17 Electromagnetic Interactions

KEY IDEA

Electricity and magnetism are two aspects of the same force—the electromagnetic force.

PHYSICS AROUND US . . . The Electrical World

During the next hour or so, look around you and notice all the electric equipment that affects your life. Are you in a building? Electrons flowing through copper wires in the walls are what make the lights go on. They supply power to the outlets on the walls—the places where you plug in everything from stereos to vacuum cleaners. Are you listening to your Walkman or using a laptop computer? Then you are using the energy stored in batteries to create a flow of electrons to run your equipment. Drying your hair? The fan is driven by an electric motor. Starting your car? The battery turns the engine over when you use your ignition key.

It would be hard to imagine the modern world without electricity. Yet all of these electronic devices (and countless more) spring from a few discoveries made by basic researchers in the mid-nineteenth century. In this chapter, we examine these discoveries. Many of them involve the close relationship between electric and magnetic forces, which only becomes apparent when we look at electric charges in motion. We are no longer looking just at static electricity; now we are studying the complete range of electromagnetic phenomena.

FORCES ON MOVING CHARGES

In our everyday experience, static electricity and magnetism seem to be two unrelated phenomena. After all, what could be more different than static cling and refrigerator magnets? Yet scientists in the nineteenth century, probing deeper into the electric and magnetic forces, discovered remarkable connections between the two—a discovery that transformed every aspect of technology.

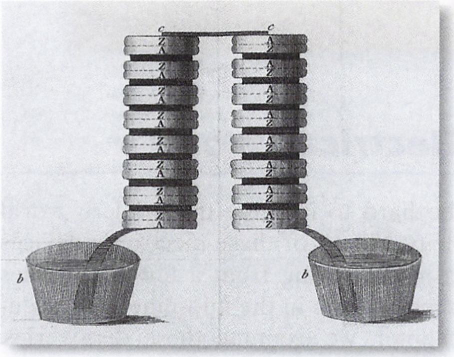
In Chapter 16 we examined the forces acting between two or more stationary charges. It turns out that moving electric charges experience very different forces in addition to the force of static electricity. These additional forces are magnetic. There's a beautiful symmetry at work here: moving electric charges give rise to magnetic fields, and changing magnetic fields give rise to electric fields. In this chapter we discuss these effects one at a time and then show how they can be brought together into one description of the **electromagnetic force.**

Despite the fact that people had known about both electricity and magnetism for millennia, their fundamental connection could not be discovered until scientists had at their disposal a mundane device that we use every day without thinking—the storage battery. The battery enabled scientists to have a reliable source of electricity for use in experiments. As our understanding of electricity and magnetism grew, the importance of batteries for supplying electric energy in applications became evident.

BATTERIES AND ELECTRIC CURRENT

Although we encounter static electricity in our everyday lives, most of our contact with electricity comes from moving charges. In your home, for example, negatively charged electrons move through wires to run all of your electric appliances. A flow of charged particles is called an **electric current.**

Until the work of the Italian scientist Alessandro Volta (1745–1827), scientists could not produce persistent electric currents in their laboratories and therefore knew little about them. As a result of his investigations into the work of Luigi Galvani (see Physics in the Making on page 355), Volta developed the first **battery,** a device that converts stored chemical energy in the battery materials into kinetic energy of electrons flowing through an outside wire.



A woodcut engraving of Volta's early metal disk battery shows alternating disks of two metals connected to containers of salt water. These two containers served as the positive and negative terminals of this primitive battery.

The first batteries were crude affairs that featured alternating disks of two different metals, such as lead and silver, in salt water. We now use much more sophisticated batteries to start our cars and run all sorts of portable electric equipment, but the principle is the same. Your car battery, a reliable and beautifully engineered device that routinely performs for years before it needs replacing, is also made of alternating plates of two kinds of material (lead and lead oxide) immersed in a bath of dilute sulfuric acid. When the battery is being discharged, the lead plate interacts with the acid, producing lead sulfate (the white crud that collects around the posts of old batteries) and some free electrons. This process causes free electrons in an external wire to travel toward the other plates, where they interact with the lead oxide and sulfuric acid to form more lead sulfate. The electrons flowing through the outside wire are what enable you to start your car.

When the battery is completely discharged, it consists of plates of lead sulfate immersed in water, a configuration from which no energy can be obtained. Running a current backward through the battery, however, runs all the chemical reactions in reverse and restores the original configuration. We say that the battery has been recharged. Once this is done, the whole cycle can proceed again. In your car, the generator constantly recharges the battery whenever the engine is running, so it is always ready to use.

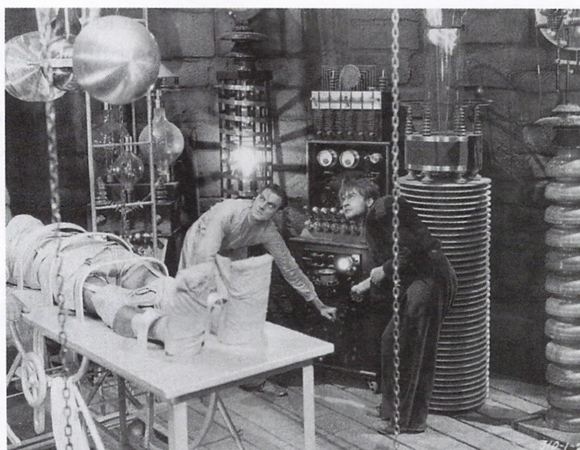
We use many other kinds of batteries in our everyday life—small ones to power miniature electronic devices, larger ones to run our laptop computers. Some of these batteries, like the one in your car, can be recharged, while others we simply use, recycle, and replace. All of them, however, provide us with a source of electric current. It was this feature of Volta's invention that led to the discovery of the connection between electricity and magnetism.

Physics in the Making

Luigi Galvani and Life's Electric Force

Scientists of the eighteenth century discovered remarkable links between life and electricity. Of all the phenomena in nature, none fascinated these scientists more than the mysterious "life force" that allowed animals to move and grow. An old doctrine called vitalism held that this force is found only in living things and not found in the rest of nature. Luigi Galvani (1737–1798), an Italian physician and anatomist, added fuel to the debate about the nature of life with a series of classic experiments demonstrating the effects of electricity on living things.

Galvani's most famous investigations employed an electric spark to induce convulsive twitching in amputated frogs' legs—a phenomenon not unlike a person's involuntary reaction to a jolt of electricity. Later he was able to produce a similar effect simply by poking a frog's leg simultaneously with one fork of copper and one of iron. In modern language, we would say that the electric charge and the presence of the two metals in the salty fluid in the frog's leg led to a flow of electric charge in the frog's nerves, a process that caused contractions of the muscles.



The idea behind the legend of Frankenstein may have been suggested by early experiments on animal electricity.

Galvani, however, argued that his experiments showed that there was a vital force in living systems, something he called "animal electricity," that made them different from inanimate matter. This idea gained some acceptance among the scientific community, but provoked a long debate between Galvani and the Italian physicist Alessandro Volta. Volta argued that Galvani's effects were caused by chemical reactions between the metals and the salty fluids of the frogs' legs. In retrospect, both of these scientists had part of the truth. Muscle contractions are indeed initiated by electric signals, even if there is no such thing as animal electricity, and electric charges can be induced to flow by chemical reactions.

