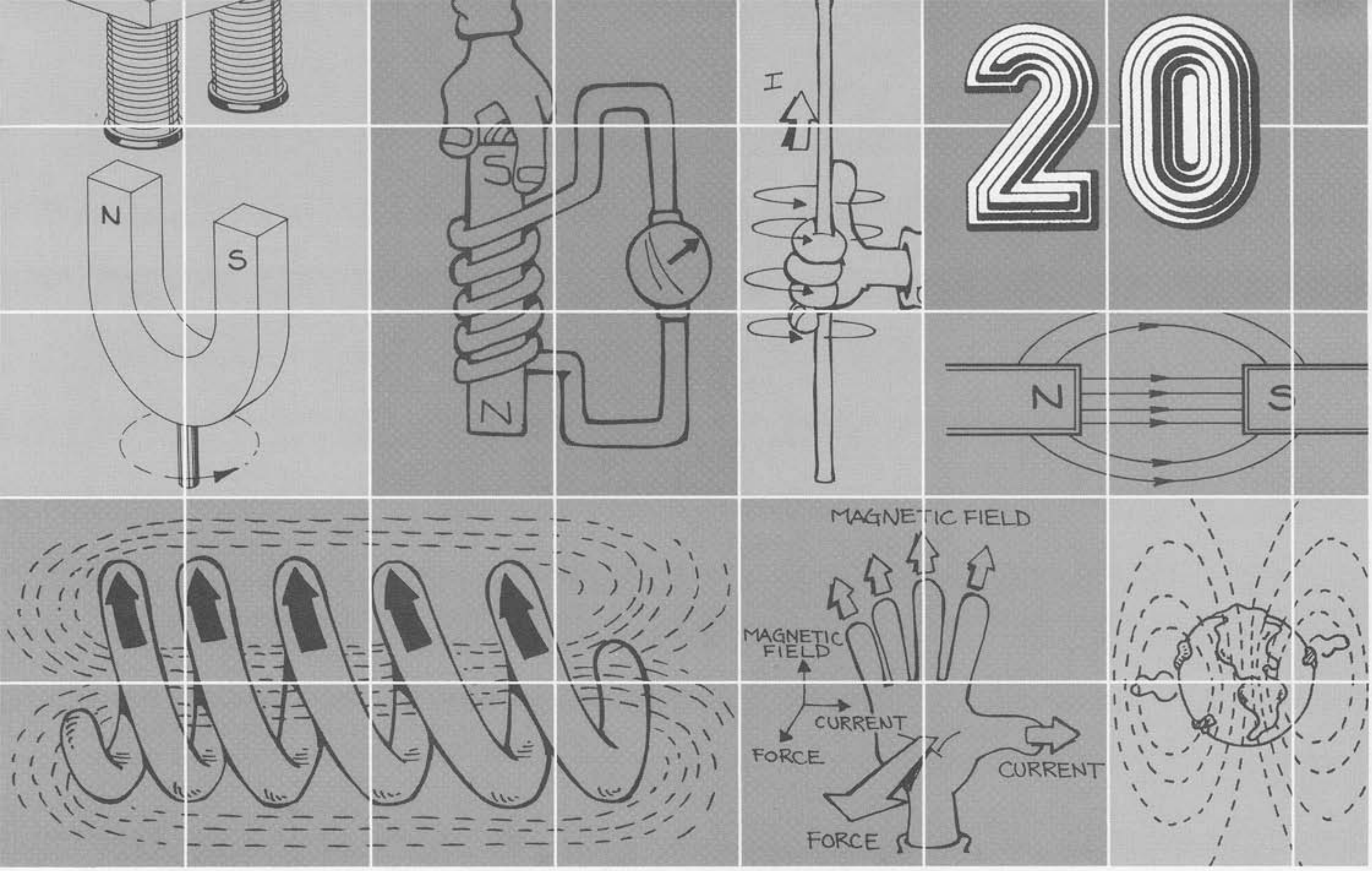


Electromagnetism

Man is a singular creature. He has a set of gifts which make him unique among the animals: so that, unlike them, he is not a figure in the landscape—he is a shaper of the landscape. In body and in mind he is the explorer of nature, the ubiquitous animal, who did not find but has made his home in every continent.

Jacob Bronowski, *The Ascent of Man*

Shaper of landscape . . . explorer of nature. These phrases from the opening paragraph of Jacob Bronowski's *The Ascent of Man* describe the inseparable relationship between technology and science. Nowhere is this relationship more obvious than in the development of electromagnetism during the nineteenth century. In 1820 Hans Christian Oersted discovered that electrical currents create magnetic fields. Four years later the first electromagnet was built. Michael Faraday discovered the reverse effect: Changing magnetic fields create a voltage. Less than a year later, in 1832, early models of the electric generator began to appear. James Maxwell published his complete theory of electromagnetism in 1873. Twenty-three years later the prototype of the electrical generating plant was delivering electrical energy to Buffalo, New York.

As explorers of nature, physicists during the nineteenth century forged one of the most awesome theories in the history of scientific thought. Rivaled in breadth only by Newton's mechanics, Maxwell's theory of electromagnetism unites phenomena ranging from the forces between electric charges to the movement of light waves. As shapers of the landscape, physicists and inventors revolutionized our way of life. Because of the ease with which electrical energy can be generated and distributed, it has completely altered our work, our leisure, and our landscape.

Beginning with an overview of *magnetism,* this chapter traces the discovery of the relationships between electricity and magnetism. Currents create *magnetic fields* and changing magnetic fields create voltages, a phenomenon called *electromagnetic induction.* These two principles provide the structure for the theory of *electromagnetism* and for the development of new technologies, including electric power, radio, and television.

MAGNETISM

Magnets come in a variety of shapes and sizes. Play around with a couple of magnets for a bit and . . . CLUNK, they stick together. Turn one of the magnets around, and you can chase the other one all over the table. Put a piece of paper over a magnet and sprinkle some iron filings about. The filings line up in a definite pattern. Put a magnet on a refrigerator door and it stays. Put it on an aluminum pan and it falls. These and a host of other observations are integrated into our present model of magnetism.

Magnetic Poles

Magnets exert forces on one another—forces that you can feel if you are holding the magnets or that you can see as one magnet pushes the other around the table. In many respects magnetic forces behave like electrical forces; they are exerted at a distance. Magnets do not need to touch each other in order to interact. Magnetic forces can be either attractive or repulsive, depending upon which ends of the magnet are held near one another. The strength of the magnetic force depends on the distance separating the two magnets. These and other similarities to the electrical interaction led physicists to develop a two-pole model of magnetism that is analogous to the two-charge model of electricity.

Magnets have at least two regions, called **magnetic poles,** which exert magnetic forces on other magnets. All magnets have two types of poles, called (by convention) **north** and **south** poles. For a bar magnet, these poles are located at the two ends. (A horseshoe magnet is just a bar magnet that has been bent, so its poles are at its two ends.) Others, such as ring magnets and ceramic magnets, have poles located on their faces. The two kinds of poles interact with one another, as do the two kinds of electric charge. Like poles (north-north, south-south) repel; unlike poles (north-south) attract.

