16 Electric and Magnetic Forces

KEY IDEA

Electricity and magnetism are fundamental forces of nature.

PHYSICS AROUND US . . .
Late for Work at the Copy Center

Imagine waking up on a cold, dry winter day and discovering you're late for work. You rush to throw on your clothes and comb your hair with rapid, vigorous strokes. Looking in the mirror, you realize that the folds of your shirt are sticking together and your hair is standing on end. When you finally get to work, you try to photocopy an important report, only to find the copies sticking to each other, slowing your efforts. Static electricity has struck.

Imagine walking home from work on a hot, humid summer day, listening to a radio station on your headphones. The sky is dark and you hear the distant rumble of thunder. The radio has a lot of static. Suddenly, a jagged lightning bolt slices the horizon. You decide to take the subway and hurry to get home before the thunderstorm. You swipe your train pass through the turnstile, but it takes a couple of tries before it registers. Static electricity has, quite literally, struck again.

Believe it or not, the force that causes your clothes to stick together and your hair to stand on end in the cold, dry winter is exactly the same force that causes lightning in the hot, humid summer. It is the force of static electricity. The force that enables your radio to play and the card reader to operate is a different force, but it is affected by electricity. This is the force of magnetism. We examine both of these forces in this chapter.

NATURE'S OTHER FORCES

According to Newton's laws of motion, nothing accelerates without a force. However, the law of gravitational force that Newton described cannot explain many everyday events. How does a refrigerator magnet cling to metal, defying gravity? What makes a compass needle swing around to the north? How could gravity make static cling wrinkle your shirt or lightning shatter an old tree? These phenomena point to the existence of underlying forces that are different from gravity.

The forces we are talking about have been known (and even used) by people for a long time. They go by the names "electricity" and "magnetism." In this chapter, we explore the properties of these forces. In the next chapter, we look at one of the most amazing facts about them—the fact that they are connected to one another, despite their apparent differences.

Newton may not have thought much about electricity and magnetism, but he did give us a method for studying them: First, observe natural phenomena and learn how they behave. Then, organize those observations into a series of natural laws. Finally, use those laws to predict future behavior of the physical world. This is the process we have called the *scientific method.*

In particular, we find Newton's first law of motion (see Chapter 4) to be very useful in our investigation of nature's other forces. According to this law, whenever we see a change in the motion of any material object, we know that a net force has acted to produce that change. Thus, whenever we see such a change and can rule out the action of known forces such as gravity, we can conclude that the change must have been caused by a hitherto unknown force. We use this line of reasoning to show that electric and magnetic forces exist in the natural world.

STATIC ELECTRICITY

The modern understanding of static electricity began in the eighteenth century with a group of scientists in Europe and North America who called themselves "electricians." These researchers were fascinated by the many curious phenomena associated with nature's unseen forces. Their thoughts were not focused on practical applications, nor could they have imagined how their work would transform the world.

Various phenomena related to electricity have been known since ancient times. The Greeks knew that if you rub a piece of amber with cat's fur and then touch other objects with the amber, those other objects repel one another. The same thing happens, they found, if you rub a piece of glass with silk: objects touched with the glass repel one another. On the other hand, if you bring objects that have been touched with the amber near objects touched with the glass, they attract one another. Objects that behave in this way are said to possess **electric charge,** or to be "charged."

The force that moves objects toward and away from one another in these simple demonstrations was named **electricity** (from "electro," the Greek word for amber). In these simple experiments, the electric charge doesn't move once it has been placed on an object, so the force is also called **static electricity.**

The electric force is clearly different from gravity. Unlike the electric force, gravity is never repulsive: when a gravitational force acts between two objects,

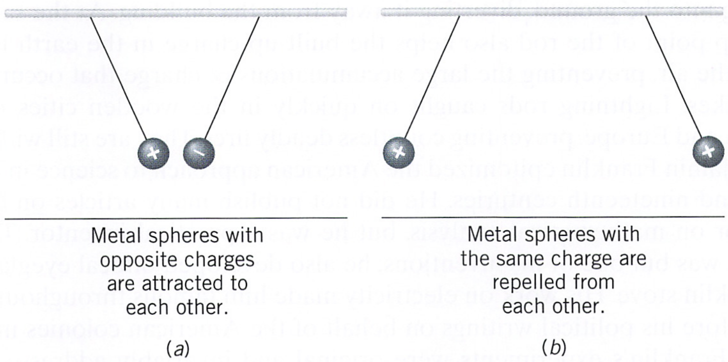


FIGURE 16-1. There are two kinds of electric charges, designated positive and negative. (*a*) Opposite charges attract, while (*b*) like charges repel.

When the girl touches the electrically charged sphere, her hair becomes electrically charged as well. Individual hairs repel one another and thus stand on end.

it always pulls them together. The electric force, on the other hand, can attract some objects toward one another and push other objects apart. The electric force, furthermore, is vastly more powerful than gravity. A pocket comb charged with static electricity easily lifts a piece of paper against the gravitational pull of the entire Earth.

Today, we understand that the properties of the electric force arise from the existence of two kinds of electric charge (Figure 16-1). We say that objects touched by the same source, be it amber or glass, have the same electric charge and are repelled from one another. On the other hand, an object touched with amber has a different electric charge than a second object touched with glass. This difference is reflected in their behavior—they attract one another. We can summarize this behavior by saying

Like charges repel each other, unlike charges attract each other.

Physics in the Making

Benjamin Franklin and Electric Charge

The most famous North American "electrician" was Benjamin Franklin (1706–1790), one of the pioneers of electrical science as well as a central figure in the founding of the United States of America. Franklin began his electric experiments in 1746 with a study of electricity generated by friction. Most scientists of the time thought that electric effects resulted from the interaction of two different electric fluids. Franklin, however, became convinced that the transfer of a single electric fluid from one object to another could explain all electric phenomena. He realized that objects could have an excess or a deficiency of this fluid, and he applied the names negative and positive to these two situations.

Following this work, Franklin demonstrated the electric nature of lightning in June 1752 with his famous (and extremely dangerous) kite experiment. A mild lightning stroke hit his kite and passed along the wet string to produce sparks and an electric shock. Not content with acquiring theoretical knowledge, Franklin followed his discovery of the electric nature of lightning with the invention of the lightning rod, a metal rod with one end in the ground and the other end sticking up above the roof of a building. The rod carries the electric charge of

Lightning rods allow charge accumulated in the ground during thunderstorms to leak harmlessly into the air. If the charge becomes great enough, lightning can be attracted to the metal rod and the electricity run harmlessly into the ground. Benjamin Franklin first introduced lightning rods such as this.

lightning into the ground, diverting it away from the building. At the same time, the sharp point of the rod also helps the built-up charge in the earth leak gently into the air, preventing the large accumulations of charge that occur in lightning strikes. Lightning rods caught on quickly in the wooden cities of North America and Europe, preventing countless deadly fires. They are still widely used.

Benjamin Franklin epitomized the American approach to science in the eighteenth and nineteenth centuries. He did not publish many articles on electrical theory or on mathematical analysis, but he was a practical inventor. The lightning rod was but one of his inventions; he also developed bifocal eyeglasses and the Franklin stove. His work on electricity made him famous throughout Europe years before his political writings on behalf of the American colonies made him famous. Franklin's experiments were original and invariably addressed key issues in the science he was investigating. His practical approach made him the pioneer of American engineers and inventors, whose successors included Joseph Henry (the man behind the electrical transformer), Alexander Graham Bell (the telephone), Thomas Edison (the lightbulb, the phonograph, moving pictures) and the Wright Brothers (the airplane). ●

The Movement of Electrons

We now understand that there are two kinds of electric charge, called *positive* and *negative* after Franklin's terminology. This fact enables us to explain observations of both the attractive and repulsive behavior of charged objects. As we have seen in Chapter 9, all objects are made up of minute building blocks called *atoms*. As we'll see in Chapter 21, atoms are made up of still smaller particles, many of which have an electric charge. In the modern view, negatively charged electrons move around a heavy, positively charged nucleus located at the center of every atom. Electrons and the nucleus have opposite electric charges, so an attractive force exists between them. This force in atoms plays a role similar to that played by gravity in keeping the solar system together. Most atoms are electrically neutral because the positive charge of the nucleus cancels the negative charge of the electrons. (Again, we stress that, in speaking of electric charge in terms of electrons, we are applying modern ideas. Benjamin Franklin didn't even know about atoms, much less electrons and nuclei.)