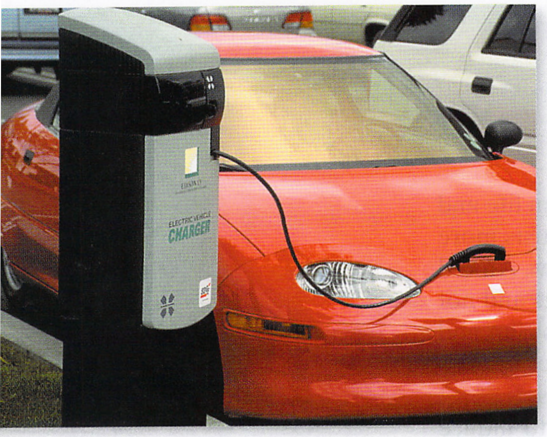
The controversy that surrounded Galvani's experiments had many surprising effects. On the practical side, as we discuss in this chapter, Volta's work on chemical reactions led to the development of the battery and, indirectly, to our modern understanding of electricity. However, the notion of animal electricity proved a great boon to medical quacks and con men, and for centuries various kinds of electric devices were palmed off on the public as cures for almost every known disease.

Finally, in a bizarre epilogue to Galvani's research, other researchers used batteries to study the effects of electric currents on human cadavers. In one famous public demonstration, a corpse was made to sit up and kick its legs by electric stimulation. Such unorthodox experiments helped inspire Mary Shelley's famous novel, *Frankenstein.* ●

Connection

Batteries and Electric Cars

Modern urban areas are troubled by pollutants introduced into the air by the burning of gasoline in cars and trucks. A possible solution to this problem is the introduction of battery-powered electric cars. In these cars, chemical energy stored in batteries, rather than in gasoline, provides the motive power.



Battery-powered electric cars store chemical energy in batteries rather than in gasoline.

Many electric vehicles, such as golf carts, are already in use, but much more powerful batteries are needed for cars traveling on modern highways. The most difficult technical problem standing in the way of developing practical electric cars is the fact that batteries actually store rather small amounts of energy for their weight. For example, for the kind of lead-acid battery that you use to start your car to supply as much energy as a gallon of gasoline, you would need a battery weighing 3500 newtons (800 pounds). Because the car has to move the batteries as well as its normal load, this heavy weight leads to problems.

Perhaps the most severe problem is the comparatively short distance an electric car can go before the batteries need to berecharged, a distance called the car's range. Many first-generation electric cars have effective ranges of only 65–80 kilometers (40–50 miles), although engineers are steadily improving the performance of these cars. Two types of advanced batteries—nickel-cadmium (the type you probably use in your laptop computer) and other designs using nickel and other metals—deliver about twice the power of lead-acid batteries. Before long, many of us may be driving electric cars with ranges of more than 100 miles.

The primary advantage of electric cars is that they don't emit exhaust in the area where they are driven. We should keep in mind, however, that the electricity used to charge the batteries was most likely generated by nuclear or coal-burning electrical plants somewhere outside the city. You can't get energy for free! ●

MAGNETIC EFFECTS FROM ELECTRICITY

In the spring of 1820, a strange thing happened during a physics lecture in Denmark. The lecturer, Professor Hans Christian Oersted (1777–1851), was using a battery to demonstrate some properties of electricity. By chance he noticed that whenever he connected the battery to a circuit (so that an electric current began to flow through the wire), a nearby compass needle began to twitch and turn. When he disconnected the battery, the needle went back to pointing north. Connecting the battery in the opposite direction, and thus reversing the direction of current flow, caused the compass needle to swing in the opposite direction. This accidental discovery led the way to one of the most profound insights in the history of science. Oersted had discovered that electricity and magnetism—two forces that seem as different from one another as night and day—are in fact intimately related to one another. They are two sides of the same coin.

In subsequent studies, Oersted and other physicists established that whenever electric charge flows through a wire, a magnetic field appears around that wire. A compass brought near the wire will twist around until it points along the direction of the magnetic field. This observation leads to an important experimental finding in electricity and magnetism:

The motion of electric charges creates magnetic fields.

The magnetic field produced by a current in a wire, as shown in Figure 17-1, is in the form of concentric circles with the current at the center. Thus, if a compass in front of the wire points to the right, a compass at a corresponding point behind the wire will point to the left. The direction of the magnetic field, in fact, is given by a simple mnemonic known as a *right-hand rule*. For the wire shown in Figure 17-1, the rule works like this: You put the thumb of your right hand in the direction of the current. (For historical reasons, we assume the current consists of positive charges. If the current consists of electrons, you point your thumb in the opposite direction to the electron flow.) When you have done this, the fingers of your right hand are curling in the direction of the magnetic field (that is, your fingers point in the same direction that a compass needle would if it were in the same spot). Note that this right-hand rule, which gives the direction of a magnetic field, is different from the right-hand rule given in Chapter 16, which gives the direction of the force on a moving particle and the rule for angular momentum (Chapter 7).

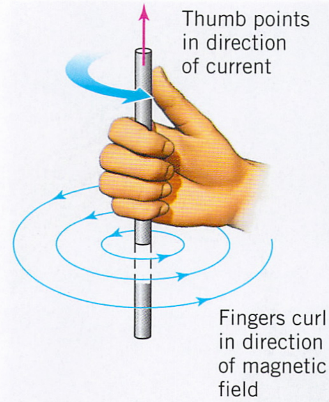


FIGURE 17-1. The right-hand rule states that when the thumb of the right hand points in the direction of a positive electric current, the fingers curl in the direction of the resultant magnetic field.

Develop Your Intuition: Magnetic Field of a Straight Current-Carrying Wire

Suppose you align a wire in part of a circuit in a straight line so that electrons are moving from east to west. If you place a compass above the wire, in what direction will the needle point? What happens if you place the compass below the wire?

The compass needle will point in the direction of the magnetic field of the wire, so we use the right-hand rule to determine the direction of that field. If electrons are flowing from east to west, then the direction of a *positive* current is from west to east, so point your thumb to the east. If you then look along the wire from east to west, your fingers are curling around the wire in a counterclockwise direction. If you place a compass above the wire, it will point south; if you place the compass below the wire, it will point north.

Like all fundamental discoveries, the discovery of this law of nature had important practical consequences. Perhaps most important, it led to the development of the **electromagnet,** a device composed of many coils of wire that produces a magnetic field whenever an electric current flows through the wire. Almost every electric appliance in modern technology uses this device.

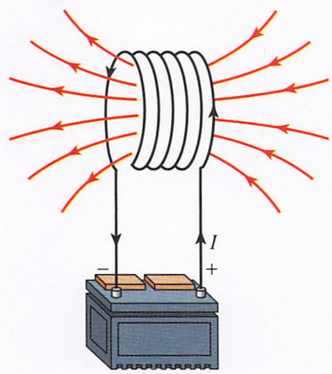


FIGURE 17-2. A schematic drawing of an electromagnet reveals the principal components—a loop of wire and a source of electric current. When current goes around the loop, a magnetic field forms through it.

The Electromagnet

Electromagnets work on a simple principle, as illustrated in Figure 17-2. If an electric current flows in a loop of wire, then a magnetic field is created around the wire, just as Oersted discovered in 1820. That magnetic field has the shape sketched in the figure, a shape familiar to you as the dipole magnetic field shown in Figure 16-10. The direction of the field is given by the right-hand rule.

The important point about the magnetic field associated with a loop of wire is that it has exactly the same shape as the field of a permanent magnet. You could, in fact, imagine replacing the loop of wire by a bar magnet and this replacement would not affect the magnetic field in the region.

We can, in other words, create the equivalent of a magnetized piece of iron simply by running electric current around a loop of wire. The stronger the current (i.e., the more electric charge we push through the wire), the stronger is the magnetic field. However, unlike a bar magnet, an electromagnet can be turned on and off. To differentiate between these two sorts of magnets, we often refer to magnets made from materials such as iron as "permanent magnets."

Electromagnets, which can be turned on and off, are ideal for moving scrap iron at a junkyard.

Electromagnets are used in all sorts of practical ways, including buzzers, switches, and electric motors. In each of these devices a piece of iron is placed near the magnet. When a current flows in the loops of wire, the iron is pulled toward the magnet. In some cases, the electromagnet can be used to complete a second electric circuit by pulling an iron switch closed. As soon as the current is turned off in the electromagnet, a spring pushes the iron back and the current in the second circuit also shuts off.