While magnetic poles behave similar to electric charges in some ways, they exhibit one important difference. Isolated electric charges are commonplace, while isolated magnetic poles are not. If we break a bar magnet in half,

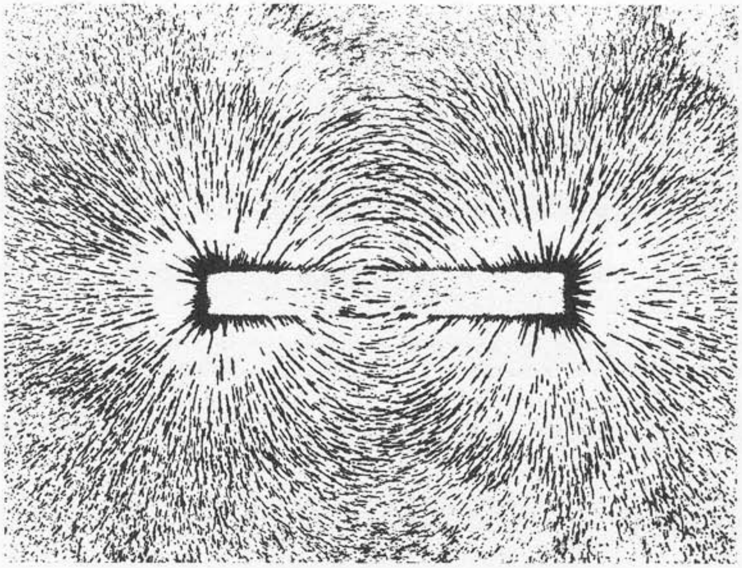


Figure 20-1
Iron filings trace out a pattern of lines called *magnetic field lines* in the space surrounding a magnet.

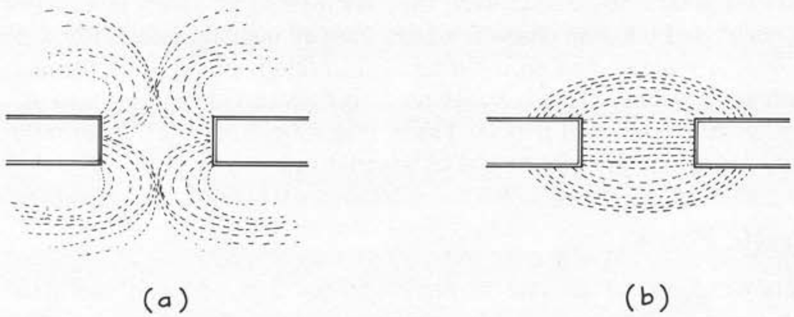


Figure 20-2
Magnetic field lines provide us a mental picture of the forces **(a)** between two like poles and **(b)** between two unlike poles.

each half still behaves as a complete magnet. Breaking each half gives us four fragments, each of which still behaves as a complete magnet. We could continue breaking off pieces of the magnet, but we would never isolate a single magnetic pole. Magnetic poles exist in pairs.

Magnetic Fields

We can demonstrate the interactions of magnetic poles using tiny iron filings. When sprinkled on a piece of paper, the filings do not form any special pattern. But, if we hold the paper over a bar magnet, the filings trace out a pattern of curved lines (Figure 20-1). Distinct lines spread out from one pole, circle one side of the magnet, and return to the other pole. Examine the patterns produced with two like poles (Figure 20-2(a)) and with two unlike poles (Figure 20-2(b)). The way the lines bend away or toward one another reflects our experience with magnets: Like poles repel and unlike poles attract.

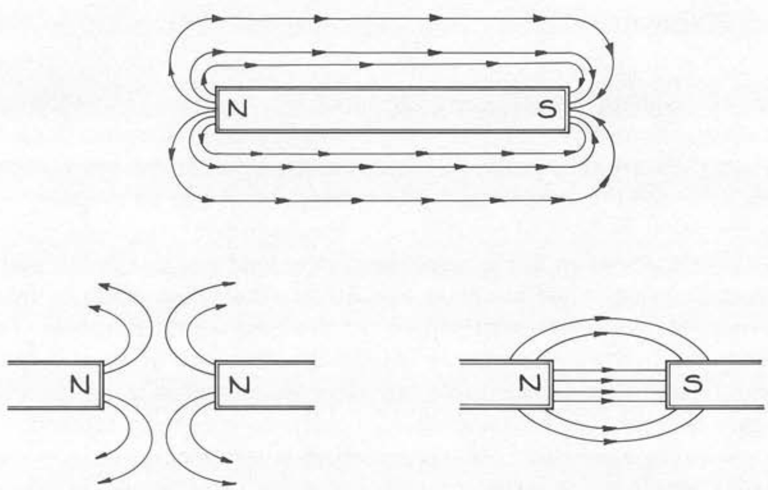


Figure 20-3

Magnetic fields have a direction that shows the force on a north pole at each point in the space surrounding the magnet.

The patterns produced by the iron filings represent the *magnetic fields* of the magnets. The field is a set of vectors that describes how a magnet affects other magnets. Another magnet, when placed in a magnetic field, will tend to line up its poles with the magnetic field. Thus the magnetic field provides us with a picture of the magnet's action at a distance.

The relative strength of the magnetic field can be determined by looking at the lines traced out by the magnetic field. Places where the lines are close together represent locations where the magnetic force is strong, while areas where the lines are far apart have weaker magnetic forces. The density of the lines in the drawing of a magnetic field shows the strength of the force.

Since a magnetic field represents the force due to a magnet, it must have a direction. By convention we define the direction of a magnetic field to be the direction of the force on a north magnetic pole. When a magnet is placed in the magnetic field of another magnet, the north poles of the two magnets will repel one another. Thus the direction of any magnet's field is away from its north pole and toward its south pole. The drawings in Figure 20-3 show these fields for a bar magnet and for the configurations shown in Figure 20-2.

The largest magnet on earth is the earth itself. The poles of the earth's magnet are located fairly close to the geographic north and south poles defined by the earth's rotation. As shown in Figure 20-4, the earth's magnetic field can be approximated by the field produced by a bar magnet tilted at about 11.5° relative to the earth's axis of rotation. The terms *north* and *south* as applied to magnetic poles are derived from the way in which magnets rotate in the earth's field. The north pole (more precisely called the *north-seeking pole*) of any magnet rotates so that it points north when the magnet is suspended in the earth's field. Since the north pole of a magnet is attracted to the earth's pole, which is located in northern regions, the earth's magnetic pole located up north is really the south pole of a magnet. Magnetic compasses are simply tiny magnets pivoted so that they are free to rotate. The tip of the needle is a north pole and will always point north—to the relief of many pilots, ship captains, and scouts.

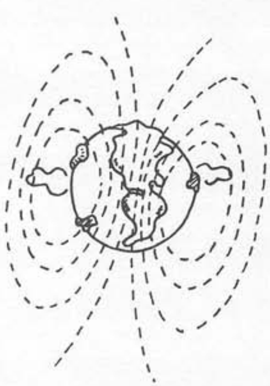


Figure 20-4

The earth's magnetic field can be approximated by the field produced by a bar magnet tilted 11½° relative to the earth's axis of rotation.

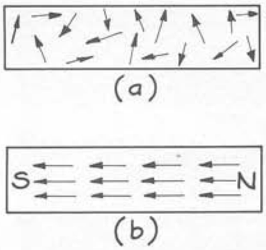


Figure 20-5
The magnetic behavior of different metals can be described in terms of the alignment of magnetic domains. **(a)** Oriented randomly, the magnetic domains produce magnetic fields that cancel one another. The metal demonstrates little, if any, magnetic properties. **(b)** Aligned with one another, the magnetic domains produce magnetic fields that add. The strength of the magnet depends on the number of domains that are aligned.