Electrons, particularly those in the outer orbits, tend to be rather loosely bound to their parent nucleus. These electrons can be removed from the atom and, once removed, can move freely (until attracted to some other positive charge). When electrons are pulled out of a material, they no longer cancel the positive charges in the nuclei. The result is a net excess of positive charge in the object, and we say that the object as a whole has acquired a positive electric charge. Similarly, an object acquires a negative electric charge when extra electrons are pushed onto it. This happens when you run a comb through your hair on a dry day: electrons are knocked onto the comb from your hair, so the comb acquires a negative charge. Simultaneously, your hair loses electrons, so individual strands become positively charged.

During a thunderstorm, the same transfer of charge occurs on a much larger scale as wind and rain disrupt the normal distribution of electrons in clouds. When a negatively charged cloud passes over a tall tree or tower, the violent electric discharge called lightning may result from the attraction of positive charges on the ground and negative charges in the cloud. (Note that in the case of lightning, both the positive and negative charges move.)

Although historical investigations of electric charge tended to concentrate on somewhat artificial experiments, we have come to know that electrically charged particles play important roles in many natural systems. For example, virtually all the atoms in the Sun have lost electrons and thus are positively charged. Atoms that have lost or gained electrons from their normal neutral state are called **ions.** Ions may be positive (the atom has lost electrons) or negative (the atom has gained electrons). In all advanced life forms, including human beings, ions routinely move into and out of cells to maintain the processes of life. As you read these words, for example, positively charged potassium and sodium ions are moving across the membranes of cells in your optic nerve to carry signals to your brain.

Some Facts About Electric Charge

If we think of the electric charge on an object as being the sum of the electric charges on particles in that object's atoms, then several interesting points follow.

1. **Objects can acquire an electric charge through friction,** which allows electrons to move from one body to another. In the examples already discussed, electrons move either to or from an object being rubbed, depending on the details of the materials involved. If electrons move out, the object becomes positively charged; if electrons move in, it becomes negatively charged.
2. **Objects can acquire a charge through the process of induction.** Suppose you have a metal ball, as shown in Figure 16-2, and you bring a negatively charged object near it. The negatively charged electrons are repelled and move to the far side of the ball. If you give them a way of moving away from the metal ball (for example, by connecting a wire between the ball and the ground, as shown), the electrons leave the ball. If you now disconnect the wire and then take the original negatively charged object away, you will find that the ball has a positive charge (because it has lost some of its electrons) even though it was never touched by any charged object. This process is known as charging by induction.

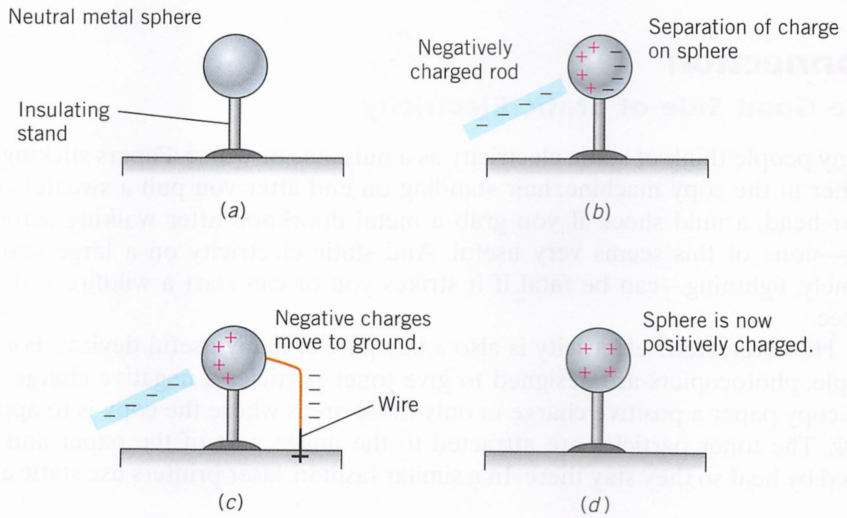


FIGURE 16-2. A hollow metal sphere illustrates the process of charging by induction. (*a*) The sphere is initially neutral. (*b*) If a negatively charged rod is brought close to the sphere, charges redistribute on the sphere's surface. (*c*) Negative charge can be drained off the far side of the sphere. (*d*) The result is a positively charged sphere, even though the rod did not touch it.

Develop Your Intuition: Charging by Induction

How can you use induction to produce a negatively charged metal ball?

In this case, you connect the wire to the metal ball and bring up a positively charged object. Electrons in the metal ball move toward the positively charged object, leaving the far side of the ball with a positive charge. Electrons from the ground are then attracted to that positive charge and flow into the ball. Remove the wire and the ball will have acquired a negative charge because of those excess electrons.

3. **The total amount of electric charge in a closed system remains the same.** If electric charge is really carried as discrete particles inside the atom and if in the normal course of affairs these particles are not created or destroyed, then an important consequence follows. If you think of these particles as being like two colors of marbles in a jar, then there are many things you can do—you can move one or both colors around, put them in other jars, put some back in the original jar, and so on. However, no matter what you do, the total number of marbles of each color remains the same. In just the same way, the total number of positive and negative charges in a closed system stays the same, which means that the net charge on that system does not change. In the language we introduced in Chapter 6, the electric charge of a system is conserved, a result that is known as the law of **conservation of electric charge.**
4. **The basic unit of electric charge is the coulomb.** Like other physical quantities, the amount of electric charge on an object can be measured and assigned a unit. In the case of electric charge, that unit is called the *coulomb* (C) after a French scientist whose work we will describe in a moment. The easiest way to think of the coulomb is to say that if you have a pile of 6.25×10^{18} electrons, the magnitude of their total charge is 1 coulomb. This may seem like a very large number of electrons, but remember that electrons are very small. For reference, if you turn on an ordinary reading lamp, about this many electrons pass by a point in the wire each second.

Connection

The Good Side of Static Electricity

Many people think of static electricity as a nuisance or worse. Papers sticking together in the copy machine, hair standing on end after you pull a sweater over your head, a mild shock if you grab a metal doorknob after walking across a rug—none of this seems very useful. And static electricity on a large scale—namely, lightning—can be fatal if it strikes you or can start a wildfire if it hits a tree.

However, static electricity is also a key part of many useful devices. For example, photocopiers are designed to give toner particles a negative charge and the copy paper a positive charge in only those areas where the copy is to appear dark. The toner particles are attracted to the image part of the paper and are fused by heat so they stay there. In a similar fashion, laser printers use static electricity to attract toner particles to those places where the laser has hit on the paper being printed (Figure 16-3).

Large electrostatic precipitators are used in industry to remove particles of soot and dust from waste gases released to the environment. The tiny particles are attracted to a charged grid as the exhaust fumes pass through the smokestack; it is then a simple matter to turn off the grid and remove the accumulated soot without having it become air pollution.

On a more basic level, atoms in molecules are held together in chemical bonds by electrostatic forces. In fact, atoms consist of positive protons and negative electrons held together by their electric force of attraction. It's hard to think of a more fundamental force than that!

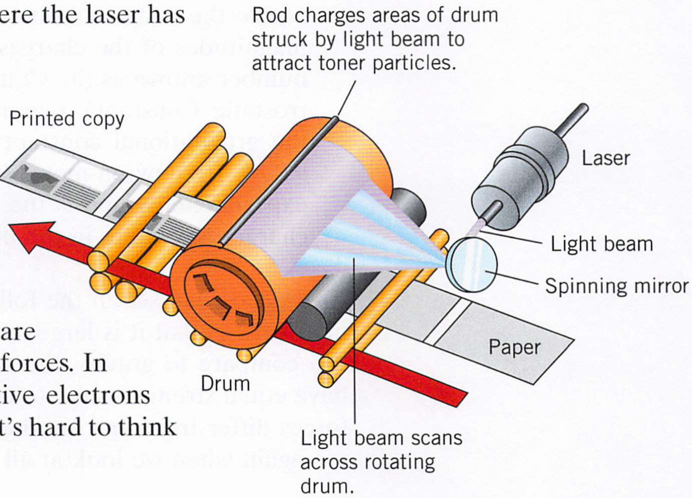


FIGURE 16-3. In a laser printer, light from a laser beam scans across a rotating drum, affecting the ability of the drum to hold a charge. A rod then applies a charge of static electricity to only those areas of the drum struck by the light. These areas attract toner particles, which are then pressed against the paper to be printed.

