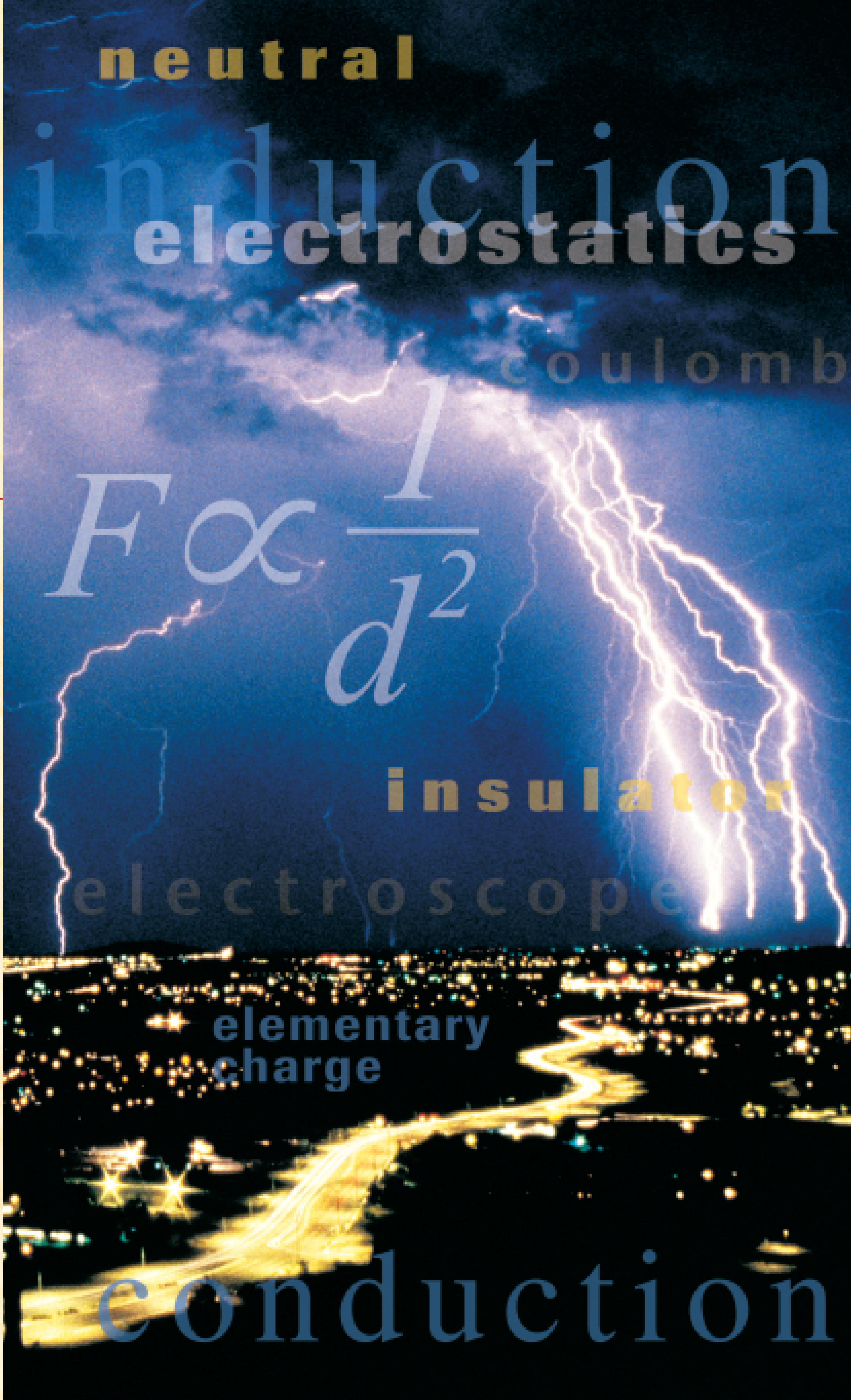
Sky Light

During a thunderstorm, Molly and Paresh were watching lightning bolts light up the sky. Paresh was impressed by the patterns of the lightning. Molly asked Paresh, "Why do you suppose lightning jumps between a cloud and Earth?" What explanation might Paresh give?

Look at the text on page 470 for the answer.



CHAPTER

20 Static Electricity

Nature provides few more dazzling displays than lightning. Is there a way to experience lightning close-up, perhaps safely at home or in the school lab? Is lightning related to some everyday occurrences? If you have ever scuffed your feet on the carpet so that you could create a small spark between your fingers and a friend's nose, then you may be able to answer these questions.

The connection between rubbing surfaces together and sparks has been known for a long time. However, researchers had not made the connection between sparks and lightning. After all, sparks were seldom more than 1 or 2 centimeters long. Lightning, on the other hand, could be several kilometers long. How could they be related?

It took Benjamin Franklin's ingenuity to see how a link between lightning and sparks could be established. He reasoned that if lightning was electricity, it had to be a great deal of electricity. In 1752, Franklin performed his famous kite experiment. He flew the kite with a key attached to the string while a thunderstorm approached. During the flight, the loose threads of the kite string began to stand up and avoid one another. When Franklin brought his knuckle close to the key he experienced a spark. This event was proof that "electrical fire" could be obtained from a cloud. Franklin's experiment set off a flurry of research in the field of electricity. Over the next several chapters, you will investigate electric phenomena and develop models to explain what you observe.

WHAT YOU'LL LEARN

- You will classify electrical charge and analyze how charge interacts with matter.
- You will infer the rules of how charge pushes and pulls on the world.

WHY IT'S IMPORTANT

- In this age of microprocessors and sensitive circuitry, a knowledge of static electrical charge may save your electronic components from damage.

PHYSICS Online

To find out more about static electricity, visit the Glencoe Science Web site at **science.glencoe.com**

CLICK HERE

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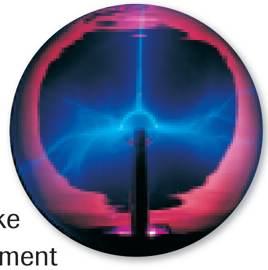
20.1 Electrical Charge



You may have had the experience of rubbing your shoes on the carpet hard enough to create a lightning-like spark when you touched someone. Franklin's kite experiment showed that lightning is similar to electricity caused by friction. Electrical effects produced this way are called *static electricity*. In this chapter, you will investigate **electrostatics,** the study of electrical charges that can be collected and held in one place. Current electricity, produced by batteries and generators, will be explored in later chapters.

OBJECTIVES

- **Recognize** that objects that are charged exert forces, both attractive and repulsive.
- **Demonstrate** that charging is the separation, not the creation, of electrical charges.
- **Describe** the differences between conductors and insulators.