Making Magnets

Two paper clips sitting on your desk neither attract nor repel each other—they are not magnets. Yet, they are attracted to a magnet, just as though they were magnets themselves. In fact, the paper clips do acquire north and south poles when they are in a magnet's field. Paper clips can be magnetized.

When placed in a magnetic field, materials that can be magnetized form either permanent or temporary magnets. **Permanent magnets** continue to behave as magnets when the external magnetic field has been removed. They can attract or repel other magnets and attract materials made of iron. The various magnets we have discussed so far are permanent magnets. **Temporary magnets** behave as magnets only in the presence of an external magnetic field. Paper clips, for example, are strongly attracted to a magnet. Once the magnet is removed, however, they display no magnetic attraction or repulsion toward one another. Their magnetism is temporary.

Magnetism is a property of some, but not all, materials. A magnet will turn a refrigerator door—but not an aluminum pan—into a temporary magnet. Magnets attract safety pins and paper clips but not pennies. Bar magnets are made from alloys containing iron, nickel, or cobalt but not copper or zinc. Some materials can be magnetized; others cannot.

Magnetic Domains

The difference between magnetic and nonmagnetic materials is their ability to form magnetic domains. A **magnetic domain** is a small section of matter that behaves like a tiny magnet. When the domains are oriented in random fashion, the magnetic fields produced by each cancel the fields of others. When the domains line up with one another, their fields add (Figure 20-5). The strength of a magnet depends upon the number of magnetic domains that are aligned.

Magnetic domains enable us to understand the difference between permanent and temporary magnets. When some types of iron bars are placed in an external magnetic field, most of their magnetic domains are forced into alignment with the field. The alignment is so complete that the domains hold one another in place once the external field is removed. Thus, the iron bar becomes a permanent magnet. In a temporary magnet, fewer domains are forced into alignment. Once the external field is removed, molecular motion causes the aligned domains to return to a random arrangement. Pins and paper clips, for example, become temporary magnets as their domains align with an external magnetic field. When the field is removed, the domains return to randomness. Still other materials cannot have magnetic domains aligned at all. Aluminum, for example, does not become a magnet even temporarily.

SELF-CHECK 20A

If you drop a permanent magnet, it can lose some if its magnetic strength. Use the concept of magnetic domains to explain why.

Storing Information with Magnetic Domains

A spy in a hostile country, you arrange a secret code with an accomplice. You will place magnets along the inside of your house. Different orientations and strengths of the magnets will correspond to the different letters of the alphabet. Your accomplice need only walk by the outside of the house with a magnetic compass in hand to receive the message. While James Bond may never find this technique convenient, it illustrates the process by which magnetic domains can be used to store information.

Magnetic recording tapes and disks that are used in audio, video, and computer applications consist of a thin layer of iron or chromium oxide deposited on a plastic surface. Both iron and chromium oxide have magnetic domains that can be aligned by external magnetic fields. Information is stored on the tape or disk by aligning small sections of magnetic domains according to a coded format. The domains then remain aligned so that the tape or disk may be played back and the information retrieved. The player can collect the information by sensing the orientations of the magnetic domains. Consequently, information can be retrieved and still remain on the magnetic medium for future use. The information can be erased by moving the tape through a magnetic field so that all the domains are aligned in one direction rather than arranged according to a standard code. Thus, the information on a disk or tape can accidentally be removed if the medium is placed next to a magnet.

In a slightly different context, information about the earth's magnetic field is stored in the magnetic material trapped inside rocks. Many minerals contain bits of iron similar to the iron filings that we use to map magnetic fields. These rocks have been created from molten material of volcanic eruptions or from deposits at the bottom of oceans. At the time the rocks were being formed, iron was not trapped in a fixed position as it is now. Since they are magnetic, the small bits of iron rotated to align themselves with the earth's magnetic field. As the rocks hardened into their present form, the iron was trapped—recording the orientation of the earth's magnetic field. We can retrieve this information by looking at the bits of iron in rocks.

An examination of rocks from different periods of the earth's development provides us with a history of the earth's magnetic field. Investigations show startling changes. The earth's field has reversed itself fourteen times during the past 4.5 million years, changing the location of the magnetic north pole from one geographic pole to the other. Exactly how and why these changes occur is not well understood. The earth's field may die down to nothing and then build back up in the opposite direction, or it may tip over slowly somewhat like turning around a bar magnet. However, the time scale is well known. The earth reverses its field approximately once every half-million years and takes about 1000 years to complete the reversing process. Sometime in the next few hundred thousand years, the earth's field will reverse itself. Then, the magnetic north pole of the earth's field will be near the geographic north pole. That will make less confusion in describing the poles, but all our compasses will point in the wrong direction.

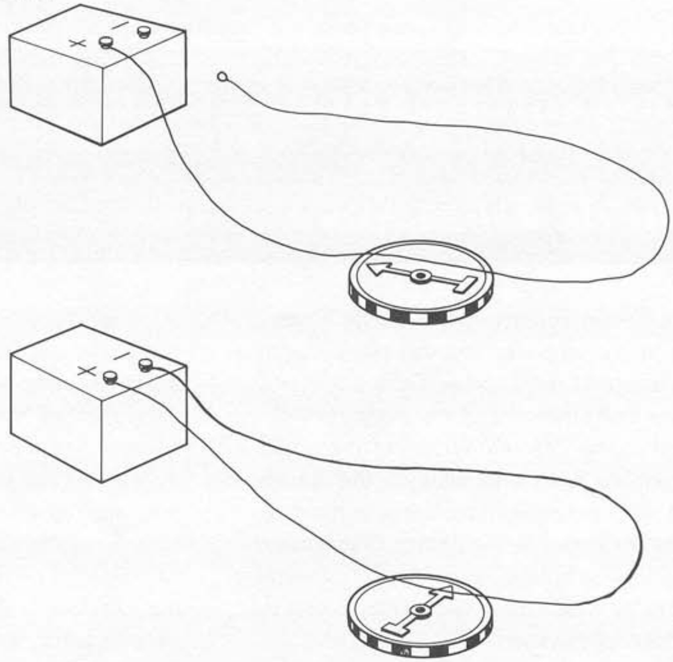


Figure 20-6

Oersted placed a long wire parallel to a magnetic compass. When an electric current moved through the wire, the compass rotated so that it was perpendicular to the wire.

ELECTRIC CURRENTS AND MAGNETIC FIELDS

Similarities between electricity and magnetism were so striking that by the beginning of the nineteenth century most physicists were convinced that the two phenomena were related. Reports circulated that lightning had magnetized sewing needles and tableware: yet physicists were unable to detect any such relationship. Finally, Oersted noticed that currents could affect a magnetic compass. By the end of the century, this single observation had grown into a comprehensive model of electromagnetism.

Moving Charges Produce Magnetic Fields

Oersted's experiment turned out to be remarkably simple. In fact, he first performed the experiment accidentally while giving a physics lecture to his students. A magnetic compass was lying on a table when he placed a current-carrying wire near it. Both the compass needle and the wire were oriented in a north-south direction (Figure 20-6). When an electric current moved through the wire, the compass needle rotated toward the east. When the direction of the current was reversed, the compass needle turned to the west. When the current was turned off, the needle again aligned itself with the earth's magnetic field. The behavior of the compass tells us that a current-carrying wire produces a magnetic field.