COULOMB'S LAW

Electricity remained something of a mild curiosity until the mid-eighteenth century, when scientists began applying the scientific method to investigate it. One of the first tasks was to develop a precise statement about the nature of the electric force. The French scientist Charles Augustin de Coulomb (1736–1806) was most responsible for this work. During the 1780s, at the same time the United States Constitution was being written by Benjamin Franklin and others, Coulomb devised a series of experiments in which he passed different amounts of electric charge onto objects and then measured the force between them.

Coulomb observed that if two electrically charged objects are moved farther away from one another, the force between them gets smaller, just as with gravity. In fact, if the distance between two objects is doubled, the force decreases by a factor of four—the familiar 1/distance^2, or inverse-square relationship, that we have seen in the law of universal gravitation in Chapter 5. Coulomb also discovered that the size of the force depends on the product of the charges of the two objects—double the charge on one object and the force doubles, double the charge on both objects and the force increases by a factor of four, and so on.

After repeated measurements, Coulomb summarized his discoveries in a simple relationship known as **Coulomb's law:**

1. In words:

The force between any two electrically charged objects is proportional to the product of their charges divided by the square of the distance between them.

2. In an equation with words:

$$\text{Force (in newtons)} = k \times \frac{\text{First charge} \times \text{Second charge}}{(\text{Distance between them})^2}$$

3. In an equation with symbols:

$$F = k \times \frac{q_1 \times q_2}{d^2}$$

where the distance d between the two charges is measured in meters; the magnitudes of the charges q_1 and q_2 are measured in coulombs; and k is a number known as the Coulomb constant (also known as the Universal Electrostatic Constant) a number that plays the same role in electricity that the gravitational constant G plays in gravity. In SI units, k has the value 9.00×10^9 newton-meter²/coulomb². This number, like G, can be determined experimentally and is the same for all charges and all separations of those charges anywhere in the universe.

As you can see in the following example, the most striking thing about the number k is that it is large. In fact, now that we have a force in nature that we can compare to gravity, the first thing we notice is that the two forces do not have equal strengths: one (electricity) is much stronger than the other. Nature's forces differ from one another—this is a feature of the world we live in, as we see again when we look at all the fundamental forces in Chapter 27.

EXAMPLE 16-1

Electric and Gravitational Forces Compared

The simplest atom is hydrogen, in which a single electron circles a single positively charged particle known as a *proton* (Figure 16-4). The masses of the electron and proton are 9×10^{-31} kg and 1.7×10^{-27} kg, respectively. The charge on the proton is 1.6×10^{-19} C, and the charge on the electron has the same magnitude but is negative. A typical separation of these two particles in an atom is 10^{-10} m. Given these numbers, what are the values of the electric versus the gravitational forces of attraction between these two particles?

REASONING AND SOLUTION: We need to apply Newton's equation for gravitational force (which requires two masses and a distance) and Coulomb's equation for electric force (which requires two charges and a distance).

For gravity, the force between an electron and a proton is

$$F \text{ (in newtons)} = \frac{G \times \text{Mass}_1 \text{ (kg)} \times \text{Mass}_2 \text{ (kg)}}{\text{Distance}^2 \text{ (m)}}$$

$$= \frac{(6.7 \times 10^{-11} \text{ m}^3/\text{kg-s}^2) \times (1.7 \times 10^{-27} \text{ kg}) \times (9 \times 10^{-31} \text{ kg})}{(10^{-10} \text{ m})^2}$$

$$= 1.0 \times 10^{-47} \text{ N}$$

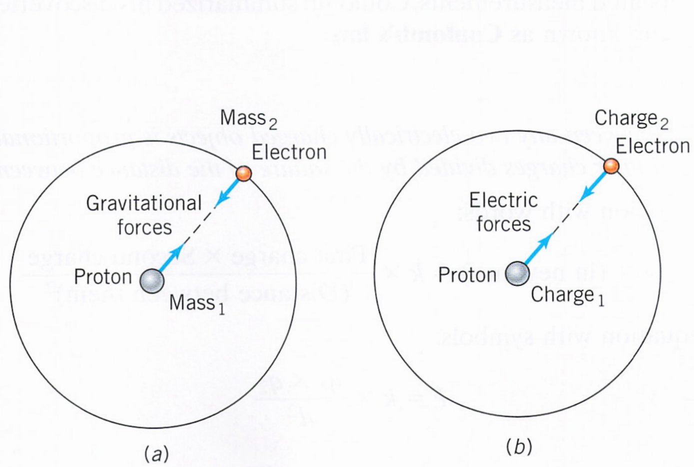


FIGURE 16-4. The gravitational attraction between an electron and a proton in a hydrogen atom (*a*) is many orders of magnitude smaller than the electrical attraction between these two charged particles (*b*).

For electricity, the force between these two charged particles is

$$F \text{ (in newtons)} = \frac{k \times \text{Charge}_1 \text{ (C)} \times \text{Charge}_2 \text{ (C)}}{\text{Distance}^2 \text{ (m)}}$$

$$= \frac{(9 \times 10^9 \text{ N-m}^2/\text{C}^2) \times (1.6 \times 10^{-19} \text{ C}) \times (1.6 \times 10^{-19} \text{ C})}{(10^{-10} \text{ m})^2}$$

$$= 2.3 \times 10^{-8} \text{ N}$$

From this calculation we can see that, in the atom, the electric force (2.3×10^{-8} N) is many orders of magnitude (or factors of 10) larger than the gravitational force (1.0×10^{-47} N). This is why, in our discussion of the atom in subsequent chapters, we ignore the effects of gravity completely.

Polarization

Because of the inverse square nature of Coulomb's law, it is possible for an object to exert an electric force even though it has no net electric charge. For example, in some molecules the internal structure is such that the positive charges are located on one side of the molecule and the negative charges on the other, as shown in Figure 16-5. In this case, the total charge on the molecule is 0. However, if we put an electric charge at a point near the molecule, such as the point labeled *A* in Figure 16-5*b*, then an electric force appears on the molecule. This net electric force occurs because the force exerted by the charge at *A* on the negative charges on the molecule is greater than the force exerted on the positive charges, simply because the negative charges are closer to point *A*. This effect, known as *polarization*, is common in nature. In fact, it occurs whenever the charge within a molecule is not distributed symmetrically.

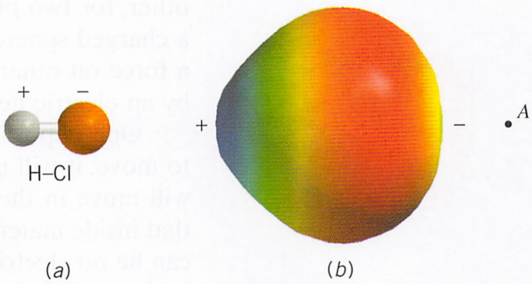


FIGURE 16-5. (*a*) A polar molecule such as HCl (hydrogen chloride, which dissolves in water to form hydrochloric acid) is electrically neutral, but it has regions that are more positive and regions that are more negative. Such a molecule will align itself with an electric field. (*b*) These electrically charged regions can be represented by colors—red for negative and blue for positive.

You see the results of polarization every day in the behavior of ordinary water. Water molecules, which are composed of two hydrogen atoms linked to one oxygen atom, have a negatively charged side and a positively charged side. When you sprinkle the compound sodium chloride (ordinary salt crystals) into water, the positively charged sodium atoms and negatively charged chlorine atoms interact with the positive and negative sides of water molecules. These forces enable the salt to dissolve in the water.

