is placed on a conducting object? Because like charges repel each other, they will push against each other until they are as far apart as they can get. Because the charge can move in a conductor, it moves to the outer surfaces of the object. Figure 18.9(a) shows schematically how an excess negative charge spreads itself evenly over the outer surface of a metal sphere.

What happens if the same is done with an insulating object? The electrons still repel each other, but they are not able to move, because the material is an insulator. Thus, the excess charge stays put and does not distribute itself over the object. Figure 18.9(b) shows this situation.

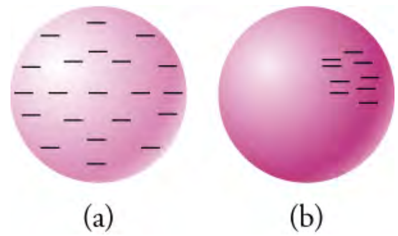

Figure 18.9 (a) A conducting sphere with excess negative charge (i.e., electrons). The electrons repel each other and spread out to cover the outer surface of the sphere. (b) An insulating sphere with excess negative charge. The electrons cannot move, so they remain in their original positions.

Transfer and Separation of Charge

Most objects we deal with are electrically neutral, which means that they have the same amount of positive and negative charge. However, transferring negative charge from one object to another is fairly easy to do. When negative charge is transferred from one object to another, an excess of positive charge is left behind. How do we know that the negative charge is the mobile charge? The positive charge is carried by the proton, which is stuck firmly in the nucleus of atoms, and the atoms are stuck in place in solid materials. Electrons, which carry the negative charge, are much easier to remove from their atoms or molecules and can therefore be transferred more easily.

Electric charge can be transferred in several manners. One of the simplest ways to transfer charge is charging by contact, in which the surfaces of two objects made of different materials are placed in close contact. If one of the materials holds electrons more tightly than the other, then it takes some electrons with it when the materials are separated. Rubbing two surfaces together increases the transfer of electrons, because it creates a closer contact between the materials. It also serves to present *fresh* material with a full supply of electrons to the other material. Thus, when you walk across a carpet on a dry day, your shoes rub against the carpet, and some electrons are removed from the carpet by your shoes. The result is that you have an excess of negative charge on your shoes. When you then touch a doorknob, some of your excess of electrons transfer to the neutral doorknob, creating a small spark.

Touching the doorknob with your hand demonstrates a second way to transfer electric charge, which is charging by **conduction**. This transfer happens because like charges repel, and so the excess electrons that you picked up from the carpet want to be as far away from each other as possible. Some of them move to the doorknob, where they will distribute themselves over the outer surface of the metal. Another example of charging by conduction is shown in the top row of Figure 18.10. A metal sphere with 100 excess electrons touches a metal sphere with 50 excess electrons, so 25 electrons from the first sphere transfer to the second sphere. Each sphere finishes with 75 excess electrons.

The same reasoning applies to the transfer of positive charge. However, because positive charge essentially cannot move in solids, it is transferred by moving negative charge in the opposite direction. For example, consider the bottom row of Figure 18.10. The first metal sphere has 100 excess protons and touches a metal sphere with 50 excess protons, so the second sphere transfers 25 electrons to the first sphere. These 25 extra electrons will electrically cancel 25 protons so that the first metal sphere is left with 75 excess protons. This is shown in the bottom row of Figure 18.10. The second metal sphere lost 25 electrons so it has 25 more excess protons, for a total of 75 excess protons. The end result is the same if we consider that the first ball transferred a net positive charge equal to that of 25 protons to the first ball.

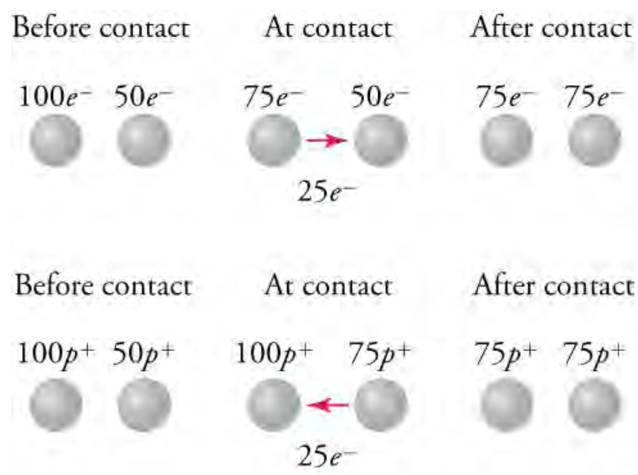

Figure 18.10 In the top row, a metal sphere with 100 excess electrons transfers 25 electrons to a metal sphere with an excess of 50 electrons. After the transfer, both spheres have 75 excess electrons. In the bottom row, a metal sphere with 100 excess protons receives 25 electrons from a ball with 50 excess protons. After the transfer, both spheres have 75 excess protons.