Charged Objects

Have you ever noticed the way your hair is attracted to the comb when you comb your hair on a dry day? Perhaps you also have found that socks sometimes stick together when you take them out of the clothes dryer. If so, you will recognize the attraction of the bits of paper to a comb shown in **Figure 20–1.** If the weather is dry, try this yourself now. Rub a plastic comb or ballpoint pen on your clothing. (Wool clothing is best.) Then, hold the pen or comb close to a pile of paper bits. Notice the way the paper pieces jump up toward the pen or comb. There must be a new, relatively strong force causing this upward acceleration because it is larger than the downward acceleration caused by the gravitational force of Earth.

There are other differences between this new force and gravity. Paper is attracted to a comb only after the comb has been rubbed. If you wait a while, the attractive property of the comb disappears. Gravity, on the other hand, does not require rubbing and does not disappear. The ancient Greeks noticed similar effects when they rubbed amber. The Greek word for amber is *elektron,* and today this attractive property is called "electrical." An object that exhibits electrical interaction after rubbing is said to be charged.

FIGURE 20–1 Running a comb through your hair transfers electrons to the comb, giving it a negative charge. When the comb is brought close to bits of paper, a charge separation is induced on the paper bits. The attractive electrical force accelerates the paper bits upward against the force of gravity.

Like charges You can explore electrical interactions with very simple equipment such as transparent tape. Fold over about 5 mm at the end of a strip of tape for a handle and then stick the remaining 8- to 12-cm-long part of the strip on a dry, smooth surface such as your desktop. Then stick a second, similar piece next to the first. Quickly pull both strips off the desk and bring them near each other. What happens? The strips have a new property that causes them to repel each other. They are electrically charged. They were prepared in the same way, so they must have the same type of charge. Therefore, you have just demonstrated that two objects with the same type of charge repel each other.

You can learn about this charge by doing some simple experiments. You may have found that the tape is attracted to your hand. Are both sides attracted, or just one? If you wait a while, especially in humid weather, you'll find that the electrical charge disappears. You can restore it by again sticking the tape to the desk and pulling it off. You also can remove its charge by gently rubbing your fingers down both sides of the tape.

Opposite charges Now, stick one strip of tape on the desk and place the second strip on top of the first, as shown in **Figure 20–2a.** Use the handle of the bottom strip of tape to pull the two off the desk together. Rub them with your fingers until they are no longer attracted to your hand. You've now removed all the electrical charge. With one hand on the handle of one strip and the other on the handle of the second strip, quickly pull the two strips apart. You'll find that they're now both charged. They once again are attracted to your hands. But, do they still repel each other? No, they now attract each other. They are charged, but they are no longer charged alike. They have opposite charges and attract each other.

Is tape the only object that you can charge? Once again, stick one strip of tape to the desk and the second strip on top. Label the bottom strip B and the top strip T. Pull the pair off together. Discharge them, then pull them apart. Stick the handle end of each strip to the edge of a table, the bottom of a lamp shade, or some similar object. The two should hang down a short distance apart, as shown in **Figure 20–2b.** Finally, rub the comb or pen on your clothing and bring it near first one strip of tape and then the other. You will find that one strip will be attracted to the comb, the other repelled from it. You can now explore the interactions of charged objects with the strips of tape.

F.Y.I.

Charged objects will eventually return to their neutral state. The charge "leaks off" onto the water molecules in the air. On humid or rainy days it is difficult to make any object hold its charge for long.

a b

FIGURE 20–2 Strips of tape can be given opposite charges **(a),** then used to demonstrate the interactions of like and opposite charges **(b).**

Color Conventions

- Positive charges are **red.**
- Negative charges are **blue.**

Experimenting with charge Try to charge other objects such as plates, glasses, and plastic bags. Rub them with different materials such as silk, wool, and plastic wrap. If the air is dry, scuff your shoes on the carpet and bring your finger near the strips of tape. You should find that most charged objects attract one strip and repel the other. To test silk or wool, slip a plastic bag over your hand before holding the cloth. After rubbing, take your hand out of the bag and bring both the bag and cloth near the strips of tape.

You will never find an object that repels both strips of tape, although you might find some that attract both. Bring your finger near first one strip, then the other. You will find that it attracts both. We will explore this effect later in this chapter.

Types of charge From your experiments, you can make a list of objects labeled B for bottom, which have the same charge as the tape stuck on the desk. Another list can be made of objects labeled T, which have the same charge as the tape stuck on the top of the other tape. There are only two lists; thus, there are only two types of charge. You could give these types the names "yellow" and "green." Benjamin Franklin called them positive and negative charges. Using Franklin's convention, when hard rubber and plastic are rubbed, they become negatively charged. When materials such as glass and wool are rubbed, they become positively charged.

Just as you showed that an uncharged pair of strips of tape became oppositely charged, you were probably able to show that if you rubbed plastic with wool, the plastic became charged negatively, the wool positively. The two kinds of charges were not created alone, but in pairs. These experiments suggest that matter normally contains both charges, positive and negative. Friction in some way separates the two. To explore this further, you must consider the microscopic picture of matter.

A Microscopic View of Charge

Electrical charges exist within atoms. In 1890, J.J. Thomson discovered that all materials contain light, negatively charged particles he called electrons. Between 1909 and 1911, Ernest Rutherford, a New Zealander, discovered that atoms have a massive, positively charged nucleus. If the positive charge of the nucleus exactly balances the negative charge of the surrounding electrons, then the atom is **neutral.**

With the addition of energy, the outer electrons can be removed from atoms. An atom missing electrons has an overall positive charge, and consequently any matter made of these electron-deficient atoms is positively charged. The freed electrons can remain unattached or become attached to other atoms, resulting in negatively charged particles. From a microscopic viewpoint, acquiring charge is a process of transferring electrons.

HELP WANTED

OFFICE EQUIPMENT TECHNICIAN

Must be skilled in installing, servicing, and operating computers and other office equipment. Prefer graduate of two-year course at a technical institute or community college. High school courses should include algebra and other math, computer science, language arts, and physics or chemistry. Growing opportunity for those with computer skills. May work in a manufacturing plant, a corporation, or a repair shop. For more information, join a computer user group or contact:

Institute of Electrical and Electronics Engineers
445 Hoes Lane
Piscataway, NJ
08855-0459

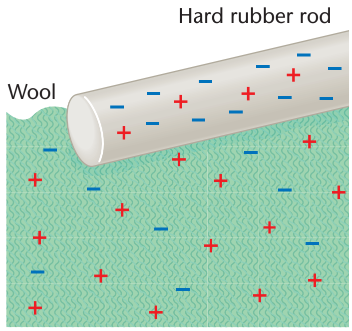


FIGURE 20–3 As the rubber rod strokes the wool, electrons are removed from the wool atoms and cling to the rubber atoms. In this way, both objects become charged.

Separation of charge If two neutral objects are rubbed together, each can become charged. For instance, when rubber and wool are rubbed together, electrons from atoms on the wool are transferred to the rubber, as shown in **Figure 20–3.** The extra electrons on the rubber result in a net negative charge. The electrons missing from the wool result in a net positive charge. The combined total charge of the two objects remains the same. Charge is conserved, which is one way of saying that individual charges are never created or destroyed. All that happened was that the positive and negative charges were separated through a transfer of electrons.