We can describe the shape and direction of this magnetic field in more detail with the help of iron filings and magnetic compasses. When the iron filings are sprinkled on a piece of paper that lies parallel to the current-carrying wire, no pattern is formed (Figure 20-7(a)). Perpendicular to the wire, however, the iron filings arrange themselves in a circular pattern (Figure 20-7(b)).

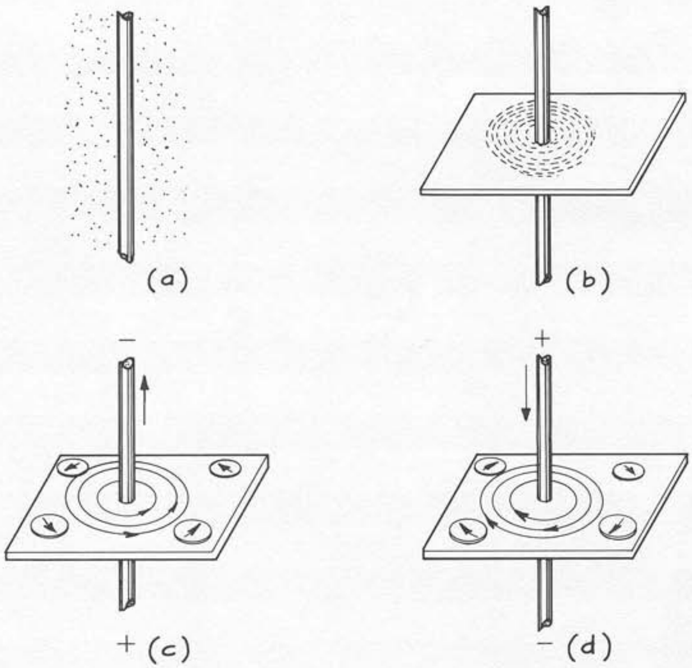


Figure 20-7
Iron filings and magnetic compasses trace out the magnetic field produced by the current-carrying wires. **(a)** No magnetic field exists in a plane parallel to the current-carrying wire. **(b)** Perpendicular to the wire, the iron filings arrange themselves in a circular pattern. **(c)** The magnetic field lines are counterclockwise when the current moves upward and **(d)** clockwise when the current moves downward.

The iron filings show the pattern but not the direction of the magnetic field. A series of small compasses can show both (Figure 20-7(c) and (d)). A circular magnetic field around a single wire is present whenever an electrical current exists in the wire.

This observation leads to the **right-hand rule** for determining the direction of a field created by a current in a wire. However, before we state the rule, we must define the direction of the electric current. Early researchers in electricity did not know that the moving charges were negative. So, they defined the direction of electric current to be from the positive side to the negative side of an energy source. When discussing magnetism, we still use this convention. Determine the direction of the current by assuming it moves from positive to negative. Then, hold your right hand so that four fingers form part of a circle and your thumb points away from the rest of your hand. If you place the thumb of your right hand in the direction of the electric current inside the wire, your fingers curl in the direction of the magnetic field (Figure 20-8). The right-hand rule reflects Oersted's discovery that the direction of the magnetic field changes in response to changes in the direction in which the electric current flows.

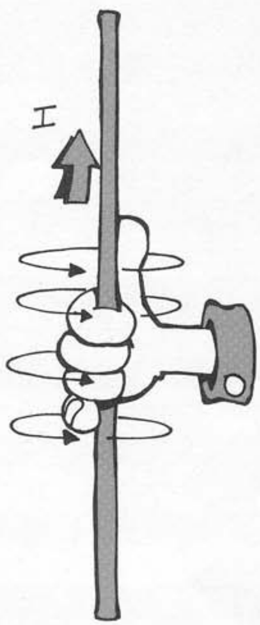


Figure 20-8
If you place the thumb of your right hand in the direction of the electric current, your fingers curl in the direction of the magnetic field lines.

The strength of the magnetic field around a current-carrying wire is related to the size of the current in the wire. Measurements of the field strength and the current would show us that the magnetic field strength increases as the current increases. The relationship between the two is a direct one: Doubling the current causes the magnetic field strength to double.

Oersted's experiment provided the first reproducible observation of a relationship between electricity and magnetism. A current-carrying wire produces a magnetic field whose strength depends on the amount of the current flowing and whose direction depends on the direction that the current flows.

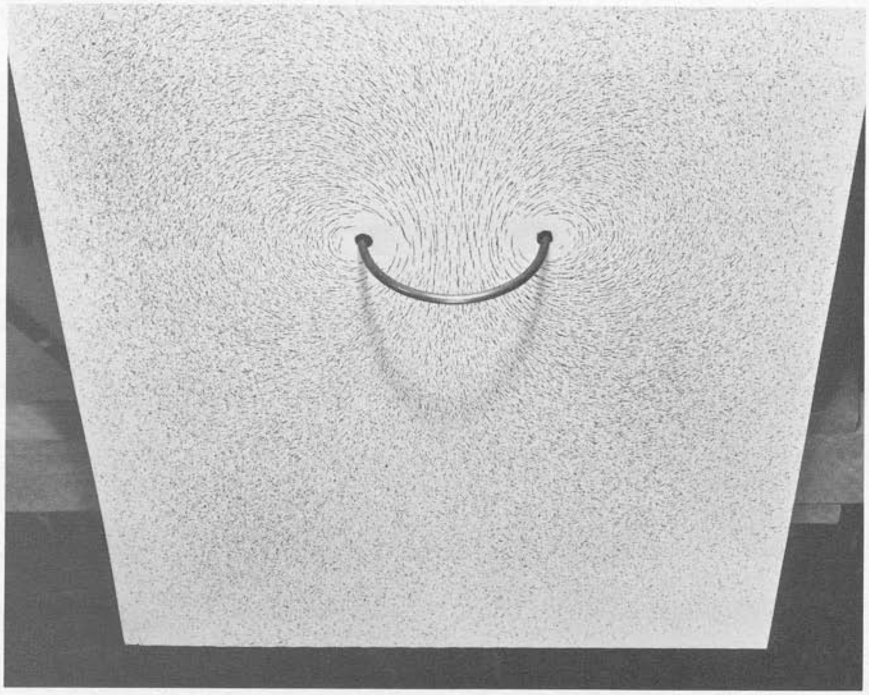


Figure 20-9
If we loop the wire, the magnetic fields produced by the different segments overlap. The fields add, producing a stronger magnetic field than that of the straight wire.

Clearly, the electric current itself gives rise to the magnetic field. Within a decade, this observation led to the development of powerful electromagnets and, ultimately, to an atomic explanation of magnetism.