The Electric Field

Imagine that you have an electric charge sitting at a point. The charged object could be a piece of lint, an electron, or one of your hairs. If you brought a second charged object to a spot near the first, the second object would feel a force. If you then moved the second object to another spot, it would still feel a force, but the force would, in general, have a different magnitude and point in a different direction than at the first spot. In fact, the second charged object would feel a force at every point in space around the first object.

You can make a picture that represents this fact, as in Figure 16-6. The arrow at each point around a positively charged object represents the force that would be felt by a second, tiny, positively charged object if that second object

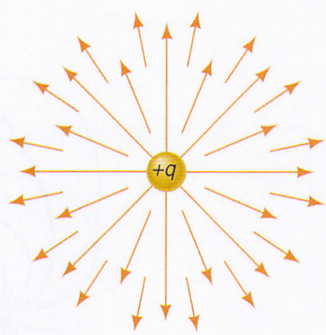


FIGURE 16-6. An electric field surrounding a positive charge, $+q$, may be represented by arrows radiating outward. Any charged object that approaches $+q$ experiences a greater electric force the closer it gets. Positively charged objects are repelled, while negatively charged objects are attracted.

were brought to the point in space where the arrow originates. The collection of all the arrows that represent these forces is called the **electric field** of the original charged object. We can think of every charged object as being surrounded by such a field, as shown in the figure. Notice that the electric field is defined as the force that would be felt by a positive charge if that charge were located at a particular point, so that the field is present even if no other charge is actually there.

Technically, the electric field at a point is defined as the force that would be felt by a +1-coulomb charge if it were brought to that point. The field is usually drawn so that the direction of the arrow corresponds to the direction of that force and the length of the arrow corresponds to its magnitude. Figure 16-7 shows the shape of the electric field for two equal and opposite charges near one another, for two plates with equal and opposite electric charges on them, and for a charged sphere. In each case, the fact that the charge on the object can exert a force on other charges means that we can envision the object as surrounded by an electric field that permeates space.

One important point about electric fields is that if a positive charge is free to move, it will move in the direction indicated by the field. (A negative charge will move in the direction opposite to that indicated by the field.) This means that inside materials such as metals, in which there are many free electrons, there can be no electric field at all. If there were, the electrons would move until they had changed the charge configuration in such a way as to cancel the field. This phenomenon, known as *shielding,* illustrates an important difference between the electric and gravitational fields (see Chapter 5). Nothing can shield the gravitational force—Earth pulls on you whether you're inside your car or not. The metal casing of the car, however, can shield you from electric fields generated on the outside. This is why the safest place to be in a lightning storm is inside a metal container such as a car. The charges in the lightning bolt may move around the car's surface, but they (and their attendant fields) can't establish a stable field

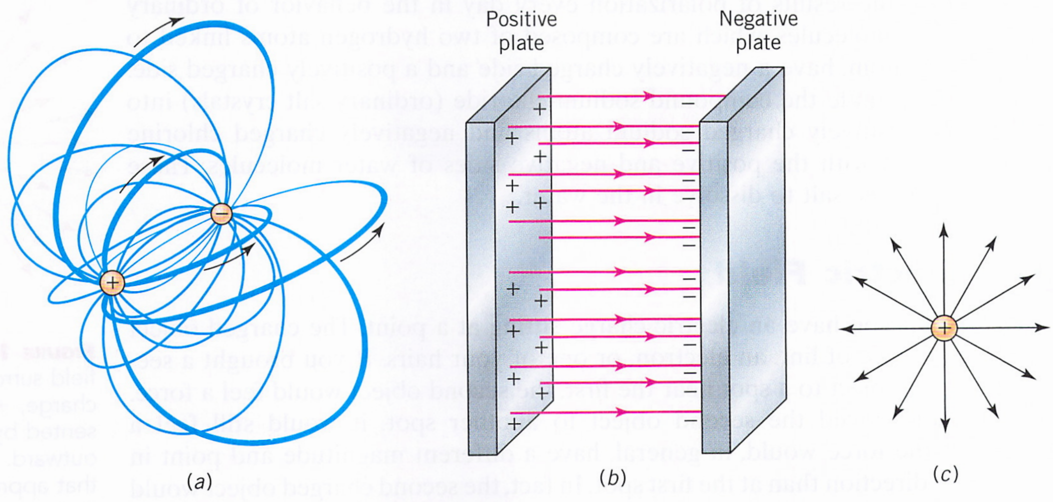
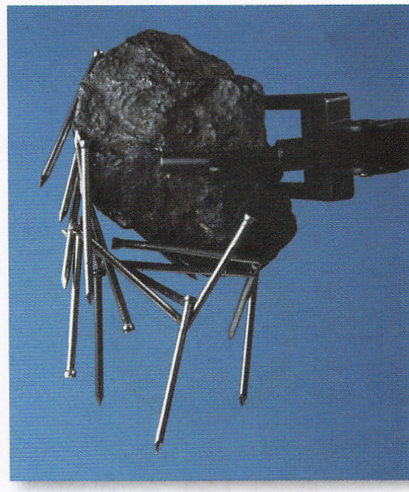


FIGURE 16-7. Electric fields may be represented as lines connecting positively and negatively charged objects. A positively charged object will move in the direction of the field lines. (*a*) Two equal and opposite charges near one another. (*b*) Two flat plates with equal and opposite electric charges. (*c*) A charged sphere.

within the shielding provided by the metal surfaces. For the same reason, airplanes can fly in bad weather without putting the passengers at risk of lightning strikes.

MAGNETISM

Just as electricity was known to the ancient philosophers, so too was the phenomenon we call *magnetism.* The first known **magnets** were naturally occurring iron minerals. If you bring one of these minerals (a common one is called "magnetite," or "lodestone") near a piece of iron, the iron is attracted to it. You have undoubtedly seen experiments in which magnets were placed near nails, which jumped up and hung from the magnets.



The common mineral magnetite is a natural magnet.

Nails are electrically neutral, so electrical attraction doesn't make the nails move. Similarly, gravity cannot cause the nails to jump up. The fact that the nails behave in this way tells you that there must be yet another force in nature, a force different from both electricity and gravity. The simple experiment of picking up a nail with a magnet illustrates beyond a shadow of a doubt that there is a **magnetic force** in the universe—a force that can be identified and described by the same methods we used to investigate gravity and electricity.

Whereas electricity remained a curiosity until well into modern times, magnetism was put to practical use very early. The compass, invented in China and used by Europeans to navigate the oceans during the age of exploration, is the first magnetic device on record. A sliver of lodestone, left free to rotate in a horizontal plane, will align itself in a north-south direction. We use compasses so often these days that it's easy to forget how important it was for early travelers to know directions, particularly travelers who ventured in sailing ships out of sight of land.

In the late sixteenth century, the English scientist William Gilbert (1544–1603) conducted the first serious study of magnets. Although revered in his day as a doctor (he was physician to both Queen Elizabeth I and King James I), his most lasting fame came from his discovery that every magnet can be characterized by what he called *poles.* If you take a piece of naturally occurring magnet and let it rotate, one end of the magnet points north and the other end points south. These two ends of the magnet are called **poles** and are given the labels **north** and **south.**

In the course of his research, Gilbert discovered many important properties of magnets. He learned to magnetize iron and steel rods by stroking them with a lodestone. He discovered that hammered iron becomes magnetic and that the iron's magnetism can be destroyed by heating. He realized that Earth itself is a giant magnet, a fact that, as we shall see, explains the operation of the compass.

Gilbert also documented many of the most basic aspects of the magnetic force. He found that if two magnets are brought near one another so that the north poles are close together, a repulsive force develops between the magnets and they are forced apart. The same thing happens if two south poles are brought together. However, if the north pole of one magnet is brought near the south pole of another magnet, the resulting force is attractive. In this respect, studies of magnetism seem to mimic the eighteenth-century studies of static electricity. William Gilbert's results can be summarized in a simple statement:

Every magnet has two poles; like magnetic poles repel each other, while unlike poles attract each other.