Contact between the tires of a moving car or truck and the road can cause the tires to become charged. Processes inside a thundercloud can cause the cloud bottom to become negatively charged and the cloud top to become positively charged. In both these cases, no charge is made, only separated.

Conductors and Insulators

Hold a plastic rod or comb at its midpoint and rub only one end. You will find that only the rubbed end becomes charged. In other words, the charges you transferred to the plastic stayed where they were put, they did not move. **Figure 20–4** shows static charges—charges that are not moving—on an insulator. The strips of tape that you charged earlier in this chapter acted in the same way. Materials through which charges will not move easily are called electrical **insulators.** Glass, dry wood, most plastics, cloth, and dry air are all good insulators.

Suppose that you support a metal rod on an insulator so that it is isolated, or completely surrounded by insulators. If you then touch the charged comb to one end of the metal rod, you will find that the charge spreads very quickly over the entire rod. Materials such as metals that allow charges to move about easily are called electrical **conductors.** Electrons

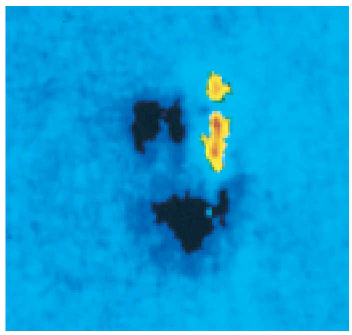


FIGURE 20–4 A piece of plastic 0.02 mm wide was given a net positive charge. Areas of negative charge are visible as dark regions. Areas of positive charge are visible as yellow regions.

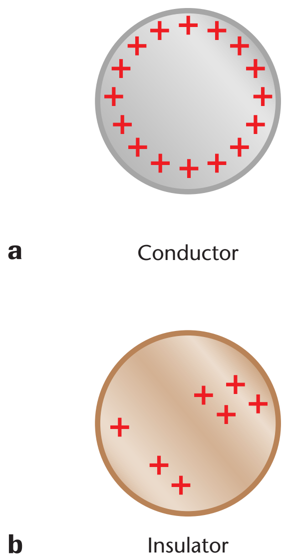


FIGURE 20–5 Charges placed on a conductor will spread over the entire surface **(a).** Charges placed on an insulator will remain where they are placed **(b).**

carry, or conduct, electric charge through the metal. Metals are good conductors because at least one electron on each atom of the metal can be removed easily. These electrons act as if they no longer belong to any one atom, but to the metal as a whole; consequently, they move freely throughout the piece of metal. **Figure 20–5** illustrates how charges behave when placed on a conductor or an insulator. Copper and aluminum are both excellent conductors and are used commercially to carry electricity. Plasma, a highly ionized gas, and graphite, the form of carbon used in pencils, also are good conductors of electrical charge.

When air becomes a conductor Air is an insulator. However, under certain conditions, sparks or lightning occurs, allowing charge to move through air as if it were a conductor. The spark that jumps between your finger and a doorknob after you have rubbed your feet on the carpet discharges you. That is, you have become neutral because the excess charges have left you. Similarly, lightning discharges a thundercloud. In both these cases, for a brief moment, air became a conductor. Recall that conductors must have charges that are free to move. For a spark or lightning to occur, free moving charged particles must be formed in the normally neutral air. In the case of lightning, excess charges in the cloud and on the ground are great enough to remove electrons from the molecules in the air. The electrons and positively or negatively charged atoms become free to move. They form a conductor that is a plasma. The discharge of Earth and the thundercloud moving through this conductor forms a luminous arc called lightning. In the case of your finger and the doorknob, the discharge is called a spark.

20.1 Section Review

1. How could you find out which strip of tape, B or T, is positively charged?
2. Suppose you attach a long metal rod to a plastic handle so that the rod is isolated. You touch a charged glass rod to one end of the metal rod. Describe the charges on the metal rod.
3. In the 1730s, Stephan Gray tried to see how far metal rods could conduct electrical charge. He hung metal rods by thin silk cords from the ceiling. When the rods were longer than 293 feet, the silk broke. Gray replaced the silk with stronger wires made of brass, but then the experiments failed. The metal rods would no longer transmit a charge from one end to the other. Why not?
4. **Critical Thinking** Suppose there were a third type of charge. What experiments could you suggest to explore its properties?

What's the charge?

Problem

Can you see the effects of electrostatic charging? How can you increase the amount of charge on an object without discharging it?

Materials

30 cm × 30 cm block of polystyrene
22-cm aluminum pie pan
plastic cup
drinking straw
transparent tape
pith ball (or small piece of plastic foam packing material)
liquid graphite
wool
thread

Procedure

1. Paint the pith ball with graphite and allow it to dry.
2. Tape the inverted cup to the aluminum pie pan. Secure the straw to the top of the cup and use the thread to attach the ball as shown in the photograph.
3. Rub the foam with wool, then remove the wool.
4. Holding onto the plastic cup, lower the pie pan until it is about 3 cm above the foam block and then slowly lift it away.
5. Place the pie pan directly on the charged foam block and lift it away.
6. Bring your finger near the ball until they touch.
7. Place the pie pan on the foam block and touch the edge of the pie pan with your finger. Then remove the pie pan from the foam block and touch the ball again with your finger.
8. Repeat step 7 several times without recharging the foam block.

Data and Observations	
Description of Event	Observations

9. When finished, recycle or dispose of appropriate materials. Put away materials that can be reused.

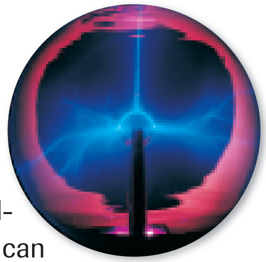
Analyze and Conclude

1. **Forming a Description** As the pie pan was brought near the charged block, could you detect a force between the neutral pie pan and the charged foam? Describe it.
2. **Interpreting Observations** Explain what happened to the ball in step 4 and step 5.
3. **Analyzing Results** Make a drawing to show the distribution of charges on the neutral pie pan as it is lowered toward the charged foam block.
4. **Inferring Relationships** What was the reason for using the ball on a thread? Explain the back-and-forth motion of the ball in step 6.
5. **Interpreting Observations** Does the polystyrene block seem to run out of charges in step 8?

Apply

1. Clear plastic wrap is sold to seal up containers of food. Suggest a reason why it clings to itself.

20.2 Electrical Force



Electrical forces must be strong because they can easily produce accelerations larger than the acceleration caused by gravity. We also have seen that they can be either repulsive or attractive while gravitational forces are always attractive. Many scientists made attempts to measure electrical force. Daniel Bernoulli, otherwise known for his work on fluids, made some crude measurements in 1760. In 1770, Henry Cavendish showed that electrical forces must obey an inverse square force law, but, being extremely shy, he did not publish his work. His manuscripts were discovered over a century later, after all his work had been duplicated by others.