Electromagnets

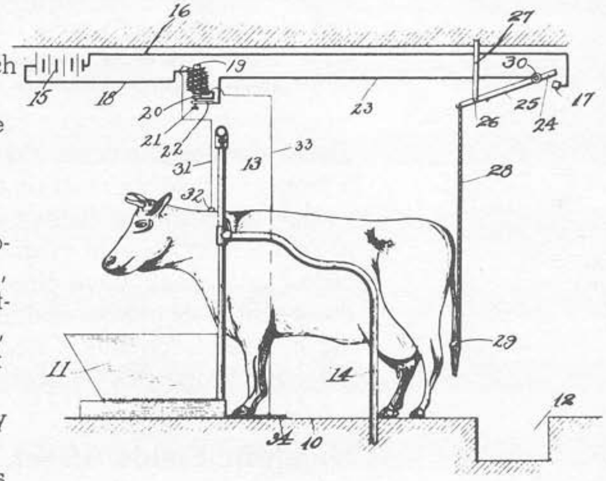
The magnetic field produced by an ordinary wire is not very large. A current of a few amperes produces a field that is barely large enough to rotate a compass needle. To be of practical value, fields need to be much larger. One way to create these larger fields is to arrange different segments of the same wire so that their fields add.

A single current-carrying wire produces a circular magnetic field along its entire length. If we loop the wire (Figure 20-9), the magnetic fields produced by different segments of the wire overlap. The fields add, producing a stronger magnetic field that looks somewhat like the field produced by a bar magnet. If we make a longer series of loops (a coil), the current-carrying wire produces a magnetic field that looks exactly like that produced by a bar magnet (Figure 20-10).

Placing a piece of iron inside the loops of a coil, we have an electromagnet. An **electromagnet** consists of a coil of current-carrying wire into which an iron bar has been placed. The magnetic field produced by the coil draws the magnetic domains in the iron into alignment, creating a magnetic field that can be a thousandfold stronger than the field produced by the coil itself. Even more useful is the control we have over the field. By turning off the current, we turn off the magnetic field. In allowing us control over the magnetic field, the electromagnet has been useful in a variety of applications.

MOVE, COW, MOVE

The application of circuits and magnetism to a typical farm problem resulted in an invention by Elmer Swensen in 1922. Mr. Swensen wanted to make sure that when something other than milk came out of his cows, it went into a place where he would not step in it. Electrical circuitry, magnetism, and a little knowledge of cow behavior provided a solution. Just before the dirty deed, the cow raises its tail, which is attached to a rope (29). The rope becomes slack and no longer holds open the switch (24). The closed switch completes the circuit between 17 and 30. The battery (15) then provides current to an electromagnet (19). In turn, the electromagnet attracts an iron switch, and a second circuit closes. This second circuit is attached by wire (33) to a pad (34) under the cow's feet and by a second wire (31) to the cow (32). Because these wires are connected to the battery, the cow now becomes part of a complete circuit. To stop the current the cow steps backwards and is in the correct position relative to the "toilet" (12).



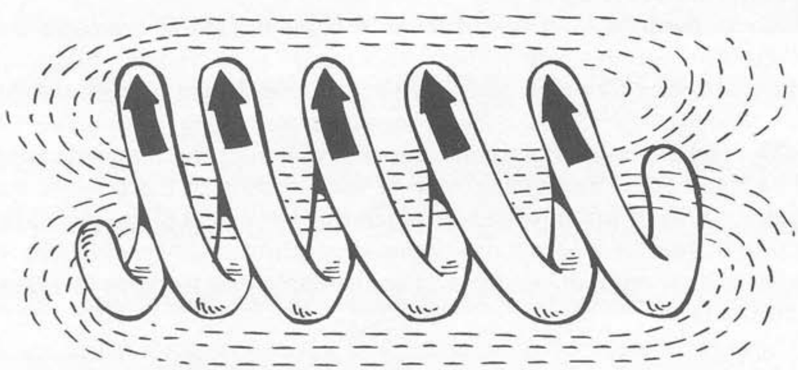


Figure 20-10

The magnetic field produced by a coil of wire looks very similar to the field created by a bar magnet.

SELF-CHECK 20B

The piece of iron in an electromagnet is removed and replaced by an identically shaped piece of aluminum. Will the strength of the electromagnet increase, decrease, or stay the same? Explain your answer using the field in the coil and the magnetic domains.

The Atomic Basis of Magnetism

The discovery that currents produce magnetic fields gave us more than just more powerful, controllable magnets. The realization that electric currents produce magnetic fields led many physicists to suspect that magnetic properties in general might arise from electric currents. Research into the internal structure of the atom revealed that they were right.

Atoms contain from one to more than a hundred electrons. Each electron moves constantly as it orbits the atomic nucleus and as it spins on its axis. These motions of electric charge are, in effect, small currents. Each produces a magnetic field. In most materials the electron spins and orbits are oriented so that the magnetic fields associated with them cancel each other, and each atom is left with no net magnetic field. However, a few materials, such as iron, nickel, and cobalt, have atoms that end up with a small net magnetic field. In these materials groups of atoms align themselves in each other's fields, forming magnetic domains. Once these domains are aligned, they produce the magnetic properties we observe.

Magnetic Fields Affect Moving Charges

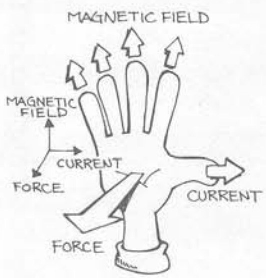


Figure 20-11

If you place the fingers of your right hand in the direction of the magnetic field and your thumb in the direction of the electric current, your palm points in the direction in which the force acts.

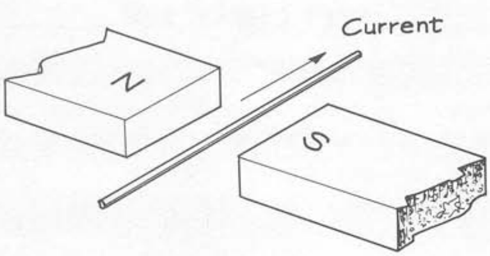
If a wire is placed between the poles of a horseshoe magnet, the wire remains stationary only as long as no current flows in it. Once the current starts, the wire jumps away. Magnets exert forces on current-carrying wires.

We can explain this observation in terms of an interaction between two magnetic fields. Both the magnet and the current-carrying wire have magnetic fields. In the region where the two fields overlap, an interaction occurs, and the two fields repel one another. Since the wire is substantially less massive than the magnet, it jumps away.

We can describe both the direction and magnitude of the force exerted on the current-carrying wire without necessarily analyzing the two magnetic fields in detail. The direction of the force is perpendicular to both the current and the magnetic field; it can be determined from a *right-hand rule*. If you place the fingers of your right hand in the direction of the magnetic field produced by the magnet and your thumb in the direction of the electric current, your palm points in the direction in which the force acts (Figure 20-11). The magnitude of the force depends on the strength of the two magnetic fields. Increasing the strength of the magnet or the current in the wire increases the force on the wire.

These results can be generalized and applied to other situations. If we think of the magnet as supplying an external magnetic field and the current-

Figure 20-12



carrying wire as supplying a moving electric charge, then we can conclude that an external magnetic field exerts a force on a moving electric charge. The external magnetic field can be provided by a permanent magnet, an electromagnet, or even another current-carrying wire. The moving electric charge can be a stream of electrons, a stream of positively charged particles, or the conventional current in a wire.

SELF-CHECK 20C

A wire is placed between the poles of two magnets, as shown in Figure 20-12. In which direction will the wire move if a current is allowed to flow as shown?

Magnetic Forces Run Motors

The forces that magnetic fields exert on moving electric charges have been exploited in a number of applications, most notably the electric motor. An electric motor is a device that converts electrical energy into kinetic energy. In a simplified version (Figure 20-13), a motor consists of a wire coil placed in the magnetic field between two poles of a permanent magnet. When the current moves in the coil, the permanent magnetic field interacts with the coil's magnetic field and exerts a force that rotates the coil. A shaft attached so that it rotates with the coil then makes this motion available for performing useful work. The electrical energy supplied by the current is converted into kinetic energy of the shaft.