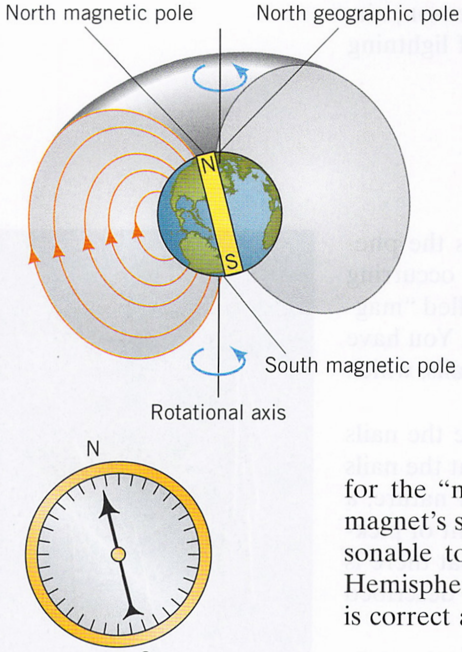


FIGURE 16-8. A compass needle and Earth. Any magnet will tend to twist because of the forces between its poles and those of Earth. Note that Earth's north and south magnetic poles don't quite line up with Earth's axis of rotation.

Once you know that a magnet has two poles, you can understand how a compass behaves. Earth itself is a giant magnet, with one pole in northern Canada and the other pole in Antarctica. If a piece of magnetized iron (for example, a compass needle) is allowed to rotate freely, one of its poles will be attracted to and twist around toward Canada in the north, and the other end will point to Antarctica in the south (see Figure 16-8). There is a confusing matter of nomenclature we need to address here. The first people who used magnetic compasses understandably painted an "N" on the pole that pointed north. Given that we now know that opposite magnetic poles attract each other, we have two options: (1) We can call the pole labeled "N" the north pole of the compass, in which case it is the south magnetic pole of the Earth that is located in Canada. Alternatively, we can say that the north magnetic pole of the Earth is located in Canada and that the "N" on the magnetic compass stands for the "north-seeking pole," with the understanding that this is actually the magnet's south pole. Since many people (the authors included) find it more reasonable to keep north poles, either magnetic or geographic, in the Northern Hemisphere, the second option is the one most used. Either procedure, however, is correct and consistent with what we know about magnets.

The Magnetic Field

Just as the electric force can be represented in terms of an electric field, so too can the magnetic force be represented in terms of a magnetic field. If a small compass needle is brought near a magnet, as shown in Figure 16-9, the forces exerted by the magnet twist the needle around. (In the language of Chapter 7, we say that the forces exert a torque on the compass needle.) In general, the needle's direction is different at different locations around the magnet.

We can imagine mapping out a magnetic field by using the procedure shown in Figure 16-9. We lay down a large magnet and then bring a compass needle, as shown, to its north pole. The compass aligns itself, pointing toward the magnet's north pole. After the needle has settled down, we bring up another compass and align it nose to tail with the first, then bring up a third, a fourth, and so on until we have a line of compasses stretching from the north to the south pole of the original magnet, as shown. We draw a line through these compasses and then repeat the operation for other initial orientations of the first compass. This results in a series of lines around the magnet, as shown in Figure 16-10*a*.

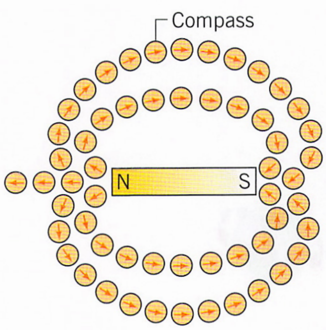


FIGURE 16-9. Magnetic field lines curve from the north pole to the south pole of a magnetic dipole. Small compass needles placed in this field will align with these field lines.

Just as we can imagine any collection of electric charges as being surrounded by an electric field—imaginary field lines—we can imagine every magnet as being surrounded by an imaginary set of lines such as those in the figure. These lines are drawn so that if a compass were brought to a point in space, the needle would turn and point along the line passing through that point. The number of lines in a given area is a measure of the strength of the forces exerted on the compass. Collections of lines that map out the directions in which compass needles would point are called **magnetic field lines.** They help us visualize the shape of the **magnetic field** around a magnetized object.

The magnetic field shown in Figure 16-10 is a particularly important one because it is the field associated with a bar magnet with a north and a south pole, called a *dipole field,* and we encounter this sort of field often in the natural world.

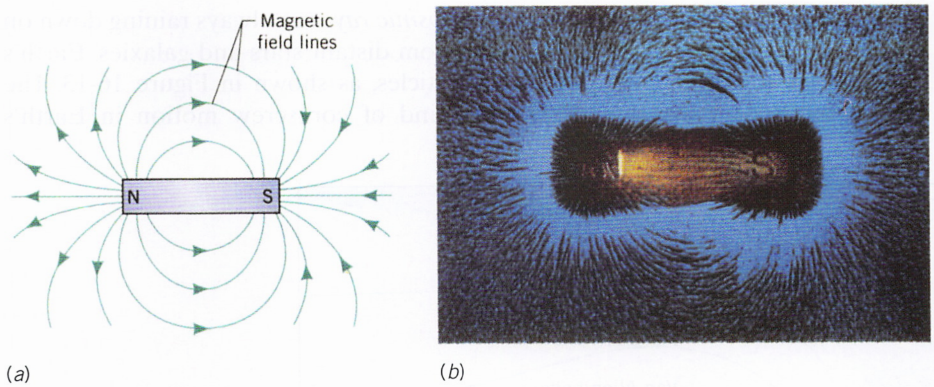


FIGURE 16-10. (*a*) A bar magnet and its magnetic dipole field. (*b*) Iron filings placed near a bar magnet align themselves along the field.

Isolated Magnetic Poles

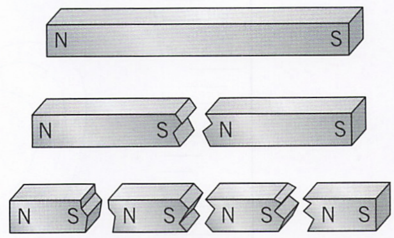


FIGURE 16-11. Cut magnets. If you break a dipole magnet in two, you get two smaller dipole magnets, not an isolated north or south pole.

All magnets found in nature have both north and south poles—you never find one without the other. Even if you take an ordinary bar magnet and cut it in two, you don't get a north and a south pole in isolation. Instead, you get two small magnets, each with a north and a south pole (Figure 16-11). If you take each of those halves and cut it in half, you will continue to get smaller and smaller dipole magnets. In fact, it seems to be a general rule of nature that

There are no isolated magnetic poles in nature.

In the language of physicists, a single isolated north or south magnetic pole would be called a "magnetic monopole." Although physicists have conducted extensive searches for monopoles, no experiment has yet found unequivocal evidence for their existence. In the next chapter we see why.