In this discussion, you may wonder how the excess electrons originally got from your shoes to your hand to create the spark when you touched the doorknob. The answer is that *no* electrons actually traveled from your shoes to your hands. Instead, because like charges repel each other, the excess electrons on your shoe simply pushed away some of the electrons in your feet. The electrons thus dislodged from your feet moved up into your leg and in turn pushed away some electrons in your leg. This process continued through your whole body until a distribution of excess electrons covered the extremities of your body. Thus your head, your hands, the tip of your nose, and so forth all received their doses of excess electrons that had been pushed out of their normal positions. All this was the result of electrons being pushed out of your feet by the excess electrons on your shoes.

This type of charge separation is called **polarization**. As soon as the excess electrons leave your shoes (by rubbing off onto the floor or being carried away in humid air), the distribution of electrons in your body returns to normal. Every part of your body is again electrically neutral (i.e., zero excess charge).

The phenomenon of polarization is seen in . The child has accumulated excess positive charge by sliding on the slide. This excess charge repels itself and so becomes distributed over the extremities of the child's body, notably in his hair. As a result, the hair stands on end, because the excess negative charge on each strand repels the excess positive charge on neighboring strands.

Polarization can be used to charge objects. Consider the two metallic spheres shown in Figure 18.11. The spheres are electrically neutral, so they carry the same amounts of positive and negative charge. In the top picture (Figure 18.11(a)), the two spheres are touching, and the positive and negative charge is evenly distributed over the two spheres. We then approach a glass rod that carries an excess positive charge, which can be done by rubbing the glass rod with silk, as shown in Figure 18.11(b). Because opposite charges attract each other, the negative charge is attracted to the glass rod, leaving an excess positive charge on the opposite side of the right sphere. This is an example of charging by **induction**, whereby a charge is created by approaching a charged object with a second object to create an unbalanced charge in the second object. If we then separate the two spheres, as shown in Figure 18.11(c), the excess charge is stuck on each sphere. The left sphere now has an excess negative charge, and the right sphere has an excess positive charge. Finally, in the bottom picture, the rod is removed, and the opposite charges attract each other, so they move as close together as they can get.

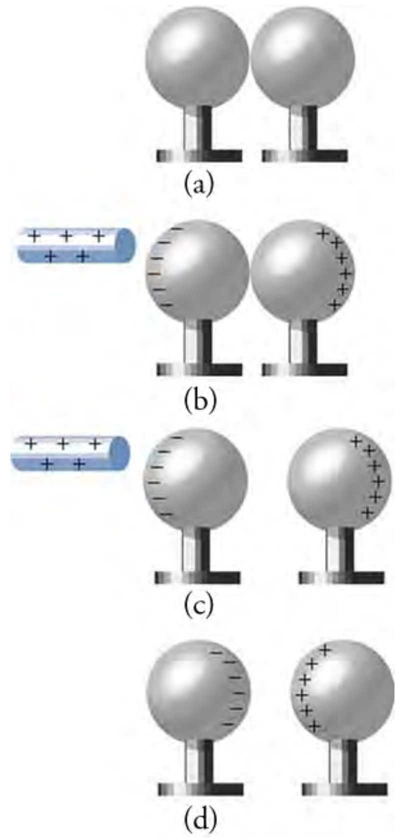

Figure 18.11 (a) Two neutral conducting spheres are touching each other, so the charge is evenly spread over both spheres. (b) A positively charged rod approaches, which attracts negative charges, leaving excess positive charge on the right sphere. (c) The spheres are separated. Each sphere now carries an equal magnitude of excess charge. (d) When the positively charged rod is removed, the excess negative charge on the left sphere is attracted to the excess positive charge on the right sphere.

FUN IN PHYSICS

Create a Spark in a Science Fair

Van de Graaff generators are devices that are used not only for serious physics research but also for demonstrating the physics of static electricity at science fairs and in classrooms. Because they deliver relatively little electric current, they can be made safe for use in such environments. The first such generator was built by Robert Van de Graaff in 1931 for use in nuclear physics research. Figure 18.12 shows a simplified sketch of a Van de Graaff generator.

Van de Graaff generators use smooth and pointed surfaces and conductors and insulators to generate large static charges. In the version shown in Figure 18.12, electrons are “sprayed” from the tips of the lower comb onto a moving belt, which is made of an insulating material like, such as rubber. This technique of charging the belt is akin to charging your shoes with electrons by walking across a carpet. The belt raises the charges up to the upper comb, where they transfer again, akin to your touching the doorknob and transferring your charge to it. Because like charges repel, the excess electrons all rush to the outer surface of the globe, which is made of metal (a conductor). Thus, the comb itself never accumulates too much charge, because any charge it gains is quickly depleted by the charge moving to the outer surface of the globe.