OBJECTIVES

- **Summarize** the relationship between forces and charges.
- **Describe** how an electroscope detects electric charge.
- **Explain** how to charge by conduction and induction.
- **Use** Coulomb's law to **solve** problems relating to electrical force.
- **Develop** a model of how charged objects can attract a neutral object.

Forces on Charged Bodies

The forces you observed on tape strips also can be demonstrated by suspending a negatively charged hard rubber rod so that it turns easily, as shown in **Figure 20–6.** If you bring another negatively charged rod near the suspended rod, it will turn away. The negative charges on the rods repel each other. It is not necessary for the rods to make contact; the force, called the electrical force, acts over a distance. If a positively charged glass rod is suspended and a similarly charged glass rod is brought close, the two positively charged rods also will repel each other. If a negatively charged rod is brought near the positively charged rod, however, the two will attract each other, and the suspended rod will turn toward the oppositely charged rod. The results of your tape experiments and these observations with charged rods can be summarized in this way:

- There are two kinds of electrical charges, positive and negative.
- Charges exert force on other charges over a distance.
- The force is stronger when the charges are closer together.
- Like charges repel; opposite charges attract.

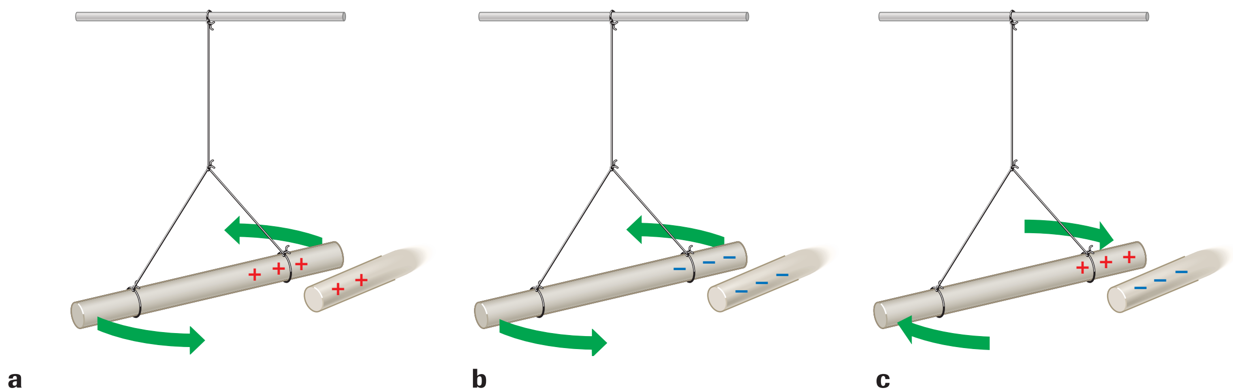


FIGURE 20–6 A charged rod, when brought close to another suspended rod, will attract or repel the suspended rod.

Neither a strip of tape nor a large rod hanging in open air is a very sensitive or convenient way of determining charge. Instead, a device called an **electroscope** is used. An electroscope consists of a metal knob connected by a metal stem to two thin, lightweight pieces of metal foil called leaves, as shown in **Figure 20–7.** Note that the leaves are enclosed to eliminate stray air currents.

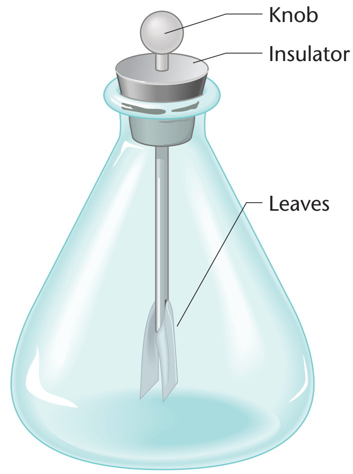


FIGURE 20–7 An electroscope is a device used for detecting electrical charges.

Charging by conduction When a negatively charged rod is touched to the knob of an electroscope, negative charges (electrons) are added to the knob. The charges spread over all the metal surfaces. As shown in **Figure 20–8a,** the two leaves are charged negatively and repel each other, causing them to spread apart. The electroscope has been given a net charge. Charging a neutral body this way, by touching it with a charged body, is called **charging by conduction.**

The leaves also will spread if the electroscope is charged positively. How, then, can you find out whether the electroscope is charged positively or negatively? The type of charge can be determined by observing what happens to the spread leaves if a rod of known charge is brought close to the knob. The leaves will spread farther apart if the electroscope has the same charge as that of the rod, as shown in **Figure 20–8b.** The leaves will fall slightly if the electroscope has a charge opposite to that of the rod, as in **Figure 20–8c.**

Separation of charge on neutral objects Earlier in the chapter, when you brought your finger near either charged strip of tape, the tape was attracted toward your finger. Your finger, however, was not charged; it was neutral and had equal amounts of positive and negative charge. You know that in materials that are conductors, charges can move easily, and that in the case of sparks, electric forces can change insulators into conductors. Given this information, you can develop a plausible model for the force your finger exerted on the charged objects.

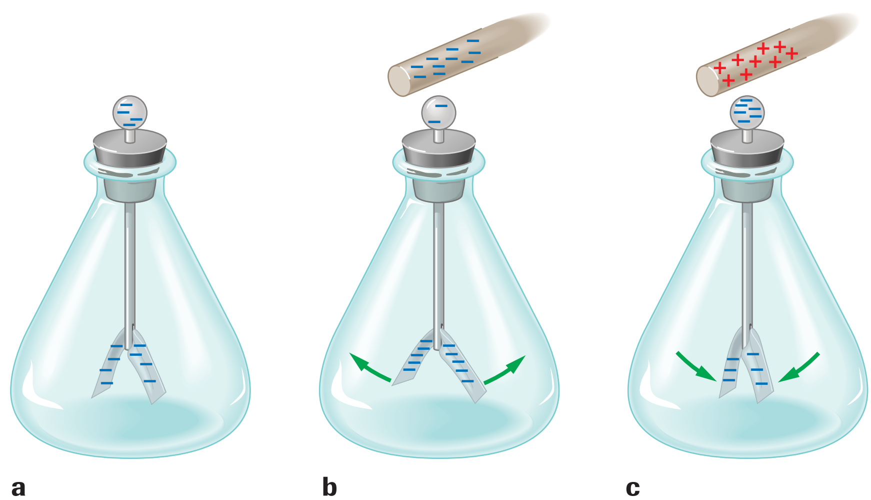


FIGURE 20–8 A negatively charged electroscope will have its leaves spread **(a).** A negatively charged rod pushes electrons down to the leaves, causing them to spread more **(b).** A positively charged rod attracts some of the electrons from the leaves, causing them to spread apart less **(c).**

Suppose you move your finger, or any other uncharged object, close to a positively charged object. The negative charges in your finger will be attracted to the positively charged object, and the positive charges in your finger will be repelled. Your finger will remain neutral, but the positive and negative charges will be separated. The electrical force is stronger for the charged objects that are closer together, therefore, the separation results in an attractive force between the neutral object and the charged object. The force of a charged comb on your hair or on neutral pieces of paper is the result of the same process, the separation of charge.