Connection
The Electric Motor

Look around your room and try to count the number of electric motors that you use every day. They appear in fans, clocks, disk drives, VCRs, CD players, hair dryers, electric razors, and dozens of other familiar objects. Electromagnets are crucial components in every one of these electric motors.

The simplest **electric motors,** as shown in Figure 17-3, employ a pair of permanent magnets and a rotating loop of wire inside the poles of the magnets. Let's say the current in the rotating loop is directed so that when the loop is oriented as shown in Figure 17-3*a* the north pole of the electromagnet lies near the north pole of the permanent magnet and the south pole of the electromagnet lies near the south pole of the permanent magnet. The repulsive forces between like poles cause the wire loop to spin. As the loop gets to the position shown in Figure 17-3*b,* attractive forces between unlike poles make the electromagnet continue to spin in the same direction. When the electromagnet gets to the position shown in Figure 17-3*c,* the current in the coil reverses, changing the poles of the electromagnet. Now the south pole of the electromagnet lies just past the south pole of the permanent magnet and the north pole of the electromagnet lies just past the north pole of the permanent magnet. The repulsive forces between like magnetic poles act to continue the rotation (Figure 17-3*d*). The complex apparatus in Figure 17.3 shows how, in practice, an electric current can be moved from a wire to a rotating shaft.

This simple diagram contains all the essential features of an electric motor, but most electric motors are much more complex. Typically, they have three or more different electromagnets and at least three permanent magnets, and the alternation of the current direction is somewhat more complicated than we have indicated. By artfully juxtaposing electromagnets and permanent magnets, inventors have produced an astonishing variety of electric motors: fixed-speed for the second hand

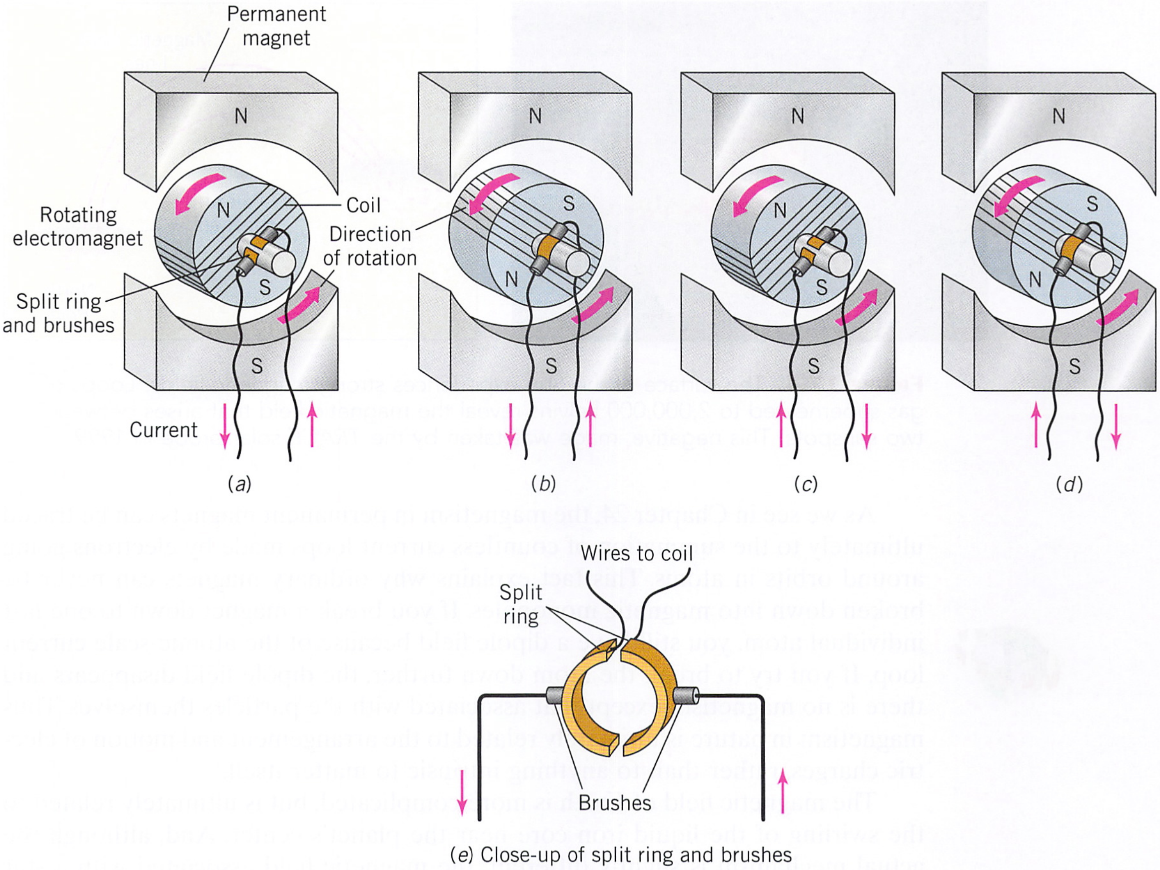


FIGURE 17-3. An electric motor. The simplest motors work by placing an electromagnet that can rotate between two permanent magnets. (*a*) When the current is turned on, the north and south poles of the electromagnet are repelled by the north and south poles of the permanent magnet. (*b*) The north and south poles of the electromagnet are attracted to the south and north poles, respectively, of the permanent magnet. Rotation continues in the same direction. (*c*) As the electromagnet rotates halfway around, the current direction is switched, reversing the poles of the electromagnet. The poles are now back in the same orientation as in part *a*. (*d*) Rotation continues in the same direction, ready for another reversal of current direction. (*e*) Close-up of split ring and brushes.

of your clock, variable-speed for your food processor, reversible motors for power screwdrivers and drills, and specialized motors for many industrial uses. ●

Magnetic Fields in Nature

The universe holds countless magnetic fields, including the Sun's powerful field, Earth's field that is responsible for the working of a compass, and the magnets on your refrigerator. As we have seen, whether large or small, every magnetic field is created by the motion of electric charges. At the atomic scale, for example, an electron in motion around an atom constitutes a current, similar to the circle of wire we discussed above. The only difference is that the current in the atomic loop consists of a single electron going around and around a nucleus, while the current in the wire consists of many electrons moving around and around in a much larger loop.

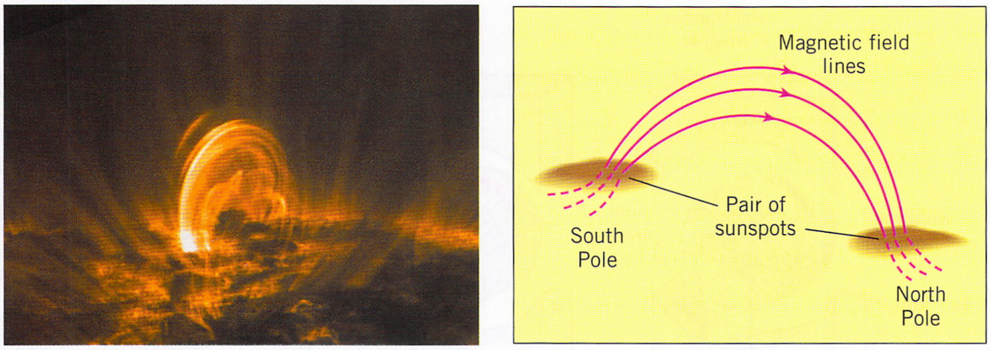


FIGURE 17-4. The surface of the Sun experiences strong magnetic fields. Loops of gas superheated to 2,000,000 kelvins reveal the magnetic field that arises between two sunspots. This negative image was taken by the *TRACE* solar probe in 1999.