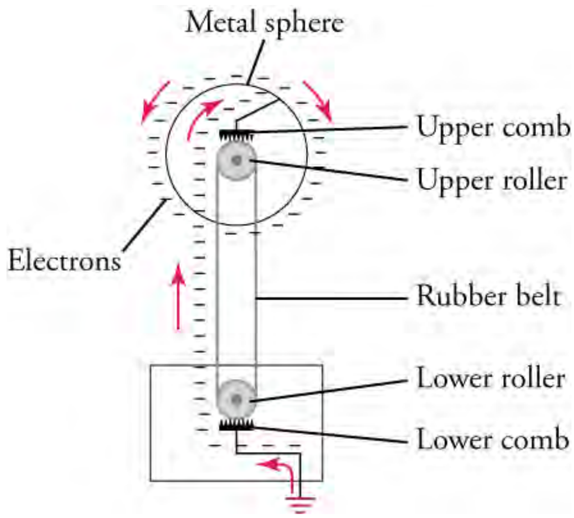

Figure 18.12 Van de Graaff generators transfer electrons onto a metallic sphere, where the electrons distribute themselves uniformly over the outer surface.

Van de Graaff generators are used to demonstrate many interesting effects caused by static electricity. By touching the globe, a person gains excess charge, so his or her hair stands on end, as shown in Figure 18.13. You can also create mini lightning bolts by moving a neutral conductor toward the globe. Another favorite is to pile up aluminum muffin tins on top of the uncharged globe, then turn on the generator. Being made of conducting material, the tins accumulate excess charge. They then repel each other and fly off the globe one by one. A quick Internet search will show many examples of what you can do with a Van de Graaff generator.

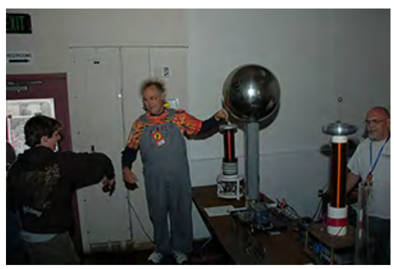

Figure 18.13 The man touching the Van de Graaff generator has excess charge, which spreads over his hair and repels hair strands from his neighbors. (credit: Jon “ShakataGaNai” Davis)

GRASP CHECK

Why don’t the electrons stay on the rubber belt when they reach the upper comb?

a. The upper comb has no excess electrons, and the excess electrons in the rubber belt get transferred to the comb by contact.
b. The upper comb has no excess electrons, and the excess electrons in the rubber belt get transferred to the comb by conduction.
c. The upper comb has excess electrons, and the excess electrons in the rubber belt get transferred to the comb by conduction.
d. The upper comb has excess electrons, and the excess electrons in the rubber belt get transferred to the comb by contact.

Virtual Physics

Balloons and Static Electricity

Click to view content (http://www.openstax.org/l/28balloons)

This simulation allows you to observe negative charge accumulating on a balloon as you rub it against a sweater. You can then observe how two charged balloons interact and how they cause polarization in a wall.

GRASP CHECK

Click the reset button, and start with two balloons. Charge a first balloon by rubbing it on the sweater, and then move it toward the second balloon. Why does the second balloon not move?

a. The second balloon has an equal number of positive and negative charges.
b. The second balloon has more positive charges than negative charges.
c. The second balloon has more negative charges than positive charges.
d. The second balloon is positively charged and has polarization.

Snap Lab

Polarizing Tap Water

This lab will demonstrate how water molecules can easily be polarized.

- Plastic object of small dimensions, such as comb or plastic stirrer
- Source of tap water

Instructions

Procedure

1. Thoroughly rub the plastic object with a dry cloth.
2. Open the faucet just enough to let a smooth filament of water run from the tap.
3. Move an edge of the charged plastic object toward the filament of running water.

What do you observe? What happens when the plastic object touches the water filament? Can you explain your observations?

GRASP CHECK

Why does the water curve around the charged object?

a. The charged object induces uniform positive charge on the water molecules.
b. The charged object induces uniform negative charge on the water molecules.
c. The charged object attracts the polarized water molecules and ions that are dissolved in the water.
d. The charged object depolarizes the water molecules and the ions dissolved in the water.

WORKED EXAMPLE

Charging Ink Droplets

Electrically neutral ink droplets in an ink-jet printer pass through an electron beam created by an electron gun, as shown in Figure 18.14. Some electrons are captured by the ink droplet, so that it becomes charged. After passing through the electron beam, the net charge of the ink droplet is $q_{\text{inkdrop}} = -1 \times 10^{-10}\,\text{C}$. How many electrons are captured by the ink droplet?