MAGNETIC FORCES ON CHARGED PARTICLES

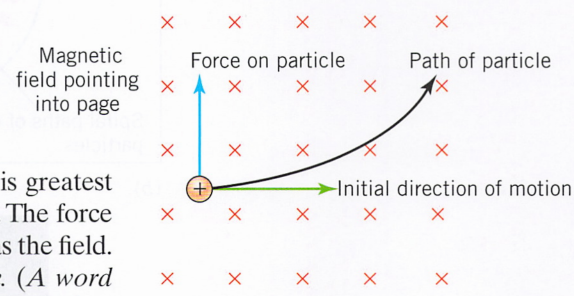


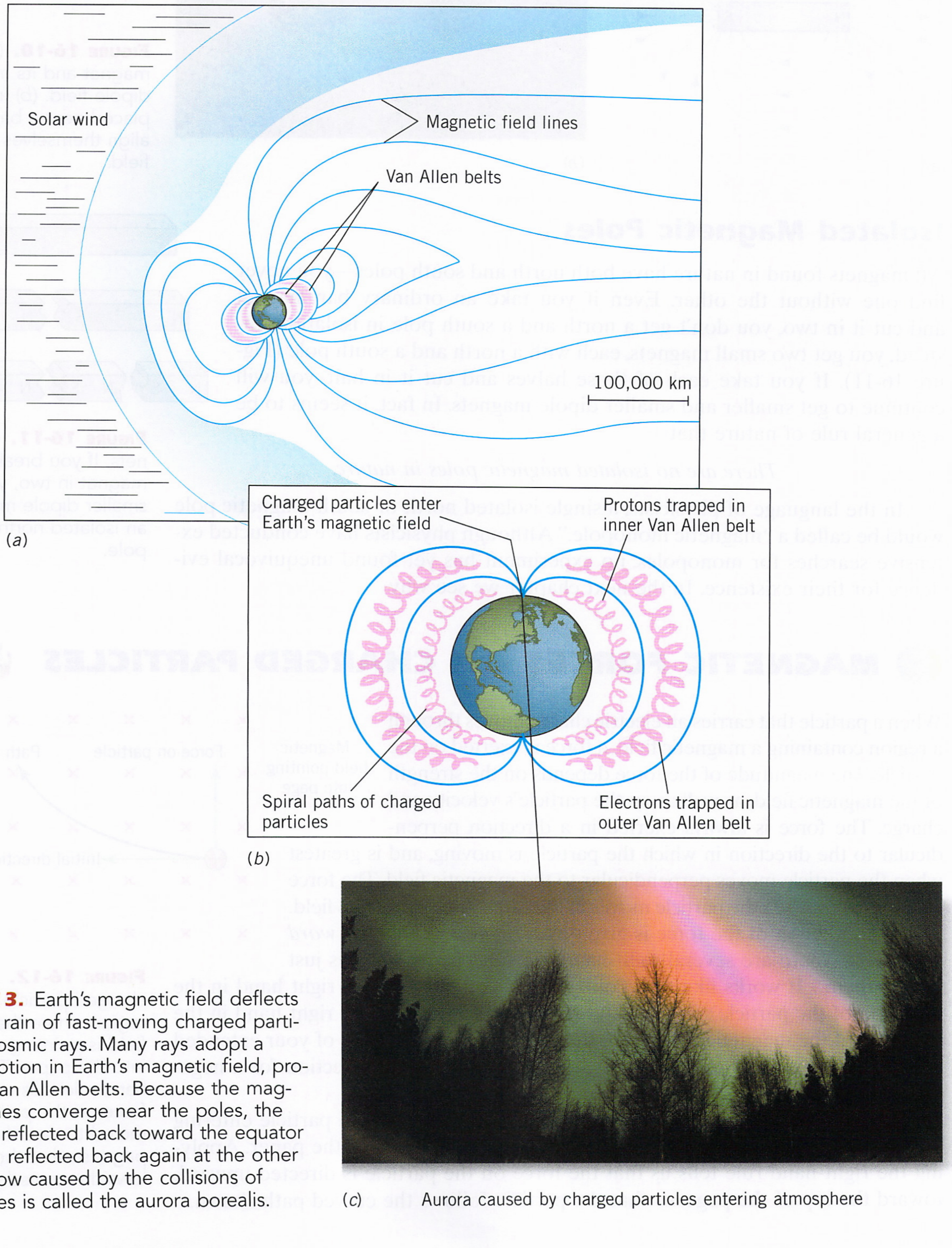
FIGURE 16-12. A positively charged particle enters a region where the magnetic field is pointing downward into the paper. The right-hand rule tells us that the force on the particle is directed toward the top of the page, so that the particle follows the curved path shown.

When a particle that carries an electric charge moves through a region containing a magnetic field, a force is exerted on the particle. The magnitude of the force depends on the strength of the magnetic field, as well as on the particle's velocity and charge. The force is always exerted in a direction perpendicular to the direction in which the particle is moving, and is greatest when the particle moves perpendicular to the magnetic field. The force becomes zero when the particle moves in the same direction as the field.

The direction of the force is given by a *right-hand rule.* (*A word of caution:* There are several right-hand rules in physics—this is just one of them.) It works like this: Point the index finger of your right hand in the direction of the particle's motion and the middle finger of your right hand in the direction of the magnetic field. Then the force is in the direction of your extended thumb for a positively charged particle and in the opposite direction for a negatively charged one.

For example, in Figure 16-12 we show a positively charged particle entering a region where the magnetic field is pointing into the plane of the paper. Applying the right-hand rule tells us that the force on the particle is directed upward, toward the top of the page, so that the particle follows the curved path shown.

Fast-moving charged particles called *cosmic rays* are always raining down on Earth. Some come from the Sun, others from distant stars and galaxies. Earth's magnetic field deflects some of these particles, as shown in Figure 16-13. The curved paths of some rays describe a kind of corkscrew motion in Earth's



Aurora caused by charged particles entering atmosphere

FIGURE 16-13. Earth's magnetic field deflects the constant rain of fast-moving charged particles called cosmic rays. Many rays adopt a corkscrew motion in Earth's magnetic field, producing the van Allen belts. Because the magnetic field lines converge near the poles, the particles are reflected back toward the equator and are then reflected back again at the other pole. The glow caused by the collisions of these particles is called the aurora borealis.

magnetic field, producing what are called the *Van Allen belts* (named after the American physicist James Van Allen, who discovered them in 1958). These two rings consist of particles that travel corkscrew paths up and down between Earth's poles. Because the magnetic field lines begin to converge near the poles, the particles are reflected back toward the equator and are then reflected back again at the other pole.

When Earth's magnetic field is distorted (as it often is when massive numbers of particles are thrown outward from the Sun), charged particles in the van Allen belts actually enter the atmosphere, producing the beautiful displays known as the "northern lights," or *aurora borealis,* and "southern lights," or *aurora australis.*

Connection

Television and Computer Screens

You don't need to live in the far north or south of the world and view the auroras in order to see the effects of magnetic forces on charged particles. All you have to do is turn on your television or computer.

Picture tubes work by shooting beams of electrons onto a coated screen (Figure 16-14*a*). The electrons are emitted by an electron gun that is basically a wire heated to high temperatures. Electrically charged plates accelerate the electron beams to high speeds directed toward the screen, which is coated with chemical phosphors that glow when the electrons strike them. The beams are guided across the screen from side to side and from top to bottom (Figure 16-14*b*) while the internal electronics adjust the beam intensities to match the incoming signal, producing dots of the right strength and color to create the desired picture.

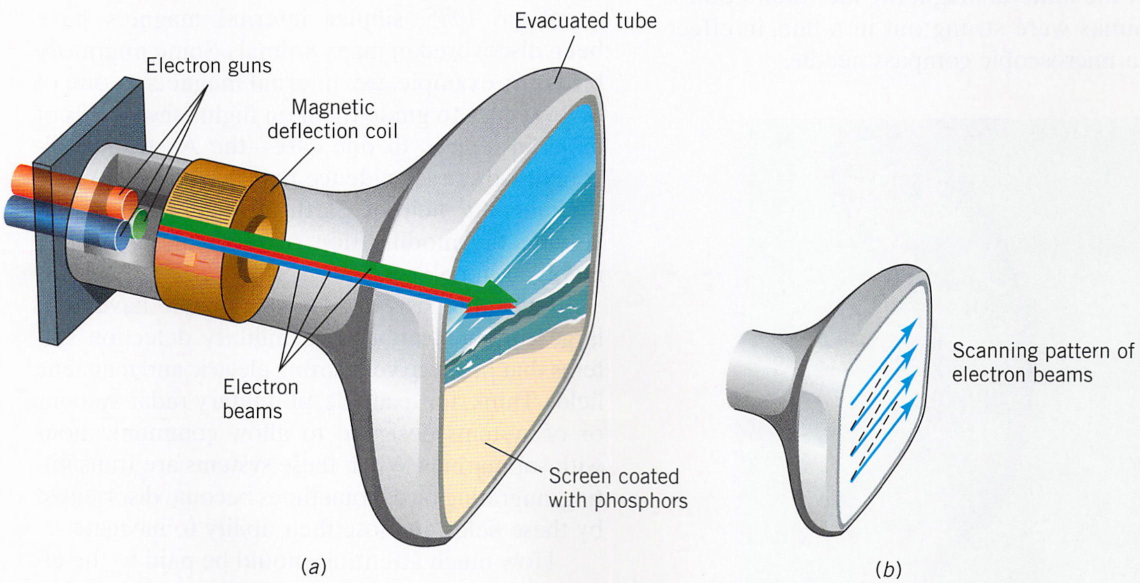


FIGURE 16-14. (*a*) A picture tube works by beaming electrons from a heated wire onto a coated screen that glows when the electrons strike it. The beam passes through the center of several wire coils that produce a changing magnetic field while internal electronics adjust the beam intensities to match the incoming signal and produce the desired picture. (*b*) This magnetic field deflects the beams back and forth from top to bottom across the entire screen.