As we see in Chapter 24, the magnetism in permanent magnets can be traced ultimately to the summation of countless current loops made by electrons going around orbits in atoms. This fact explains why ordinary magnets can never be broken down into magnetic monopoles. If you break a magnet down to one last individual atom, you still have a dipole field because of the atomic-scale current loop. If you try to break the atom down further, the dipole field disappears and there is no magnetism except that associated with the particles themselves. Thus magnetism in nature is ultimately related to the arrangement and motion of electric charges, rather than to anything intrinsic to matter itself.

The magnetic field of Earth is more complicated, but is ultimately related to the swirling of the liquid iron core near the planet's center. And, although the actual mechanism is slightly different, the magnetic field associated with a star such as the Sun can ultimately be attributed to the swirling of the plasma in the Sun's interior (Figure 17-4).

Ongoing Process of Science

Explaining Magnetic Field Reversals

If the magnetic fields of bodies such as Earth and the Sun were steady and unchanging, scientists would have little trouble explaining them. But these bodies display striking variations in their magnetic fields. The Sun's magnetic field reverses itself (that is, the north and south pole interchange) every 11 years. More amazing, the geological record shows that a similar thing happens on Earth. The magnetic field stays in the same direction for a long period of time, but the reversal itself happens quickly. Over a period of several thousand years, Earth's magnetic field diminishes in strength and vanishes, only to reappear again with the poles reversed. Geophysicists have documented dozens of such reversals over the last 100 million years. The last one occurred about 740,000 years ago and many scientists think we're due for another field reversal soon.

We now happen to live in a period when our planet's south magnetic pole is in Antarctica. But sometime in the future, probably within the next few hundred thousand years, the position of Earth's magnetic poles will flip. How can that be? To try to explain the complex behavior of flipping magnetic poles, scientists have suggested that convection cells in the liquid iron core of the planet occasionally disrupt the orderly rotation of the fluid. It is fair to say, however, that we do not yet have a detailed understanding of the behavior of the magnetic field of our own planet. ●

ELECTRIC EFFECTS FROM MAGNETISM

Once Oersted and others demonstrated that magnetic effects arise from electricity, it did not take long for scientists to realize that electric effects arise from magnetism. British physicist Michael Faraday (1791–1867) is the person who is usually associated with this discovery.

Faraday's crucial experiment took place on August 29, 1831, when he placed two coils of wire—in effect, two electromagnets—side by side in his laboratory. He used a battery to pass an electric current through one of the coils of wire, and he watched what happened to the other coil. Astonishingly, even though the second coil of wire was not connected to a battery, a strong electric current developed. We now know what happened in Faraday's experiment: as the current increased in the first loop of wire, it produced an increasing magnetic field in the neighborhood of the second loop. This changing magnetic field, in turn, produced a current in the second loop by means of a process called **electromagnetic induction** (see Figure 17-5). An identical effect was observed when Faraday

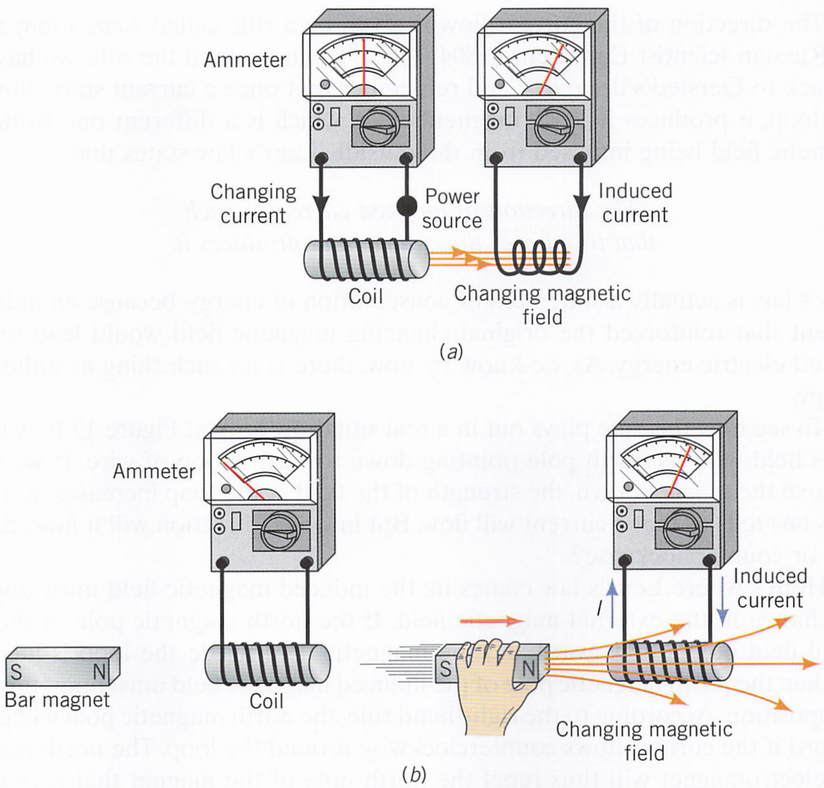


FIGURE 17-5. Electromagnetic induction. (*a*) When a changing current flows in the circuit on the left, a current is observed to flow in the circuit on the right, even though there is no battery or power source in that circuit. (*b*) Moving a magnet into the region of a coil of wire causes a current to flow in the circuit, even in the absence of a battery or other source of power.

waved a permanent magnet in the vicinity of his wire coil—he produced an electric current without a battery.

A simple law can summarize Michael Faraday's research:

Changing magnetic fields produce electric fields.

The "induced" electric field can be used to generate an electric current in a circuit.

When a magnetic field passes through a loop of wire, three actions can produce a current in that wire.

1. We can change the strength of the field (by moving the source of the field closer to or farther away from the loop, for example).
2. We can change the size of the loop.
3. We can change the orientation of the loop (by tilting it, for example).

Any one of these changes, or most combinations of them, can cause a current to flow in a circuit. Note, however, that it is the *change* that produces the current. Current does not spontaneously flow through a loop sitting in an unchanging magnetic field. Loosely speaking, if the amount of magnetic field penetrating the loop changes, then there will be an induced current in the loop.

The direction of the current flow is given by a rule called *Lenz's law,* after the Russian scientist Emil Lenz (1804–1865). To understand the rule, we have to go back to Oersted's discovery and remember that once a current starts flowing in a loop, it produces its own magnetic field, which is a different one from the magnetic field being imposed from the outside. Lenz's law states that

The direction of induced current is such that it opposes the change that produces it.

Lenz's law is actually a statement of conservation of energy, because an induced current that reinforced the original changing magnetic field would lead to unlimited electric energy. As we know by now, there is no such thing as unlimited energy.

To see how this rule plays out in a real situation, look at Figure 17-6. A magnet is held with its north pole pointing down toward a loop of wire. If we start to move the magnet down, the strength of the field at the loop increases, so Faraday's law tells us that a current will flow. But in which direction will it flow, clockwise or counterclockwise?

Here's where Lenz's law comes in: the induced magnetic field must oppose the change in the external magnetic field. If the north magnetic pole of the external field points downward and the magnetic field inside the loop is increasing, then the north magnetic pole of the induced magnetic field must point upward in opposition. According to the right-hand rule, the north magnetic pole will point upward if the current flows counterclockwise around the loop. The north pole of this electromagnet will thus repel the north pole of the magnet that is moving downward—in effect, opposing the motion of that magnet.