Though the idea is simple, it takes some ingenuity to make a motor actually work. Figure 20-14 shows a series of drawings as the coil rotates within the magnetic field. In (a) a current flowing from *A* to *B* to *C* to *D* results in the magnetic field applying a downward force on the coil segment *AB* and an upward force on segment *CD*. These forces combine to rotate the coil counter-

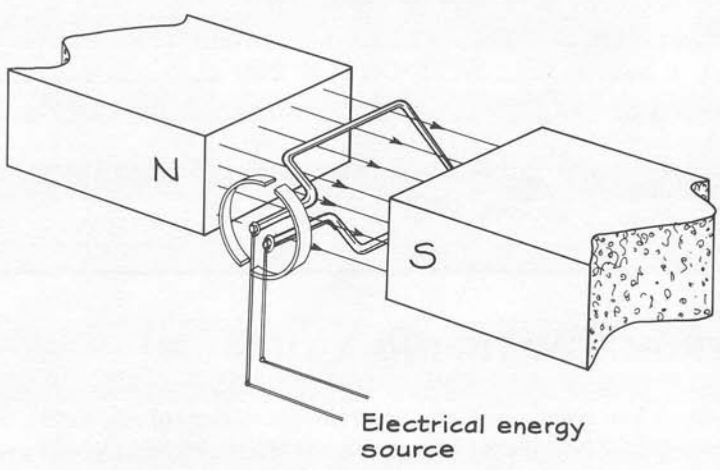


Figure 20-13
In simplified form, an electric motor consists of a wire coil placed in the magnetic field between two poles of a permanent magnet.

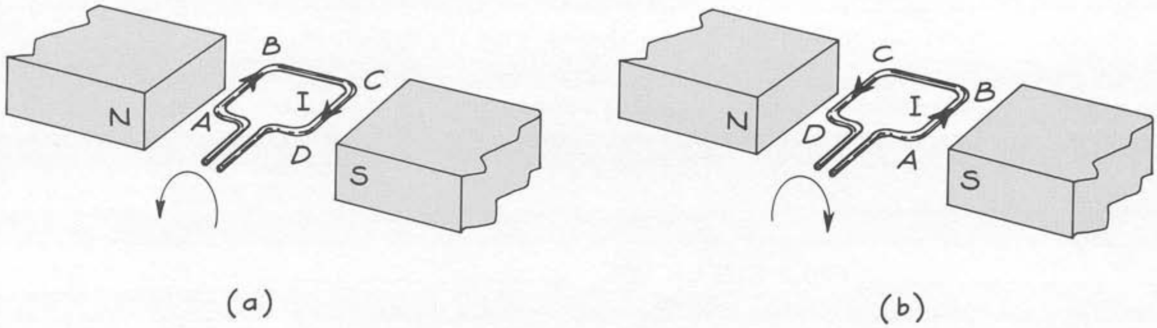


Figure 20-14

As current flows in the direction of ABCD, the permanent magnet exerts forces on segments *AB* and *CD* of the current-carrying coil.
(a) An upward force on *CD* and a downward force on *AB* rotate the coil counterclockwise.
(b) If the current continues in the same direction, a downward force on *AB* and an upward force on *CD* will rotate the coil back clockwise.

clockwise. In (b) the coil has rotated halfway around. If the current continues to flow in the same direction (*A* to *B* to *C* to *D*), a downward force will be exerted on the segment *AB* and an upward force on segment *CD*. These forces combine to rotate the coil clockwise—back in the direction from which it just came. To keep the coil rotating in the clockwise direction, we have to reverse the direction in which the current flows each time the coil completes half a revolution. The simplest way to accomplish this is to have the ends of the coil rotate about a cylindrically shaped pair of contacts so that each end touches first one contact then the other. Many motors use the arrangement shown in Figure 20-15. As the coil rotates, the end touching the positive and negative sides changes with each half revolution, and the current reverses direction.

In principle, all motors use the same design; an external magnetic field is used to rotate a current-carrying coil. In practice, motors vary depending upon the strength required in each application. The strength of a motor depends on the forces exerted on the coil which, in turn, depend on the magnetic fields. Motors used in small toys use permanent magnets to supply the external magnetic field. Larger motors use more powerful electromagnets powered by an external source of electricity. All motors increase the magnetic field produced by the coil by using many turns of wire, each of which carries the same current. Small motors use simple coils of a few hundred turns. Larger motors use thousands of turns wrapped around an iron core, forming an armature. In many cases a number of separate coils are arranged in different orientations to provide smoother rotation.

SELF-CHECK 20D

How will placing an iron core inside the coil increase the strength of the motor?

ELECTROMAGNETIC INDUCTION

Once Oersted had discovered that currents create magnetic fields, others set about looking for the inverse effect—magnetic fields that could create currents. At the beginning of the nineteenth century, the only current-producing

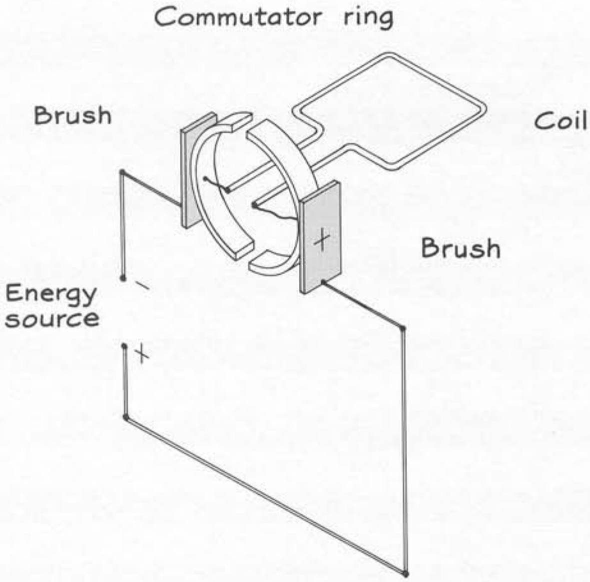


Figure 20-15
Many motors use split-ring commutators. Each end of the coil is attached to half of the ring. An electric insulator separates the two halves. Two metal contacts, called brushes, are attached to an energy source. As the commutator rotates, each half alternates contact with the positive and negative brushes. This leads to a current in the coil that reverses direction every half revolution.

device was the voltaic cell—a forerunner of our present-day battery. Hardly cost-effective, these cells required large quantities of expensive metals to produce relatively small currents. Physicists and inventors alike saw the possibility of using magnetic fields to produce currents and hoped that the process would produce a cheaper and more substantial source of energy. You need only look about at the thousands of kilometers of electrical wires that span our country to realize how fruitful their search was to be.

Moving Magnets Produce Electric Currents

Michael Faraday was the first to observe the creation of electric currents by magnetic fields. He wrapped two coils around a circular piece of iron. One coil was attached to a battery so that it could be used like an electromagnet; the second was connected to a sensitive ammeter. Faraday had hoped that the magnetic field produced by the first coil would create an electric current in the second. His hopes were fulfilled, but differently than he had expected. A current was induced in the second coil, but only as the current to the first coil was being turned on or off. When the current from the battery remained constant, no current appeared at the ammeter. Only a changing current in one coil induces a current in the second.