The negative charges at the bottom of thunderclouds also can cause charge separation in Earth. Positive charges in the ground are attracted to Earth's surface under the cloud. The forces of the charges in the cloud and those on Earth's surface can break molecules apart, separating the

a force acts between two or more charged objects. How does this force depend on the size of the charges and their separation? You

Sky Light

Answers question from page 460.

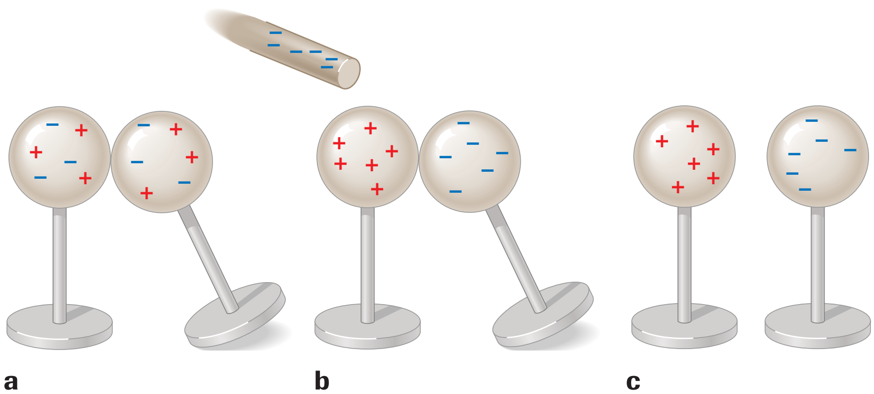


FIGURE 20–9 Start with neutral spheres that are touching **(a),** bring a charged rod near them **(b),** and then separate the spheres and remove the charged rod **(c).** This is one example of charging by induction.

CONTENTS

demonstrated in your experiments with tape some basic properties. You found that the force depends on distance. The closer you brought the charged rod to the tape, the stronger the force. You also found that the more you charged the rod, the stronger the force. But how can you vary the quantity of charge in a controlled way? This problem was solved in 1785 by French physicist Charles Coulomb (1736–1806). The type of apparatus used by Coulomb is shown in **Figure 20–10.** An insulating rod with small conducting spheres, A and A′, at each end was suspended by a thin wire. A similar sphere, B, was placed in contact with sphere A. When they were touched with a charged object, the charge spread evenly over the two spheres. Because they were the same size, they received equal amounts of charge. The symbol for charge is q. Therefore, the amount of charge on the spheres can be represented by the notation q_A and q_B.

Coulomb found how the force between the two charged spheres, A and B, depended on the distance. First, he carefully measured the amount of force needed to twist the suspending wire through a given angle. He then placed equal charges on spheres A and B and varied the distance, d, between them. The force moved A from its rest position, twisting the suspending wire. By measuring the deflection of A, Coulomb could calculate the force of repulsion. He showed that the force, F, varied inversely with the square of the distance between the centers of the spheres.

$$F \propto \frac{1}{d^2}$$

To investigate the way in which the force depended on the amount of charge, Coulomb had to change the charges on the spheres in a measured way. Coulomb first charged spheres A and B equally, as before. Then he selected an extra uncharged sphere, C, the same size as sphere B. When C was placed in contact with B, the spheres shared the charge that had been on B alone. Because the two were the same size, B now had only half its original charge. Therefore, the charge on B was only one half the charge on A. The extra sphere was then removed. After Coulomb adjusted the position of B so that the distance, d, between A and B was the same as before, he found that the force between A and B was half of its former value. That is, he found that the force varied directly with the charge of the bodies.

$$F \propto q_A q_B$$

After many similar measurements, Coulomb summarized the results in a law now known as **Coulomb's law:** the magnitude of the force between charge q_A and charge q_B, separated a distance d, is proportional to the magnitude of the charges and inversely proportional to the square of the distance.

$$F \propto \frac{q_A q_B}{d^2}$$

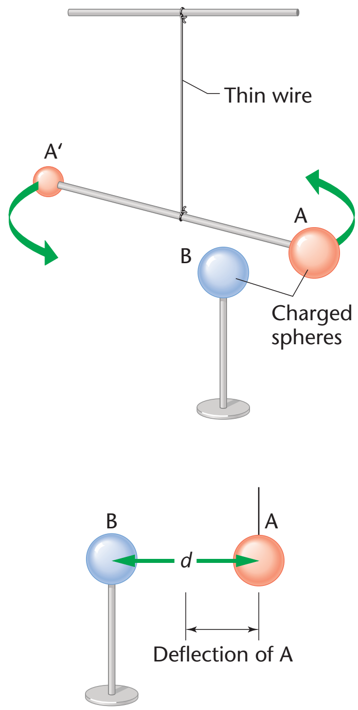


FIGURE 20–10 Coulomb used this type of apparatus to measure the force between two spheres, A and B. He observed the deflection of A while varying the distance between A and B.

Pocket Lab

Charged Up

Rub a balloon with wool. Touch the balloon to the knob of an electroscope and watch the leaves.

Analyze and Conclude
Describe the result. Make a drawing to explain the result. Touch the knob of the electroscope to make the leaves fall. Would you expect that the wool could move the leaves? Why? Try it. Explain your results.

Pocket Lab

Reach Out

Start with the leaves of an electroscope down. Predict what should happen if you bring a charged balloon near (but not touching) the top of the electroscope.

Analyze and Conclude
Explain your prediction. Try it. Describe and explain your results.

The unit of charge: The coulomb The amount of charge an object has is difficult to measure directly. Coulomb, however, showed that the quantity of charge could be related to force. Thus, he could define a standard quantity of charge in terms of the amount of force it produces. The SI standard unit of charge is called the **coulomb** (C). One coulomb is the charge of 6.25×10^{18} electrons or protons. Recall that the charge of protons and electrons is equal. The charge that produces a large lightning bolt is about 10 coulombs. The charge on an individual electron is only 1.60×10^{-19} C. The magnitude of the charge of an electron is called the **elementary charge.** Thus, as you will calculate in problem 22 in the Chapter Review, even small pieces of matter, such as the coins in your pocket, contain up to 1 million coulombs of negative charge. This enormous amount of charge produces almost no external effects because it is balanced by an equal amount of positive charge. However, if the charge is unbalanced, even as small of a charge as 10^{-9} C can result in large forces.

According to Coulomb's law, the magnitude of the force on charge q_A caused by charge q_B a distance d away can be written as follows.

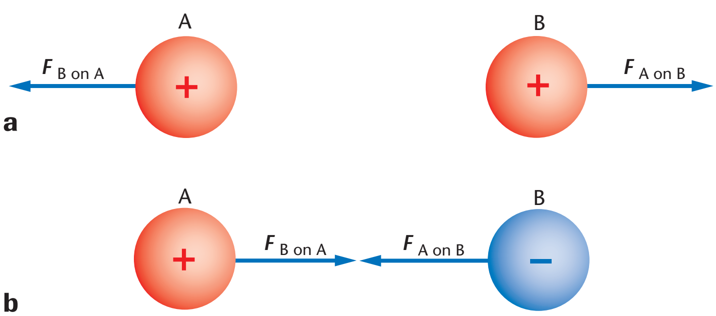
Coulomb's Law $$F = K\frac{q_A q_B}{d^2}$$

When the charges are measured in coulombs, the distance is measured in meters, and the force is measured in newtons, the constant, K, is $9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$.