By the same token, if the south magnetic pole moves downward toward the loop of wire, then Lenz's law tells us that the induced current will flow in a clockwise direction so that south magnetic poles will be opposed to each other. Thus,

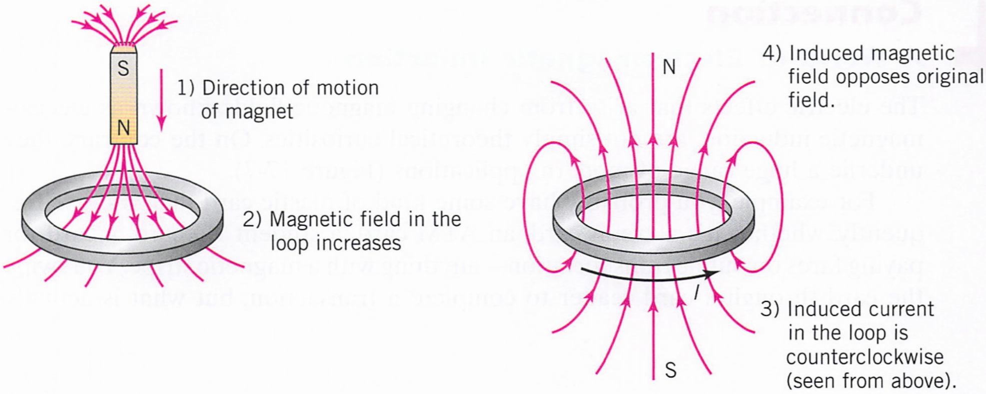


FIGURE 17-6. Lenz's law. (1) A magnet held with its north pole pointing down moves toward a loop of wire. (2) As a result, the strength of the field at the loop increases. (3) Faraday's law indicates that a current will flow, while Lenz's law states that the direction of induced current is such that it opposes the change that produces it. According to the right-hand rule, a current flowing counterclockwise around the loop produces a magnetic field with a north pole that points upward at the center of the loop. (4) This induced magnetic field will repel the north pole of the magnet that is moving downward, in effect opposing the motion of that magnet.

once we set a train of events in motion by starting to move the external magnet, the current in the loop sets up its own magnetic field to oppose that motion and produce a new electric current.

Develop Your Intuition: Direction of Induced Current

Suppose you orient a bar magnet with the north pole pointing toward a loop of wire, just as in Figure 17-6, but now you move the magnet away from the loop instead of toward it. Is a current induced in the loop? If so, in what direction does it flow?

An electric field is induced by a changing magnetic field, whether increasing or decreasing, so a current *is* induced by moving the magnet away from the loop. To determine its direction, you can work through the following sequence of steps: The magnetic field through the loop is decreasing, so the direction of current should act to increase the field. This means establishing a south pole above the loop, trying to attract the north pole of the bar magnet and increase the magnetic field. To get a south pole above the loop, current must flow clockwise around the loop, as seen from above, the opposite direction from that shown in the figure.

Note that because the induced magnetic field of a coil opposes the magnetic field of the moving magnet, you have to exert a force to move the magnet near the coil. This force does work and this work is the source of the energy of the induced magnetic field. Once again, energy does not come from nothing; you have to supply energy to get energy.

Connection

A World of Electromagnetic Induction

The electric effects that arise from changing magnetic fields, known as electromagnetic induction, are not simply theoretical curiosities. On the contrary, they underlie a huge range of modern applications (Figure 17-7).

For example, you probably have some kind of plastic card that you use frequently, whether it's a credit card, an ATM card, a student ID card, a card for paying fares on public transportation—anything with a magnetic stripe. You swipe the card through a card reader to complete a transaction, but what is actually

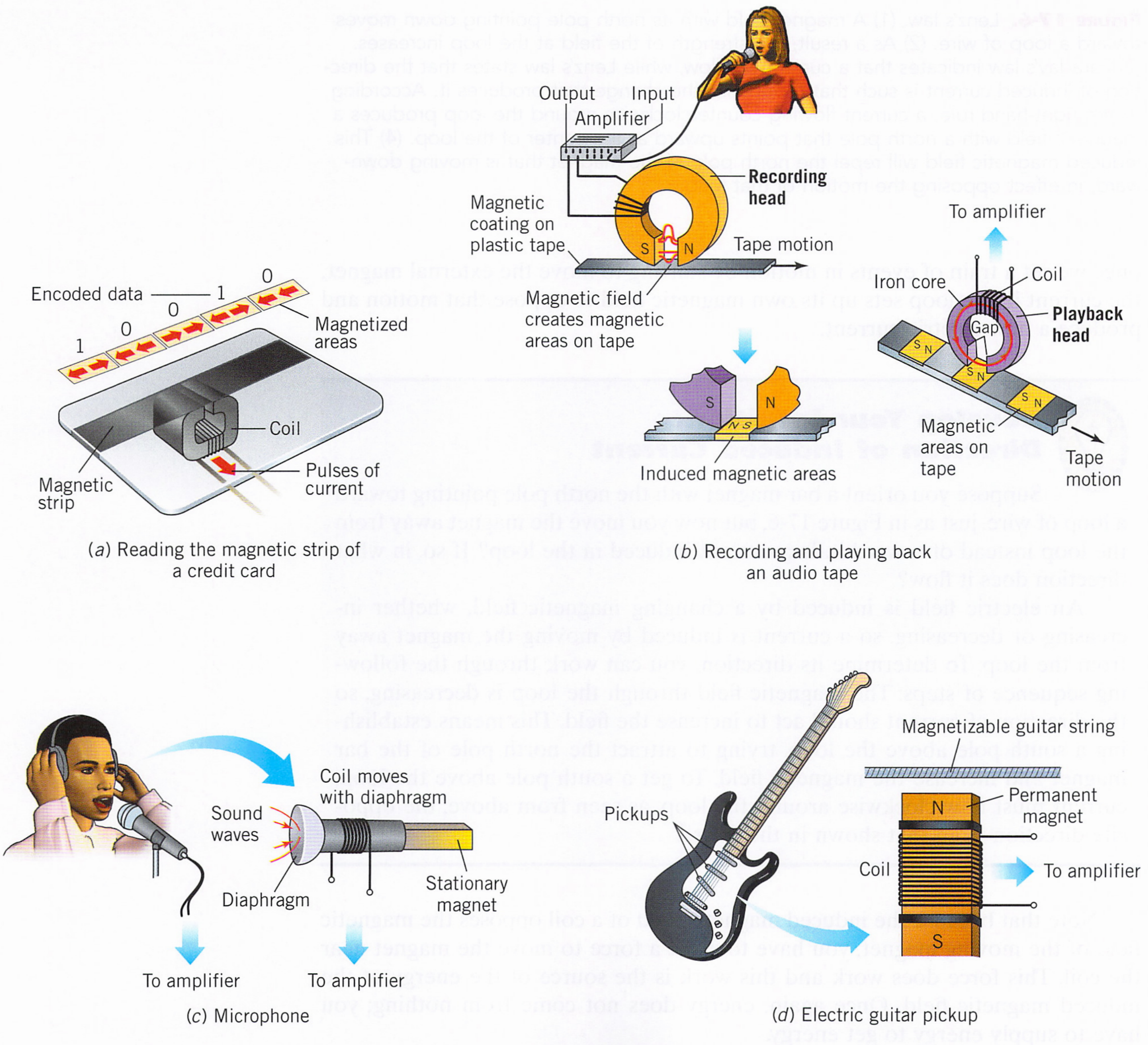


FIGURE 17-7. Examples of electromagnetic induction.

happening when you do that? Information is encoded on the magnetic stripe, in a pattern of tiny north and south poles associated with small grains of magnetic material embedded in the card. The information is usually your name, an account number, and an expiration date. When you move the card through the reader, the magnetic areas induce currents in the reading head, transmitting the information for verification.

The same idea is involved in a cassette deck (Figure 17-7*b*). When music is recorded on magnetic tape, the recording head becomes an electromagnet and creates a series of tiny magnetic poles, or areas, on the tape. The pattern of north and south poles follows the pattern of alternating current in the electromagnet, which follows the pattern of sound waves in the original music. When you play back the tape, the magnetized areas on the tape induce currents as they pass through a magnetic field in the playback head, allowing the recorder to recreate the original pattern of sound. Thus, the recording is made by using the magnetic effects of electric currents, and the recording is played back by using the electric effects of magnetic fields.