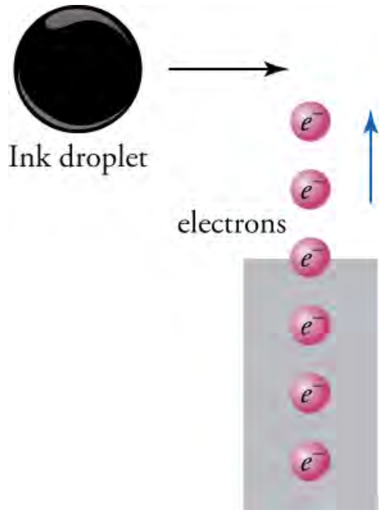

Figure 18.14 Electrons from an *electron gun* charge a passing ink droplet.

STRATEGY

A single electron carries a charge of $q_{e^-} = -1.602 \times 10^{-19}\,\mathrm{C}$. Dividing the net charge of the ink droplet by the charge q_{e^-} of a single electron will give the number of electrons captured by the ink droplet.

Solution

The number n of electrons captured by the ink droplet are

$$n = \frac{q_{\text{inkdrop}}}{q_{e^-}} = \frac{-1 \times 10^{-10}\,\mathrm{C}}{-1.602 \times 10^{-19}\,\mathrm{C}} = 6 \times 108. \tag{18.4}$$

Discussion

This is almost a billion electrons! It seems like a lot, but it is quite small compared to the number of atoms in an ink droplet, which number about 10^{16}. Thus, each extra electron is shared between about $10^{16}/\left(6 \times 10^{8}\right) \approx 10^{7}$ atoms.

Practice Problems

3. How many protons are needed to make 1 nC of charge? 1 nC = 10−9 C

a. 1.6×10^{-28}
b. 1.6×10^{-10}
c. 3×10^{9}
d. 6×10^{9}

4. In a physics lab, you charge up three metal spheres, two with $+3$ nC and one with -5 nC. When you bring all three spheres together so that they all touch one another, what is the total charge on the three spheres?

a. $+1$ nC
b. $+3$ nC
c. $+5$ nC
d. $+6$ nC

Check Your Understanding

5. How many types of electric charge exist?

a. one type
b. two types
c. three types
d. four types

6. Which are the two main electrical classifications of materials based on how easily charges can move through them?

a. conductor and insulator
b. semiconductor and insulator
c. conductor and superconductor
d. conductor and semiconductor

7. True or false—A polarized material must have a nonzero net electric charge.
a. true
b. false

8. Describe the force between two positive point charges that interact.
a. The force is attractive and acts along the line joining the two point charges.
b. The force is attractive and acts tangential to the line joining the two point charges.
c. The force is repulsive and acts along the line joining the two point charges.
d. The force is repulsive and acts tangential to the line joining the two point charges.

9. How does a conductor differ from an insulator?
a. Electric charges move easily in an insulator but not in a conducting material.
b. Electric charges move easily in a conductor but not in an insulator.
c. A conductor has a large number of electrons.
d. More charges are in an insulator than in a conductor.

10. True or false—Charging an object by polarization requires touching it with an object carrying excess charge.
a. true
b. false

18.2 Coulomb's law

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe Coulomb's law verbally and mathematically
- Solve problems involving Coulomb's law

Section Key Terms

Coulomb's law	inverse-square law

More than 100 years before Thomson and Rutherford discovered the fundamental particles that carry positive and negative electric charges, the French scientist Charles-Augustin de Coulomb mathematically described the force between charged objects. Doing so required careful measurements of forces between charged spheres, for which he built an ingenious device called a *torsion balance*.

This device, shown in Figure 18.15, contains an insulating rod that is hanging by a thread inside a glass-walled enclosure. At one end of the rod is the metallic sphere A. When no charge is on this sphere, it touches sphere B. Coulomb would touch the spheres with a third metallic ball (shown at the bottom of the diagram) that was charged. An unknown amount of charge would distribute evenly between spheres A and B, which would then repel each other, because like charges repel. This force would cause sphere A to rotate away from sphere B, thus twisting the wire until the torsion in the wire balanced the electrical force. Coulomb then turned the knob at the top, which allowed him to rotate the thread, thus bringing sphere A closer to sphere B. He found that bringing sphere A twice as close to sphere B required increasing the torsion by a factor of four. Bringing the sphere three times closer required a ninefold increase in the torsion. From this type of measurement, he deduced that the electrical force between the spheres was inversely proportional to the distance squared between the spheres. In other words,

$$F \propto \frac{1}{r^{2},} \tag{18.5}$$

where r is the distance between the spheres.

An electrical charge distributes itself equally between two conducting spheres of the same size. Knowing this allowed Coulomb to divide an unknown charge in half. Repeating this process would produce a sphere with one quarter of the initial charge, and