In order to produce a smoothly moving image on the screen, the electron beams sweep across the entire screen 30 times per second. How can the beams be guided so accurately and so rapidly at the same time? The answer is magnetic fields. The beams pass through the center of several coils placed in front of the electron guns. The coils produce a changing magnetic field that deflects the beams as needed, back and forth from top to bottom.

In recent years, newer picture screens use liquid crystals instead of electron guns. These screens can be flat for portable computers or wall-mounted televisions. However, electron-beam tubes are still used in oscilloscopes for medical and electronic diagnosis. ●

THINKING MORE ABOUT

Magnetic Navigation

Many living things in addition to humans use Earth's magnetic field for navigation. Scientists at the Massachusetts Institute of Technology demonstrated this ability in 1975 when they were studying a single-celled bacterium that lived in the ooze at the bottom of nearby swamps. They found that the bacteria incorporated about 20 little chunks of the mineral magnetite into their bodies. These chunks were strung out in a line, in effect forming a microscopic compass needle.

Grains of iron minerals in this bacterium allow it to tell up from down.

Because Earth's magnetic field dips into Earth's surface in the Northern Hemisphere and rises up out of the surface in the Southern Hemisphere, the Massachusetts bacteria have a built-in up and down indicator. This internal magnet allows the bacteria to navigate down into the nutrient-rich ooze at the bottom of the pond. Interestingly, related bacteria in the Southern Hemisphere follow the field lines in the opposite direction to get to the bottom of their ponds.

Since 1975, similar internal magnets have been discovered in many animals. Some migratory birds, for example, use internal magnets as one of several cues to guide them on flights thousands of miles in length. In one case—the Australian silvereye—there is evidence that the bird can sense the magnetic field of Earth through a process involving the modification of molecules normally involved in color vision.

Over the past few decades, people have built large communications and military detection systems that produce very strong electric and magnetic fields. Think, for example, of military radar systems or of systems designed to allow communications with submarines. When these systems are transmitting, migrating birds sometimes become disoriented by these fields and lose their ability to navigate.

How much attention should be paid to the effects of electric and magnetic fields on wildlife that we create? If human beings need to have a particular technical capability, how much risk to wildlife is acceptable?

Summary

The forces of **electricity** and **magnetism** are quite different from the universal gravitational force that Newton described in the seventeenth century. Nevertheless, Newton's laws of motion provided scientists with a way to describe and quantify a range of intriguing electromagnetic behavior.

Static electricity is the interaction of **electric charges,** such as electrons and protons. An excess of electrons imparts a **negative charge,** while a deficiency causes an object to have a **positive charge.** An **ion** is an atom that has either too many or too few electrons. The transfer of electrons between objects causes phenomena such as lightning, static cling, and the small sparks produced when you walk across a wool rug on a cold winter day. The total electric charge of a closed system stays the same. This is the law of **conservation of electrical charge.**

Objects with like charge experience a repulsive force, while oppositely charged objects attract one another. These observations are quantified in **Coulomb's law,** which states that the magnitude of the electrostatic force between any two objects is proportional to the product of the charges of the two objects and inversely proportional to the square of the distance between them.

Other scientists, investigating the very different phenomenon of magnetism, observed that every **magnet** has a **north pole** and a **south pole** and that magnets exert forces on one another. No matter how many times a magnet is divided, each of its pieces has two poles—there are no isolated magnetic poles. Like magnetic poles repel one another, while opposite poles attract one another. A compass is a needle-shaped magnet that points to the poles of Earth's magnetic field.

Electric and **magnetic forces** can be described in terms of **electric** and **magnetic fields**—imaginary lines that indicate the directions of forces that would be experienced in the vicinity of electrically charged or magnetic objects.

Charged particles traveling through a magnetic field experience a force that causes them to be deflected. The direction of deflection is different for positive or negative charges.

Key Terms

conservation of electric charge The physical law that states that the total amount of charge in the universe does not change. (p. 338)

Coulomb's law The law of physics that defines the force between electrically charged objects. (p. 339)

electric charge The property of an object or particle that quantifies its response to electric and magnetic phenomena; charges are either **positive** or **negative,** so named because their effects tend to cancel one another out. (p. 334)

electric field A measure of how much electric force an electric charge would experience at a particular location in space; it is defined as the force per unit charge. (p. 342)

electric force The force that one electric charge exerts on another. (p. 339)

electricity A general term used to define the presence and or motion of electric charges. (p. 334)

ion An atom that has lost or gained electrons, thus acquiring an electric charge. (p. 337)

magnet Material or object that possesses a magnetic property such that it is attracted to or repelled from another magnet. (p. 343)

magnetic field A measure of the effect that a magnet has on the space surrounding it, or the effect that would be felt by a magnet if it were at a particular location in space. (p. 344)

magnetic field lines Imaginary lines in space that give the direction of a compass needle. (p. 344)

magnetic force The force that a magnet exerts on other magnets or on moving electric charges. (p. 343)

poles (north and **south)** The two ends of a magnet; one is called the *north pole* and one is called the *south pole*. (p. 343)

static electricity Electric charges that are at rest; also used to describe the force due to electric charges that are at rest. (p. 334)

Key Equations

1 coulomb = Magnitude of charge on 6.25×10^{18} electrons

$$\text{Electrostatic force} = k \times \frac{\text{First charge} \times \text{Second charge}}{(\text{Distance between charges})^2}$$

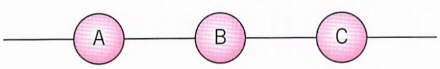
$$\text{Universal Electrostatic Constant (Coulomb constant): } k = 9.00 \times 10^9 \ \frac{\text{N-m}^2}{\text{C}^2}$$

Review

1. How do we know that there is such a thing as an electric force?
2. How do two electrically charged objects behave when brought near one another?
3. How can the movement of negative charges, such as electrons, produce a material that has a positive charge?
4. What is static electricity? What are some examples of it in everyday life?
5. When you walk across a rug to open a door, you can get a shock when you reach out toward the doorknob even if you don't actually touch it. Why is this so?
6. Compare the electric force to the force of gravity. Which is stronger? Do both depend on mass?
7. Explain how eighteenth-century scientists thought of electricity in terms of fluids. Does this make sense?
8. What were Benjamin Franklin's contributions to the understanding of electricity?
9. How does a lightning rod work?
10. What do we mean, at the atomic level, when we say that something is electrically charged?
11. How can objects acquire an electric charge through friction?
12. What type of charge results when electrons are removed from a particular material? When they are added to a material?
13. How do objects acquire charge through induction? Do the objects need to contact one another physically for this to happen? Explain.
14. What is meant by the conservation of electric charge?
15. What is the basic unit of electric charge? How many electrons are equivalent to 1 unit of charge?
16. What is Coulomb's law? How does the strength of attraction or repulsion of objects vary with the distance between them?
17. What is k, the Coulomb constant? How is this determined? Does it have the same value everywhere?
18. How can an object exert an electric force even if it has no net electric charge? What is meant by polarization?
19. What is an electric field? When does such a field exist?
20. What happens to free electrons in metals under the influence of an electric field?
21. What is shielding? What is the difference between an electric and a gravitational field with respect to shielding?
22. How do you know there is such a thing as a magnetic force?
23. What was the important result of William Gilbert's work on magnetism? How is this similar to the electric force?
24. What is a magnetic field?
25. What type of magnetic fields are found in nature?
26. What is a monopole? A dipole?