Several types of microphones work with a moving coil that induces an electric current as it moves back and forth with the vibrations of the sound (Figure 17-7*c*). The pickups of an electric guitar work the same way, with current in a coil moving in time with the metal strings of the guitar (Figure 17-7*d*). The strings have to be metal so they can be magnetized by a magnet in the pickup, which can then detect the vibrations of the string as oscillations in a magnetic field.

Metal detectors at airport security checkpoints also depend on electromagnetic induction. As you walk through the magnetic field of the detector, nothing happens. But if you have a piece of metal on you, it interacts with the field and induces a current in the detector. ●

Electric Generator

Figure 17-8 illustrates the **electric generator,** or dynamo, a vital tool of modern technology that demonstrates electromagnetic induction. Place a loop of electric wire with no batteries or other power source between the north and south poles of a strong horseshoe magnet. As long as the loop of wire stands still, no current flows in the wire. However, as soon as we begin to rotate the loop, a current flows in the wire. This current flows in spite of the fact that there is no battery or other power source in the wire.

From the point of view of the electrons in the wire, any rotation changes the orientation of the magnetic field. The electrons sense a changing magnetic field and hence, by Faraday's findings, move and form a current in the loop. If we spin the loop continuously, a continuous current flows in it. In most electric generators the current flows in one direction for half of the rotation and then flows in the opposite direction for the other half of the rotation. This vitally important device, the electric generator, followed immediately from Faraday's discovery of electromagnetic induction.

In an electric generator, some source of energy—such as water passing over a dam, steam produced by a nuclear reactor or coal-burning furnace, or wind-driven propeller blades—turns a shaft attached to the coils of wire. In your car, the energy to turn the alternator coils in a magnetic field comes from the gasoline that is burned in the motor. In every generator, the rotating shaft links to coils of wire that spin in a magnetic field. Because of the rotation, electric

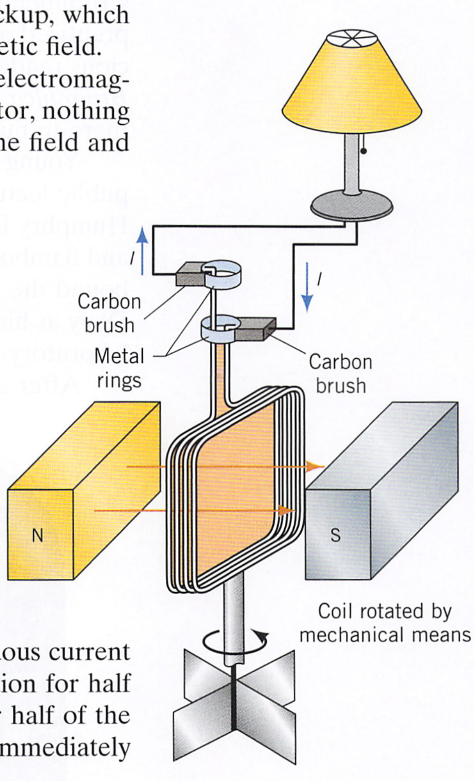


FIGURE 17-8. An electric generator. As long as the loop of wire rotates, the amount of magnetic field penetrating the loop changes and current flows in the wire.

current flows in the wire and can be tapped off onto external lines. Almost all the electricity used in the United States is generated in this way.

You may have noticed a curious fact about electric motors and generators. In an electric motor, electric energy is converted into the kinetic energy of a spinning shaft, while in a generator, the kinetic energy of a spinning shaft is converted into electric energy. Thus motors and generators are, in a sense, exact opposites in the world of electromagnetism.

Because the current in the generating coils flows first one way and then the other, it does the same thing in the wires in your home. This kind of current, the kind used in household appliances and cars, is called **alternating current (AC)** because the direction keeps alternating. In contrast, chemical reactions in a battery cause electrons to flow in one direction only and produce what is called **direct current (DC).**

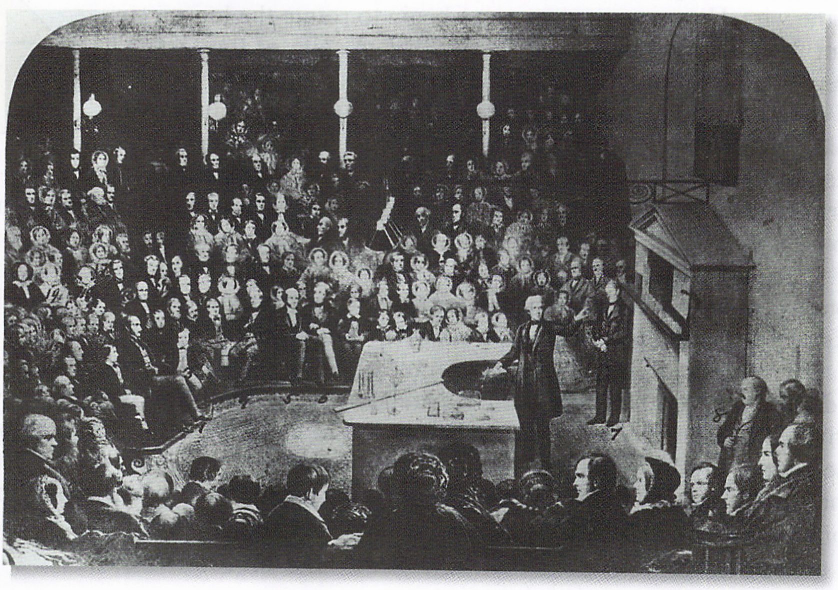
Physics in the Making

Michael Faraday

Michael Faraday, one of the most honored scientists of the nineteenth century, did not come easily to his profession. The son of a blacksmith, he received only a rudimentary education as a member of a small Christian sect. Faraday was apprenticed at the age of 14 to a London book merchant, and he became a voracious reader as well as a skilled bookbinder. Chancing upon the *Encyclopaedia Britannica,* he was fascinated by scientific articles, and he determined then and there to make science his life.

Young Faraday pursued his scientific career in style. He attended a series of public lectures at the Royal Institution by London's most famous scientist, Sir Humphry Davy, a world leader in physical and chemical research. Then, in a bold and flamboyant move, Faraday transcribed his lecture notes into beautiful script, bound the manuscript in the finest tooled leather, and presented the volume to Davy as his calling card. Michael Faraday soon found himself working as Davy's laboratory assistant.

After a decade of work with Davy, Faraday had developed into a creative



Michael Faraday (1791–1867) lecturing before an audience in London.

scientist in his own right. He discovered many new chemical compounds, including liquid benzene, and enjoyed great success with his lectures for the general London public at the Royal Institution. He is usually credited with being the first to develop the idea of electric field lines as a way of visualizing forces due to an isolated charge. However, his most lasting claim to fame was a series of classic experiments through which he discovered electromagnetic induction—a central idea that helped link electricity and magnetism. Two different units in electricity have been named after him, the faraday and the farad, as a tribute to his contributions to physics. No less an authority than Albert Einstein noted that, just as in mechanics Galileo performed the classic experiments that eventually led to Newton's laws of motion, so Faraday performed the experiments in electricity that eventually led to Maxwell's equations. ●

Maxwell's Equations

Electricity and magnetism are not distinct phenomena at all, but are simply different manifestations of one underlying fundamental entity—the **electromagnetic force.** In the 1860s, Scottish physicist James Clerk Maxwell (1831–1879) realized that the four very different statements about electricity and magnetism that we have discussed constitute a single coherent description of electricity and magnetism. These four mathematical statements have come to be known as Maxwell's equations because he was the first to realize their true import by manipulating the mathematics to make important predictions—predictions that we discuss in detail in Chapter 19. For reference, these four fundamental laws of electricity and magnetism—Maxwell's equations—are as follows:


James Clerk Maxwell (1831–1879).