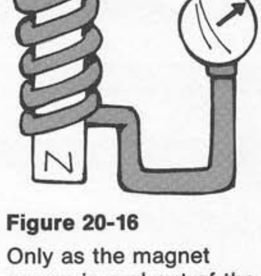


Figure 20-16
Only as the magnet moves in and out of the coil is a current induced in the coil.

A simpler demonstration of the effect is shown in Figure 20-16. A coil of wire is attached to a sensitive ammeter. We can place the coil and a permanent magnet near one another in a variety of orientations. As long as the coil and magnet remain stationary relative to each other, no current is induced in the coil. The relative motion between the coil and the magnetic field leads to an electric current.

In the experiment illustrated in Figure 20-16, a current was induced in the coil when relative motion between the coil and the magnet occurred. The coil experienced a changing magnetic field. Faraday's observations showed the same result. As the current in one coil was turned on or off, the magnetic

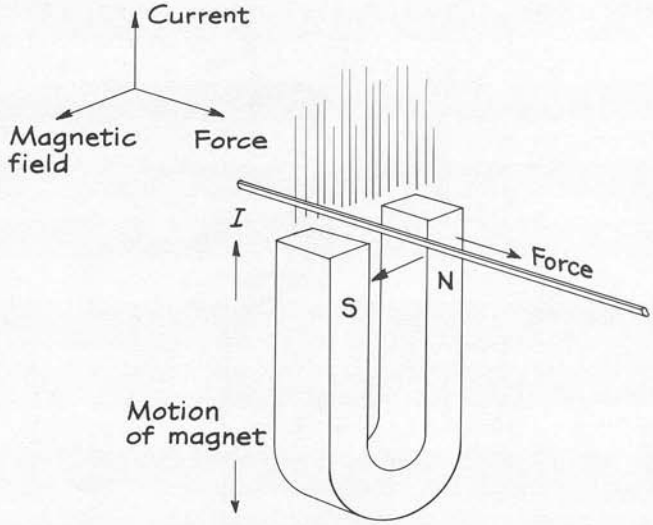


Figure 20-17

If the magnet moves downward, the electrons in the wire move upward in the magnet's reference frame. An electron motion and a magnetic field toward you result in a force that pushes electrons along the wire. This force gives rise to an electric current in the wire.

field that it produced changed. When the current remained steady, the magnetic field did not change. A current was induced in the second coil only while the magnetic field in the first coil was changing.

Faraday's Law

The process by which a changing magnetic field produces an electric current is called **electromagnetic induction.** Since a current arises from a voltage applied across the two ends of a coil, electromagnetic induction can also be described in terms of an induced voltage. Faraday found that identically changing magnetic fields induced the same voltages regardless of the composition of the wire. By contrast, the induced current depended on the resistance of the wire. Consequently, electromagnetic induction is more conveniently described in terms of induced voltages rather than currents. A voltage is induced across the two ends of a coil when the magnetic field inside the coil changes.

Electromagnetic induction arises from the forces that magnetic fields exert on moving charges. In an earlier section, we described how a current-carrying wire jumps away from the poles of a magnet. We showed that a right-hand rule describes the direction of the force applied to the wire in a magnetic field (Figure 20-11). If we look at this situation from the reference frame of the magnet, a current exists if the magnet moves past the electrons rather than the electrons moving past the magnet. For example, as the magnet in Figure 20-17 moves downward, the electrons in the wire move upward relative to the magnet. This motion constitutes a current. Placing the fingers of your right hand along the magnetic field and your thumb in the direction of the motion of the wire relative to the magnet, your palm points in the direction of the current we observe.

Faraday conducted a series of exhaustive experiments to determine the variables that influence the voltage induced by a changing magnetic field. He concluded that the voltage across the ends of a coil increases as the strength of the magnet increases or as the speed with which the magnet is moved increases. Both of these effects show that increasing the rate of change of the magnetic field increases the voltage. He also noted that as the number of turns of wire in the coil increases, so does the induced voltage. These results are summarized in **Faraday's law:** The voltage induced across the two ends of a coil is directly proportional to the number of loops in the coil and to the rate at which the magnetic field inside the coil changes.

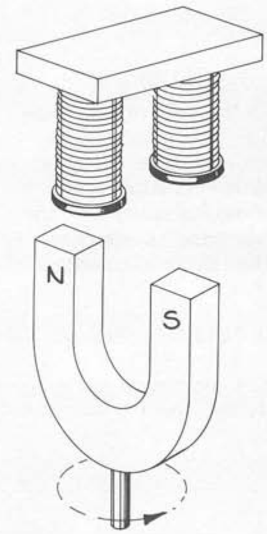


Figure 20-18

SELF-CHECK 20E

Figure 20-18 shows a device designed in 1832. A permanent horseshoe magnet is rotated beneath two stationary coils. (a) Will this device produce an electric current? (b) What would you do to increase the induced voltage?

Generators and Alternating Current

Faraday's discovery ultimately led to the development of the electrical generator. A **generator** is a device that converts kinetic energy into electrical energy. It is essentially a motor running backward. Figure 20-19 shows a simple generator. A coil of wire that can be rotated by a crank is placed in a constant magnetic field. The number of magnetic field lines enclosed inside the coil depends on the orientation of the coil. In (a) the coil has the largest number of lines inside it. As the coil rotates, (b), it encircles fewer of the field lines until at (c) the coil lies along the field lines and encloses none of them. As

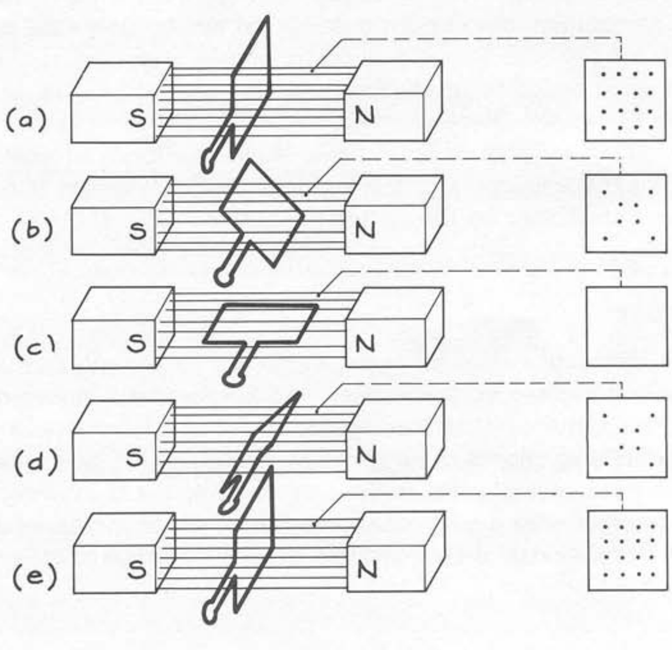


Figure 20-19
As the coil rotates, the number of magnetic field lines it encloses varies from a maximum at **(a)** to a minimum at **(c)** and back to a maximum again at (a).