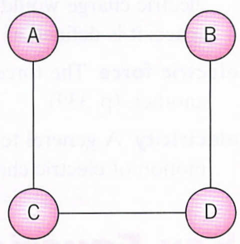
Questions

1. There is an old saying that lightning never strikes the same place twice. Given what you know about electric charge, is this statement likely to be true? Why?
2. If you double the distance between two charged objects, how does this affect the electric force between them? What if you triple the distance?
3. If you double the charge on one of two charged objects, how does the force between them change?
4. Three small spheres carry equal amounts of positive electric charge. They are equally spaced and lie along the same line, as shown. What is the direction of the net electric force on each charge due to the other two charges?



Questions 4, 5

5. Three small spheres carry electric charge. They are equally spaced and lie along the same line, as shown. They all have the same amount of charge, but sphere A and C are positive and sphere B is negative. What is the direction of the net electrical force on each sphere due to the other two spheres?
6. Four small charged spheres sit at the corners of a square, as shown in the figure. Sphere A is negatively charged and the other three have an equal amount of positive charge. Reproduce the figure and draw an arrow at sphere A that represents the net electric force on sphere A due to the other three charges. Repeat this for spheres B, C, and D. Which sphere has the greatest net force acting on it?

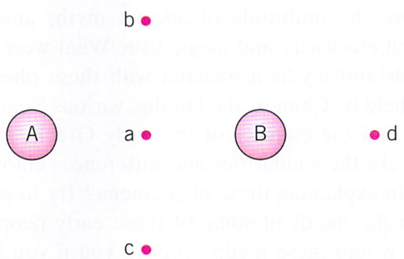


7. Two charged spheres sit near each other, as shown in the figure. They carry an equal amount of negative charge. What is the direction of the electric field created by these two charges at locations a, b, and c? (Point b is at the exact midpoint between spheres A and B.)

Questions 7, 8

8. Two charged spheres sit near each other, as shown in the figure. Sphere A is negative and sphere B carries an equal amount of positive charge. What is the direction of the electric field created by these two charges at locations a, b, and c?

9. Two spheres carry the same amount of positive charge. Reproduce the figure and draw an arrow that represents the direction and strength of the electric field at a, b, c, and d.



Questions 9, 10

10. Two spheres carry equal and opposite amounts of electric charge. Sphere A is positive and sphere B is negative. Reproduce the figure and draw an arrow that represents the direction and strength of the electric field at a, b, c, and d.

11. Static cling makes your clothes stick together. What is actually happening in your dryer to generate it? Does this make sense given what you have learned in this chapter?

12. The Greeks had a legend that there was an island in the Mediterranean Sea made entirely of lodestone. They used this story as an argument that ships should not be built with iron nails. How does this argument work? Are there other reasons for not building ships with iron nails?

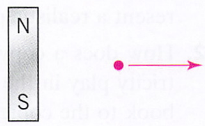
13. Object A and object B are initially uncharged and are separated by a distance of 2 meters. Suppose 10,000 electrons are removed from object A and placed on object B, creating an electric force between A and B. Is this force attractive or repulsive? If an additional 10,000 electrons are removed from A and placed on B, how much does the electric force change?

14. Object A and object B are initially uncharged and are separated by a distance of 1 meter. Suppose 10,000 electrons are removed from object A and placed on object B, creating an attractive force between A and B. If an additional 10,000 electrons are removed from A and placed on B and the objects are moved so that the distance between them is increased to 2 meters, how much does the electric force between them change?

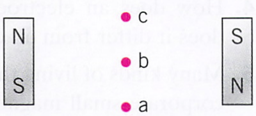
15. The magnetic field at the equator points north. If you throw a positively charged object (for example, a baseball with some electrons removed) to the east, what is the direction of the magnetic force on that object?

16. The magnetic field at the equator points north. If you throw a negatively charged object (for example, a baseball with some extra electrons) to the east, what is the direction of the magnetic force on that object?

17. A charged particle is located on the right side of a bar magnet and is moving to the right, as shown. If the particle is being deflected in such a way that its path is curving out of the page, is the particle negative or positive?



18. Two identical bar magnets are aligned as shown. What is the approximate direction of the magnetic field created by this arrangement at locations a, b, and c?



19. A small bar magnet pulls on a larger one with a force of 100 newtons. What is the magnitude of the force the larger one exerts on the smaller one?

20. A charge of +1 coulomb is placed at the 0-cm mark of a meter stick. A charge of −1 coulomb is placed at the 100-cm mark of the same meter stick. Is it possible to place a proton somewhere on the meter stick so that the net force on it due to the charges at the ends is 0? If so, where should it be placed? Explain.

21. A charge of +1 coulomb is placed at the 0-cm mark of a meter stick. A charge of +4 coulombs is placed at the 100-cm mark of the same meter stick. Is it possible to place a proton somewhere on the meter stick so that the net force on it due to the charges at the ends is 0? If so, where should it be placed? Explain.

22. Identify five objects in your room that would not be possible without discoveries in electromagnetism.

Problems

1. Based on electric charges and separations, which of the following atomic bonds is strongest? [*Hint:* You are interested only in the relative strengths, which depend only on the relative charges and distances.]

   a. A +1 sodium atom separated by 2.0 distance units from a −1 chlorine atom in table salt

   b. A +1 hydrogen atom separated by 1.0 distance unit from a −2 oxygen atom in water

c. A +4 silicon atom separated by 1.5 distance units from a −2 oxygen atom in glass

2. Assume that in interstellar space the distance between two electrons is about 0.1 cm.

a. Is the electric force between the two electrons repulsive or attractive?

b. Calculate the electric force between these two electrons.

c. Calculate the gravitational force between these two electrons. Is this an attractive or repulsive force?

d. Which force is greater and by how many orders of magnitude?

3. Repeat Problem 2 for two protons at the same distance from one another.

4. Assume that you have two objects, one with a mass of 10 kg and the other with a mass of 15 kg, each with a charge of -3.0×10^{-2} C and separated by a distance of 2 meters. What is the electric force that these objects exert on one another? What is the gravitational force between them?

Investigations

1. Read the novel *Frankenstein* (or see the classic 1931 movie with Boris Karloff and Colin Clive). Discuss the ideas about the nature of life that are implicit in the story. Does it represent a realistic picture of scientific research? Why?

2. How does a copying machine work? What role does electricity play in the transfer of an image from the pages of a book to the copied final product?

3. Explore how electric eels generate electric shocks.

4. How does an electroencephalograph (EEG) work? How does it differ from an electrocardiograph (EKG)?

5. Many kinds of living things, from bacteria to vertebrates, incorporate small magnetic particles. Investigate the ways in which living things specifically use magnetism.

6. Explore the multitude of ancient myths and legends regarding electricity and magnetism. What were some of the legends and myths associated with these phenomena that were held by Chinese, the Hindus, various Near Eastern cultures, and the cultures of the early Greeks and Romans? What are the similarities and differences among these cultures in explaining these phenomena? Try to place yourself within the minds of some of these early peoples. How rational would these myths seem to you if you lived in their times? Similarly, can you identify any beliefs held today about either electricity or magnetism that are not fully supported by mainstream scientists employing the scientific method? How should such questions be investigated?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.gel.ulaval.ca/~mbusque/elec/main_e.html** Exploring electric fields. Field plots for user-defined arrangements of charge.
2. **http://www.fi.edu/franklin/rotten.html** The life, times, and experimental history of Benjamin Franklin.
3. **http://www.aip.org/history/electron/** A site celebrating the 100th anniversary of the discovery of the electron.
4. **http://www.ee.umd.edu/~taylor/frame1.htm** A gallery of famous scientists and personalities from the historical study of electricity and magnetism.
5. **http://thorin.adnc.com/~topquark/fun/JAVA/electmag/electmag.html** A history and function of the mass spectrometer.
6. **http://www.geo.mtu.edu/weather/aurora/** A site containing breathtaking photographs of and the physics underlying the aurora borealis or "northern lights."
7. **http://pwg.gsfc.nasa.gov/istp/earthmag/demagint.htm** A collection of websites discussing Earth's magnetic field, celebrating the 400th anniversary of the publication of *De Magnete* by William Gilbert.