1. Coulomb's law: like charges repel, unlike charges attract, with a force that has an inverse-square dependence on the distance between the charges.
2. There are no magnetic monopoles in nature.
3. Magnetic phenomena can be produced by electric effects.
4. Electric phenomena can be produced by magnetic effects.

These equations, like Newton's laws of motion and the laws of thermodynamics, summarize the behavior of an entire aspect of the universe. The three sets of laws taken together described everything in the universe known to scientists at the end of the nineteenth century. Together, they make up what is usually known as *classical physics*—that is, the physics that describes normal-sized objects moving at normal speeds. In the twentieth century, the theory of relativity (which describes objects moving near the speed of light) and quantum mechanics (which describes the world of the atom) were added to the physicist's repertoire. These two subjects (which we discuss later) are often referred to as *modern physics.*

THINKING MORE ABOUT

Electromagnetism: Basic Research

It's hard to imagine modern American society without electricity. We use it for transportation, communication, heat, light, and many other necessities and amenities of life. Yet the men who gave us this marvelous gift were not primarily concerned with developing better lamps or modes of transportation. In terms of the categories we introduced in Chapter 1, they were doing basic research. Galvani and Volta, for example, were drawn to the study of electricity by their studies of frog muscles that contracted by jolts of electric charge. Volta's first battery was built to duplicate the organs found in electric fish. Scientific discoveries, even those that bring enormous practical benefit to humanity, can come from unexpected sources.

What does this tell you about the problem of allocating government research funding? Can you imagine trying to justify funding Galvani's experiments on frogs' legs to a government panel on the grounds that it might lead to something useful? Would a nineteenth-century government research grant designed to produce better lighting systems have produced the battery (and, eventually, the electric light), or would it more likely have led to an improvement in the oil lamp? How much funding do you think should go to offbeat areas (on the chance that they may produce a large payoff), as compared to projects that have a good chance of producing small but immediate improvements in the quality of life?

While you're thinking about these issues, you might want to keep in mind Michael Faraday's response when he was asked by a political leader what good his electric motor was. He is supposed to have answered, "What good is it? Why, Mr. Prime Minister, someday you will be able to tax it!"

Summary

Nineteenth-century scientists discovered that the seemingly unrelated phenomena of electricity and magnetism are actually two aspects of one **electromagnetic force.** Hans Oersted found that an **electric current** passing through a coil of wire produces a magnetic field. The **electromagnet** and **electric motor** were direct results of his work. Michael Faraday discovered the opposite effect of **electromagnetic induction** when he induced an electric current by placing a wire coil near a changing magnetic field. Faraday's work led to the first **electric generator,** which produces an **alternating current (AC). Batteries,** on the other hand, develop a **direct current (DC).**

James Clerk Maxwell realized that the many independent observations about electricity and magnetism constitute a complete description of electromagnetism.

Key Terms

alternating current (AC) Electric current that changes direction periodically in a circuit. (p. 366)

battery A device that uses stored chemical energy as an electric power source. (p. 354)

direct current (DC) Electric current that is always in the same direction in a circuit. (p. 366)

electric current A flow of charged particles. (p. 354)

electric generator A device that uses electromagnetic induction to produce electricity. (p. 365)

electric motor A device that does work by running electric current through coils of wire in the presence of permanent magnets. (p. 358)

electromagnet A device that creates a magnetic field by running electric current through coils of wire. (p. 357)

electromagnetic force The term that describes the combined effect of the electric and magnetic forces. (p. 354)

electromagnetic induction The effect in which a changing magnetic field causes electric current in a loop of wire. (p. 361)

Review

1. What is electric current?
2. What is a battery? How does a car battery work?
3. How can a battery be recharged?
4. Make a list of five everyday items that depend on battery power. In each case, what alternative sources of energy might you use?
5. What led to the discovery of the connection between electricity and magnetism?
6. What was vitalism?
7. Explain the difference between Galvani and Volta's view of the vital or electric force in living beings. Who was right?
8. How does an electric car work? What are some of the advantages and disadvantages of electric cars?
9. What happens when a current starts to flow through a wire near a compass? What does this tell us about the connection between electricity and magnetism?

10. How did Oersted show that that magnetic fields can indeed be created by the motion of electric charges?

11. What is meant by the phrase "direction of the magnetic field"?

12. What is the right-hand rule? How is this used to determine the direction of a magnetic field? Where else in this text have you seen a right-hand rule used?

13. What is an electromagnet? How is this similar to a bar magnet? How is it different?

14. How does a simple electric motor work? Give some examples of these motors in ordinary life.

15. What is alternating current, and of what importance is it in the operation of a simple electric motor?

16. How are magnetic fields created in nature? Give an example.

17. How is an electron circling an atomic nucleus similar to an electric current going through a coiled wire? Is each a true current? Explain.

18. What is the nature of a magnetic field at the atomic level? What role do electrons play in the creation of this field?

19. What is the present thinking as to what causes Earth's magnetic field? What are some of the problems with this theory? Explain.

20. How did Faraday show that electric effects arise from magnetism?

21. Describe three ways that current can be made to flow when a magnetic field passes through a loop of wire.

22. Which is more significant in Question 20, the magnetic field itself or the change in the magnetic field? Explain.

23. How do we know the direction of an induced current? Explain.

24. What is Lenz's law?

25. How does an electric generator work? How do magnets and coils of wire combine to produce the electricity generated?

26. What are the similarities and differences between a simple electric motor and an electric generator?

27. What is alternating current? Give an example.

28. What is direct current? Give an example.

29. What are the four Maxwell equations?

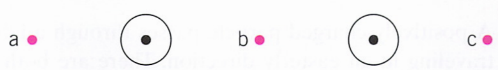
30. What do Maxwell's equations tell us about the unity of electricity and magnetism? Explain.

31. Was Faraday's classic experiment on electromagnetic induction an example of pure research or applied research?

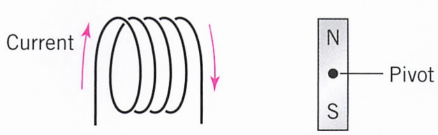
Questions

1. The figure represents two long, straight, parallel wires extending in a direction perpendicular to the page. The current in the left wire runs into the page and the current in the right wire runs out of the page. What is the direction of the magnetic field created by these wires at locations a, b, and c? (b is at the exact midpoint between the wires.)

2. The figure represents two long, straight, parallel wires extending in a direction perpendicular to the page. The current in both wires flows out of the page. What is the direction of the magnetic field created by these wires at locations a, b, and c? (b is at the exact midpoint between the wires.)

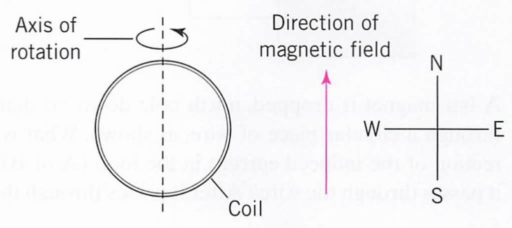


3. An electric current runs through a coil of wire as shown in the figure. A permanent magnet is located to the right of the coil. If the magnet is free to rotate, will it rotate clockwise or counterclockwise? Explain.



4. Suppose you have a Frisbee with a copper wire glued around its outer circumference. When you throw the Frisbee correctly, it maintains a constant orientation with the ground; if you throw it incorrectly, it will wobble. In which of these cases, if either, will a current be induced in the copper wire due to Earth's magnetic field?

5. Suppose you are in a location where the magnetic field of Earth points north and is horizontal to the ground. If a circular wire is rotated as shown in the figure (the axis of rotation is along the north-south direction), will there be an induced current in the wire? Explain. What if the axis of rotation were in the east-west direction?