This equation gives the magnitude of the force that charge q_A exerts on q_B and also the force that q_B exerts on q_A. These two forces are equal in magnitude but opposite in direction. You can observe this example of Newton's third law of motion in action when you bring two strips of tape with like charges together. Each exerts forces on the other. If you bring a charged comb near either strip of tape, the strip, with its small mass, moves readily. The acceleration of the comb and you is, of course, much less because of the much greater mass.

The electrical force, like all other forces, is a vector quantity. Force vectors need both a magnitude and a direction. However, Coulomb's law will furnish only the magnitude of the force. To determine the direction, you need to draw a diagram and interpret charge relations carefully. Consider the direction of force on a positively charged object called A. If another positively charged object, B, is brought near, the force on A is repulsive. The force, $F_{B\text{ on }A}$, acts in the direction from B to A, as shown in **Figure 20–11a.** If, instead, B is negatively charged, the force on A is attractive and acts in the direction from A to B, as shown in **Figure 20–11b.**

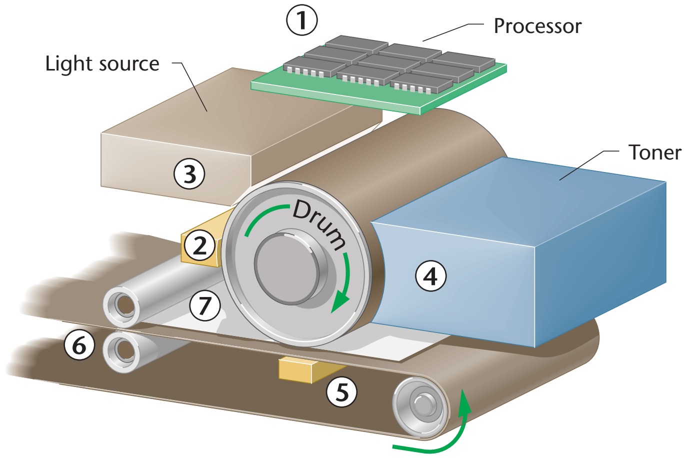
FIGURE 20–11 The rule for determining direction of force is like charges repel, unlike charges attract.



How It Works

Laser Printers

Static electricity is important to the operation of laser printers. Inside a laser printer, static electrical charges are used to transfer a black powder, commonly called toner, onto paper to create images or text. Letters and other shapes are actually composed of tiny dots of toner that are heat-bonded onto the paper. The dots are so numerous and placed so closely together that they merge to form very finely detailed images.



1. The computer sends instructions to the microprocessor that operates the laser printer. The microprocessor controls the aiming and timing of a light source, either a laser or a light-emitting diode (LED).

2. The surface of the metal drum is coated with a photosensitive semiconductor. In dark, the semiconductor is an insulator. As the drum rotates, it is sprayed with electrons, giving the surface a negative charge.

3. According to instructions received from the processor, a beam of light sweeps over the surface of the drum. Wherever the light strikes, the semiconductor becomes a conductor, and charges leak onto the supporting drum. These uncharged areas on the semiconductor correspond to the white portions of the page.

4. The drum is rotated so that it contacts uncharged toner particles. Toner contains small plastic beads coated in graphite. As the drum passes by the toner, the beads are attracted to the charged areas.

5. A sheet of paper that is being pushed by rollers through the printer's paper train receives a small opposite charge. The paper passing by the rotating drum electrically attracts the toner.

6. After picking up toner from the drum, the paper moves into the fusing system. Here the paper is exposed to heat and pressure that melts the grains of toner and binds them to the paper.

7. The drum is returned to the dark where it is an insulator. The surfaces are recharged and are ready to receive the image of another page.

Thinking Critically

1. Photocopiers also use toner, a photosensitive drum, and fusing system. Describe what you think might be some of the similarities and differences of photocopiers and laser printers?
2. In the process, notice that the areas exposed to laser light become the white part of a page. Design a process where the exposed areas become the black part of a page.

Problem Solving Strategies

Electrical Force Problems

1. Sketch the system showing all distances and angles to scale.
2. Diagram the vectors of the system; include derived vectors using dashed lines.
3. Use Coulomb's law to find the magnitude of the force.
4. Use your diagram along with trigonometric relations to find the direction of the force.
5. Perform all algebraic operations on units as well as the numbers. Make sure the units match the variable in question.
6. Consider the magnitude of your answer. Is it reasonable?

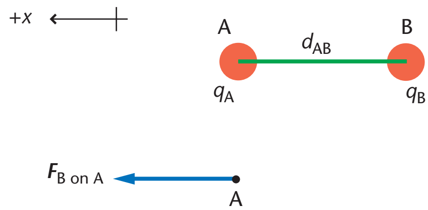
Notice in this problem solving strategy that Coulomb's law only is used to determine magnitudes. Therefore, it is unnecessary to include the sign of the charges or distance when evaluating Coulomb's law, because the answer is always positive.

Example Problem

Coulomb's Law

Two charges are separated by 3.0 cm. Object A has a charge of $+6.0\ \mu C$, while object B has a charge of $+3.0\ \mu C$. What is the force on object A?

Sketch the Problem



- Establish coordinate axes.
- Label spheres A and B.
- Draw distance d_{AB}.
- Diagram the force vectors.

Calculate Your Answer

Known:

$q_A = +6.0\ \mu C$

$q_B = +3.0\ \mu C$

$d_{AB} = 0.030$ m

Unknown:

$\boldsymbol{F}_{B \text{ on } A} = ?$

Strategy:

Use Coulomb's law. Do not include signs when using Coulomb's law.

The direction of force is determined by the diagram.

Calculations:

$$F_{B \text{ on } A} = K\frac{q_A q_B}{{d_{AB}}^2}$$

$$F_{B \text{ on } A} = (9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(6.0\ \mu C)(3.0\ \mu C)}{(3.0 \times 10^{-2}\ \text{m})^2}$$

$$\boldsymbol{F}_{B \text{ on } A} = 1.8 \times 10^2\ \text{N},\ +x \text{ direction}$$

Check Your Answer

- Are the units correct? Perform algebra on the units to ensure that your answer is in newtons.
- Does the direction make sense? It agrees with the coordinate axis and direction of push of charge B.

- Is the magnitude realistic? Look at the magnitudes in the equation $10^9 \times 10^{-6} \times 10^{-6} \div 10^{-2} \div 10^{-2} = 10^1$. This is close to the answer, so the magnitude checks.