6. If you only had a magnet and a coil of wire, how might you generate a small amount of electricity in that coil?

7. If you took an electric motor and turned it by hand, what do you think would happen in the coils of wire?

8. What is the underlying basis of the magnetic field in a magnetized piece of iron?

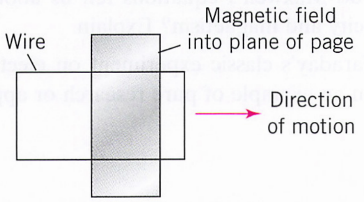
9. Why can't you find a magnetic monopole by taking an atom apart?

10. What would be the effect of using direct current to power the simple electric motor described in this chapter?

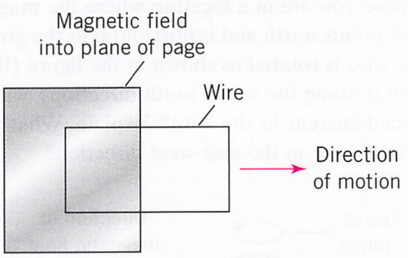
11. Explain just how motors and generators can be considered opposites in the realm of electromagnetism. How are they similar and how do they differ?

12. If a current were flowing clockwise around a loop placed on your desk, which direction would the resulting magnetic field be inside the loop?

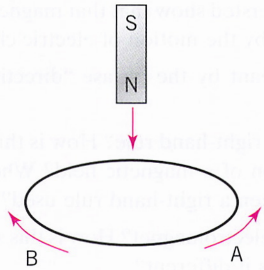
13. A rectangular piece of wire is moving to the right as shown. It passes through a region where there is a magnetic field pointing into the page, as shown (magnetic field indicated by the shaded region). When the loop of wire is in the position shown in the figure, is there an induced current in the loop? Explain.



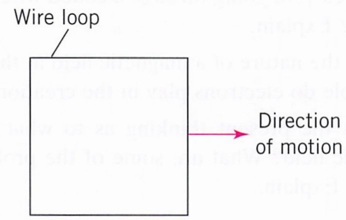
14. A rectangular piece of wire is moving to the right as shown. It passes through a region where there is a magnetic field pointing into the page, as shown (magnetic field indicated by the shaded region). When the loop of wire is in the position shown in the figure, is there an induced current in the loop? If there is an induced current, does it run clockwise or counterclockwise? Explain.



15. A bar magnet is dropped, north pole down, so that it falls through a circular piece of wire, as shown. What is the direction of the induced current in the loop (A or B) before it passes through the wire? After it passes through the wire?



16. A square loop of copper wire is moving to the right in a uniform, downward-pointing magnetic field, as shown. What is the direction of the force on an electron moving to the right in this magnetic field? Use your answer to explain why there is no induced current in this square current loop.



17. If you could wrap a wire around Earth's equator at an altitude of 200 kilometers and run an electric current through it in the westerly direction, would this have the effect of reinforcing or canceling Earth's natural magnetic field at Earth's surface?

18. A long straight wire is aligned north-south and carries current in the northerly direction. What is the direction of the magnetic field created directly below the wire? What is the direction of the magnetic field created directly to the right of the wire?

19. A long straight wire is aligned north-south and carries current in the northerly direction. What is the direction of the magnetic field created directly above the wire? What is the direction of the magnetic field created directly to the left of the wire? If a proton is traveling north directly above the wire, what is the magnetic force on the proton due to the wire?

20. A positively charged particle passes through a laboratory traveling in an easterly direction. There are both electric and magnetic fields in the room and their effects on the charged particle cancel. If the electric field points upward, what must be the direction of the magnetic field?

Problems

1. The electric field at a point in space is defined as the force per unit charge at that point in space. That is, it is the force that would be exerted on a 1-coulomb charge if one were at that point in space. Therefore, we can write the electric field E of a charge q at a distance d from that charge, experienced by a charge $Q = 1$ coulomb, as

$$E = \frac{F}{Q} = k\frac{q}{d^2}$$

The electric field has a direction such that it points toward negative charges and points away from positive charges. Suppose you rub a balloon in your hair and it acquires a static charge of -3.0×10^{-9} coulombs.

   a. What are the units of electric field?
   b. What is the strength and direction of the electric field created by the balloon at a location 1 meter due north of the balloon?
   c. What is the strength and direction of the electric field created by the balloon at a location 2 meters above the balloon?
   d. Your hair acquired an equal amount of positive charge when you rubbed the balloon on your head. What is the strength and direction of the electric field created by your head, at the location of your feet, 1.5 meters down?

2. The strength of Earth's magnetic field at the equator is approximately equal to $B = 50 \times 10^{-6}$ T, where B is the customary symbol for magnetic field and T stands for tesla, the unit of magnetic field. The force on a charge q moving in a direction perpendicular to a magnetic field is given by $F = qvB$, where v is the speed of the particle. The direction of the force is given by the right-hand rule, as described in Chapter 17. Suppose you rub a balloon in your hair and your head acquires a static charge of 3.0×10^{-9} coulombs.

   a. If you are at the equator and driving west at a speed of 30 meters per second, what is the strength and direction of the magnetic force on your head due to Earth's magnetic field?
   b. If you are at the equator and driving north at a speed of 30 meters per second, what is the strength and direction of the magnetic force on your head due to Earth's magnetic field?
   c. If you are driving east, how fast would you have to drive in order for the magnetic force on your head to equal 200 newtons (probably enough to knock you over)?

3. In the laboratory, you have arranged to have a magnetic field that is pointing north with a strength of $B = 0.5$ T an electric field that points downward with a strength of $E = 6.0 \times 10^6$ N/C. An electric charge with a magnitude $q = 10^{-9}$ C passes through the laboratory. The force on the charge due to the electric field is given by $F = qE$. The force on the charge due to the magnetic field is given by $F = qvB$, where v is the speed of the particle. The direction of the magnetic force is given by the right-hand rule, as described in Chapter 16.

   a. What direction would the charge have to travel in order that the charge passes through the room undeflected? Neglect the gravitational force. (*Hint:* What direction does the charge have to travel so that the direction of the electric force is opposite to the direction of the magnetic force?)
   b. What is the strength of the electric force?
   c. How fast would it have to travel so that it passes through the room undeflected?

Investigations

1. Read Jules Verne's *The Mysterious Island.* Do you think it is possible for castaways to build an electric generator as described in the book?

2. Take apart an old electric razor or other small motor-driven appliance and dissect the motor. How many permanent magnets are inside? How many separate coils of wire?

3. Calculate the cost per hour to run a large radio, or boom box, with batteries. Then calculate how expensive the same radio would be to run for 1 hour when plugged into a household electric outlet, using the electric rates in your area. Is there a large difference?

4. How long is the average commute between home and work for people in your area? Might electric cars be of use in the future?

5. Research the local power plants in your area. How are they the same? How do they differ? Examine the fuels used, the actual generators themselves, and the pollution produced, as well as the types of technology employed to reduce this pollution.

6. Further explore the history of the development of the electric car. Who have been the main developers of this technology, and how are obstacles to the efficiency of these cars being overcome? From your research, when do you think you will see such cars on the road in large numbers, if ever?

WWW Resources

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

1. **http://ippex.pppl.gov/interactive/electricity/** A website of the Internet Plasma Physics Education Experience (IPPEX).
2. **http://physics.uwstout.edu/staff/scott/animate.html#faraday** Animations illustrating Faraday's law of electromagnetic induction.
3. **http://physicsed.buffalostate.edu/SeatExpts/EandM/motor/index.htm** A discussion of how to construct and analyze the "world's simplest electric motor."
4. **http://www4.ncsu.edu/~rwchabay/emimovies/** A series of movies illustrating electric and magnetic interactions, including the right-hand rule.