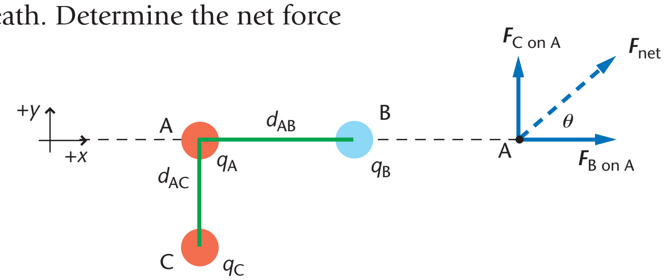
Example Problem

Coulomb's Law with Three Charges

A sphere with charge 6.0 μC is located near two other charged spheres. A -3.0-μC sphere is located 4.00 cm to the right and a 1.5-μC sphere is located 3.00 cm directly underneath. Determine the net force on the 6.0-μC sphere.

Sketch the Problem

- Establish coordinate axes.
- Draw the displacement vectors.
- Diagram the force vectors.



Calculate Your Answer

Known:

$q_A = 6.0\ \mu C$

$q_B = -3.0\ \mu C$

$q_C = 1.5\ \mu C$

$d_{AB} = 0.0400$ m

$d_{AC} = 0.0300$ m

Unknown:

$\boldsymbol{F}_{B\ on\ A} = ?$

$\boldsymbol{F}_{C\ on\ A} = ?$

$\boldsymbol{F}_{net} = ?$

Strategy:

Use Coulomb's law. Do not include signs when using Coulomb's law (refer to the problem-solving strategy). The direction of force is determined by the diagram.

Use the tangent function to find θ.

Use the Pythagorean theorem to find $\boldsymbol{F}_{net}$.

Calculations:

$$F_{B\ on\ A} = K\frac{q_A q_B}{{d_{AB}}^2} = (9.0\ GN{\cdot}m^2/C^2)\frac{(6.0\ \mu C)(3.0\ \mu C)}{(4.00 \times 10^{-2}\ m)^2}$$

$\boldsymbol{F}_{B\ on\ A} = 1.0 \times 10^2$ N, to the right

$$F_{C\ on\ A} = \frac{K\,q_A q_C}{{d_{AC}}^2} = (9.0\ GN{\cdot}m^2/C^2)\frac{(6.0\ \mu C)(1.5\ \mu C)}{(3.00 \times 10^{-2}\ m)^2}$$

$\boldsymbol{F}_{C\ on\ A} = 9.0 \times 10^1$ N, up

$$\tan\,\theta = \frac{F_{C\ on\ A}}{F_{B\ on\ A}} = \frac{9.0 \times 10^1\ N}{1.0 \times 10^{-2}\ N},\ \theta = 42°$$

$$F_{net} = \sqrt{(1.0 \times 10^2\ N)^2 + (9.0 \times 10^1\ N)^2} = 130\ N$$

$\boldsymbol{F}_{net} = 130$ N, 42° above x-axis

Check Your Answer

- Are the units correct? Perform algebra on the units to ensure that your answer is in newtons.
- Does the direction make sense? It agrees with direction of force of the charge.
- Is the magnitude realistic? A magnitude of 130 N fits with the quantities given.

a

b

FIGURE 20–12 Static electricity precipitators are used to reduce the fly ash released into the environment. In **(a)** the device is off, in **(b)** it is on.

Practice Problems

1. A negative charge of -2.0×10^{-4} C and a positive charge of 8.0×10^{-4} C are separated by 0.30 m. What is the force between the two charges?
2. A negative charge of -6.0×10^{-6} C exerts an attractive force of 65 N on a second charge 0.050 m away. What is the magnitude of the second charge?
3. Two positive charges of 6.0 μC are separated by 0.50 m. What force exists between the charges?
4. An object with charge $+7.5 \times 10^{-7}$ C is placed at the origin. The position of a second object, charge $+1.5 \times 10^{-7}$ C, is varied from 1.0 cm to 5.0 cm. Draw a graph of the force on the object at the origin.
5. The charge on B in the second Example Problem is replaced by $+3.00$ μC. Use graphical methods to find the net force on A.

Application of Electrical Forces

There are many applications of electrical forces on neutral particles. For example, these forces can collect soot in smokestacks, thereby reducing air pollution, as shown in **Figure 20–12.** Tiny paint droplets, charged by induction, can be used to paint automobiles and other objects very uniformly. Photocopy machines use static electricity to place black toner on a page so that a precise reproduction of the original document is made.

20.2 Section Review

1. How are force and charge related? Describe the force if the charges are the same charge. Opposite charges?
2. When an electroscope is charged, the leaves rise to a certain angle and remain at that angle. Why don't they rise farther?
3. Two charged spheres are on a frictionless horizontal surface. One has a $+3$ μC charge, the other a $+6$ μC charge. Sketch the two spheres, showing all forces on them. Make the length of your force arrows proportional to the strength of the forces.
4. Identify electrical forces around you. How could you demonstrate their existence?
5. **Critical Thinking** Suppose you are testing Coulomb's law using a small, positively-charged plastic sphere and a large, positively-charged metal sphere. According to Coulomb's law, the force depends on $1/d^2$, where d is the distance between the centers of the spheres. As the spheres get close together, the force is smaller than expected from Coulomb's law. Explain.

CHAPTER 20 REVIEW

Key Terms

20.1
- electrostatics
- neutral
- insulator
- conductor

20.2
- electroscope
- charging by conduction
- charging by induction
- Coulomb's law
- coulomb
- elementary charge

Summary

20.1 Electrical Charge

- There are two kinds of electrical charge, positive and negative. Like charges repel; unlike charges attract.
- Electrical charge is not created or destroyed; it is conserved.
- Objects can be charged by the transfer of electrons.
- Charges added to one part of an insulator remain on that part.
- Charges added to a conductor quickly spread over the surface of the object.

20.2 Electrical Force

- When an electroscope is charged, electrical forces cause its thin metal leaves to spread.
- An object can be charged by conduction by touching a charged object to it.
- To charge an object by induction, a charged object is first brought nearby, causing a separation of charges. Then the object to be charged is separated, trapping opposite charges on the two halves.
- Coulomb's law states that the force between two charges varies directly with the product of their charge and inversely with the square of the distance between them.
- The SI unit of charge is the coulomb. One coulomb (C) is the magnitude of the charge of 6.25×10^{18} electrons or protons. The elementary charge, the charge of the proton or electron, is 1.60×10^{-19} C.

Key Equation

20.2

$$F = K\frac{q_A q_B}{d^2}$$

Reviewing Concepts

Section 20.1

1. If you comb your hair on a dry day, the comb can become positively charged. Can your hair remain neutral? Explain.
2. List some insulators and conductors.
3. What property makes metal a good conductor and rubber a good insulator?

Section 20.2

4. Why do socks taken from a clothes dryer sometimes cling to other clothes?
5. If you wipe a stereo record with a clean cloth, why does the record then attract dust?
6. The combined charge of all electrons in a nickel is hundreds of thousands of coulombs. Does that imply anything about the net charge on the coin? Explain.
7. How does the distance between two charges impact the force between them? If the distance is decreased while the charges remain the same, what happens to the force?
8. Explain how to charge a conductor negatively if you have only a positively charged rod.

Applying Concepts

9. How does the charge of an electron differ from the charge of a proton?
10. Using a charged rod and an electroscope, how can you find whether or not an object is a conductor?
11. A charged rod is brought near a pile of tiny plastic spheres. Some of the spheres are attracted to the rod, but as soon as they touch the rod, they fly away in different directions. Explain.

12. Lightning usually occurs when a negative charge in a cloud is transported to Earth. If Earth is neutral, what provides the attractive force that pulls the electrons toward Earth?
13. Explain what happens to the leaves of a positively charged electroscope when rods with the following charges are nearby but not touching the electroscope.
   a. positive **b.** negative
14. Coulomb's law and Newton's law of universal gravitation appear to be similar. In what ways are the electrical and gravitational forces similar? How are they different?
15. The text describes Coulomb's method for obtaining two charged spheres, A and B, so that the charge on B was exactly half the charge on A. Suggest a way Coulomb could have placed a charge on sphere B that was exactly one third the charge on sphere A.
16. Coulomb measured the deflection of sphere A when spheres A and B had equal charges and were a distance d apart. He then made the charge on B one third the charge on A. How far apart would the two spheres then have to be for A to have the same deflection it had before?
17. Two charged bodies exert a force of 0.145 N on each other. If they are moved so that they are one fourth as far apart, what force is exerted?
18. The constant, K, in Coulomb's equation is much larger than the constant, G, in the universal gravitation equation. Of what significance is this?
19. Electrical forces between charges are enormous in comparison to gravitational forces. Yet we normally do not sense electrical forces between us and our surroundings, while we do sense gravitational interactions with Earth. Explain.

Problems

Section 20.2

20. Two charges, q_A and q_B, are separated by a distance, d, and exert a force, F, on each other. Analyze Coulomb's law and identify what new force will exist if
   a. q_A is doubled.
   b. q_A and q_B are cut in half.
   c. d is tripled.
   d. d is cut in half.
   e. q_A is tripled and d is doubled.
21. How many excess electrons are on a ball with a charge of -4.00×10^{-17} C?
22. How many coulombs of charge are on the electrons in a nickel? Use the following method to find the answer.
   a. Find the number of atoms in a nickel. A nickel has a mass of about 5 g. Each mole (6.02×10^{23} atoms) has a mass of about 58 g.
   b. Find the number of electrons in the coin. A nickel is 75% Cu and 25% Ni, so each atom on average has 28.75 electrons.
   c. Find how many coulombs of charge are on the electrons.
23. A strong lightning bolt transfers about 25 C to Earth.
   a. How many electrons are transferred?
   b. If each water molecule donates one electron, what mass of water lost an electron to the lightning? One mole of water has a mass of 18 g.
24. Two electrons in an atom are separated by 1.5×10^{-10} m, the typical size of an atom. What is the electrical force between them?
25. A positive and a negative charge, each of magnitude 1.5×10^{-5} C, are separated by a distance of 15 cm. Find the force on each of the particles.
26. Two negatively charged bodies, each charged with -5.0×10^{-5} C, are 0.20 m from each other. What force acts on each particle?
27. How far apart are two electrons if they exert a force of repulsion of 1.0 N on each other?
28. A force of -4.4×10^{3} N exists between a positive charge of 8.0×10^{-4} C and a negative charge of -3.0×10^{-4} C. What distance separates the charges?
29. Two identical positive charges exert a repulsive force of 6.4×10^{-9} N when separated by a distance of 3.8×10^{-10} m. Calculate the charge of each.
30. A positive charge of 3.0 μC is pulled on by two negative charges. One, -2.0 μC, is 0.050 m to the north and the other, -4.0 μC, is 0.030 m to the south. What total force is exerted on the positive charge?
31. Three particles are placed in a line. The left particle has a charge of -67 μC, the middle, $+45$ μC, and the right, -83 μC. The middle

particle is 72 cm from each of the others, as shown in **Figure 20–13.**

a. Find the net force on the middle particle.

b. Find the net force on the right particle.

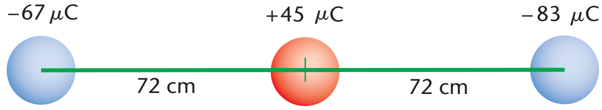


FIGURE 20–13

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

32. Three charged spheres are located at the positions shown in **Figure 20–14.** Find the total force on sphere B.

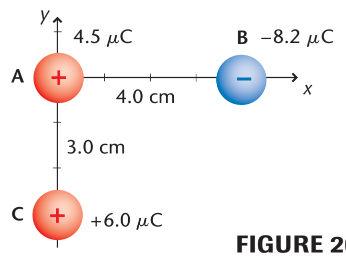


FIGURE 20–14

33. Two charges, q_A and q_B, are at rest near a positive test charge, q_T, of 7.2 μC. The first charge, q_A, is a positive charge of 3.6 μC, located 2.5 cm away from q_T at 35°; q_B is a negative charge of −6.6 μC, located 6.8 cm away at 125°.

a. Determine the magnitude of each of the forces acting on q_T.

b. Sketch a force diagram.

c. Graphically determine the resultant force acting on q_T.

34. The two pith balls in **Figure 20–15** each have a mass of 1.0 g and equal charge. One pith ball is suspended by an insulating thread. The other is brought to 3.0 cm from the suspended ball. The suspended ball is now hanging with the thread forming an angle of 30.0° with the vertical. The ball is in equilibrium with F_E, F_g, and F_T. Calculate each of the following.

a. F_g

b. F_E

c. the charge on the balls

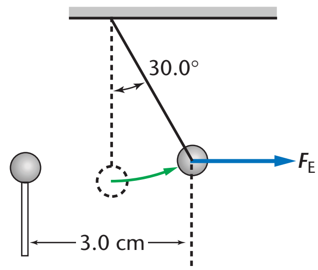


FIGURE 20–15

Going Further

Using a Graphing Calculator Determine how force depends on distance. A −1 μC charge is at $x = +8$ mm, and a +1 μC charge is at $x = -8$ mm. Find the force on a +1 μC test charge that is at $x = +10$ mm. Use Coulomb's law to calculate the force. Repeat for 11 mm, etc., until you reach 40 mm. Plot the force as a function of distance. One way to explore how the force depends on distance is to plot your results on log-paper. You also can plot the results on a calculator or computer. Use log scales on both the x and y axes.

The slope of the line, m, indicates the power to which x is raised. For example, if x changes by a factor of 10 and y changes by a factor of 1/100, then the slope is $m = -2$, and the force is proportional to x^{-2}. If the slope is not constant, then you cannot write an equation for the force as x^{-m}. Over what range of distances is the slope constant? What is its slope?

Essay Research and describe the historical development of the concept of electrical force.

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