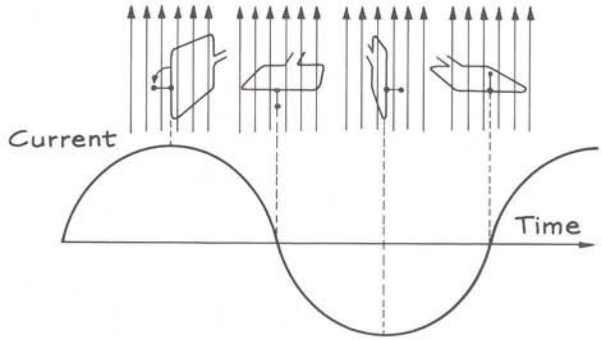


Figure 20-20
As the coil rotates, both the magnitude and direction of the induced current change. One complete rotation of the coil leads to one complete cycle in current.

the coil continues to rotate, it includes more field lines (d) while it reaches a maximum at (e) once again. As the coil rotates, the magnetic field inside it changes, and a current is induced.

The current produced by a simple generator is an alternating current. In contrast to the direct current supplied by a battery, an **alternating current** changes magnitude and direction periodically (Figure 20-20). In a motor we had to reverse the current after each half revolution to keep the coil rotating in the same direction. It comes as no surprise that a coil that continues to rotate in the same direction produces a current that reverses direction after each half revolution. The alternating current we use in our homes is produced by generators standardized so that the current changes its magnitude and direction by going through 60 cycles each second.

Most power plants use more complex and more powerful variations of the simple generator. Powerful electromagnets supply the magnetic field. Huge coils of wire designed much like the armature of a motor are placed in the magnetic fields. The energy needed to rotate either the coils or the electromagnets is provided by a turbine. Energy from wind or falling water can cause the rotation, but in most commercial power plants the turbines are driven by moving steam. Steam generators require some external fuel to produce the steam needed to rotate the turbines. Natural gas, oil, and coal are the common fuels used. More recently, nuclear fuels have been introduced to replace dwindling supplies of fossil fuels. While the forms of energy used to create the kinetic energy vary, the process used to convert it to electrical energy is that illustrated by the simple generator.

Transformers

What made electrical energy so appealing in the nineteenth century was the ease with which it could be transmitted to other locations before being used. Steam engines required that the energy be used where it was produced. Electrical generating plants could transmit energy as far as the wires would reach, which has become as far as we want to string them. However, a wire is an energy receiver with a very small resistance, which increases as the wire gets longer. Some energy is changed into heat as electrical energy is transmit-

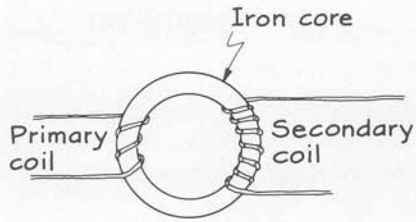


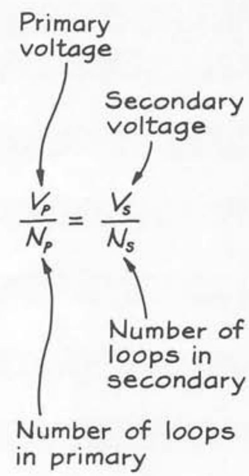
Figure 20-21
Faraday's induction coil is a simplified transformer. Alternating current to the primary coil induces an alternating current in the secondary coil.

ted along wires. These energy losses increase with the current in the wire. Thus, to make transportation of electrical energy over long distances practical, the current must be kept as small as possible. Because electrical power is equal to the product of voltage and current, we can transport energy with very low current by using high voltages. The transformer enables us to change high current and low voltage electricity to low current and high voltage electricity and, thus, is a vital link in the energy distribution network.

A **transformer** uses an alternating current and voltage in one coil to induce an alternating current and voltage in a second coil. In a simplified form, a transformer is identical to Faraday's induction coil (Figure 20-21). Alternating current supplied to the **primary coil** creates a changing magnetic field in the iron core. In turn, the constantly changing field induces an alternating voltage in the **secondary coil.** When the primary and secondary coils have different numbers of loops in their coils, the induced voltage in the secondary coil differs from the voltage in the primary.

Faraday's law provides us with a simple relationship between the two voltages and the number of loops in each coil.

$$\frac{\text{Primary voltage}}{\text{Number of loops in primary coil}} = \frac{\text{secondary voltage}}{\text{number of loops in the secondary coil}}$$



If we supply 120 volts (V) to a primary coil of 100 loops and the secondary coil has 200 loops, then the voltage in the secondary loop can be determined by (120 V)/(100 loops) = (secondary voltage)/(200 loops). Thus, the secondary voltage is 240 V.

This relationship allows us to increase or decrease the voltage of electrical energy at will. A **step-up transformer** is one that produces a larger voltage in the secondary than supplied to the primary. In this case the secondary coil has more loops than the primary. A **step-down transformer** is one that produces a smaller voltage in the secondary than that supplied by the primary. The secondary coil of a step-down transformer has fewer loops than the primary. Both types of transformers are important to the distribution of electrical power. The voltage induced by a typical electrical generating plant is 12,000 V. Before leaving the plant, this voltage is stepped up to 240,000 V. Near cities the voltage is stepped back down to 12,000 V for distribution throughout the city. Outside homes and businesses the voltage is stepped down again to provide the 120 V used in household circuits.

SELF-CHECK 20F

Transformers designed for use with typical electronic calculators transform the voltage supplied to the primary coil, 120 V, to the voltage needed by the calculator, typically 6 V. Is this a step-up or step-down transformer? How do the number of loops in the secondary coil compare to the number in the primary?

ELECTROMAGNETISM

By the middle of the nineteenth century the connections between electricity and magnetism were well established. At the same time, diffraction and interference had placed the wave model of light on very firm ground. However, the nature of light and its relation to other physical phenomena were still a puzzle. A major step toward the solution to that puzzle came from a better understanding of electricity and magnetism.

In the 1860s James Clerk Maxwell introduced a comprehensive theory of **electromagnetism,** a model that unites electricity and magnetism. In doing so, he used the idea of an electric field. This field surrounds electric charges in the same way that a magnetic field surrounds magnetic poles. Just as a magnetic field can be used to explain magnetic forces, an electric field is used to describe electric forces. With these two fields, he could express Oersted's and Faraday's results in broader terms:

A changing electric field produces a magnetic field.

A changing magnetic field produces an electric field.

A changing electric field could be produced by a current. Consequently, the first statement incorporates Oersted's results. An electric field in a wire would exert forces on the wire and create a current. Thus, the second statement includes Faraday's law. These general principles combine many of the ideas of electricity and magnetism.

However, Maxwell's theory of electromagnetism did more than just combine the results of earlier experiments. A vibrating electric charge creates a magnetic field that changes as the charge moves back and forth. This changing magnetic field creates a changing electric field, which, in turn, creates a changing magnetic field, and so forth. Maxwell was able to show that the motion of these changing fields as they move away from the source is a wave—an electromagnetic wave. Further, these waves travel in a vacuum with one speed—the speed of light. Light waves were a form of electromagnetic waves. In developing electromagnetism, Maxwell had described the wave nature of light. He also described a host of other wave phenomena, like X rays and radio waves, which were not discovered until after his death.

Human life has been radically transformed by the technology born of electromagnetism. Electromagnetic waves touch our lives daily. Electrical energy races continually across the landscape. As we use more electricity, our supply of traditional fossil fuels needed to drive our generators dwindles. Approximately 30 years after Maxwell completed his theory, a new energy source was discovered. Nuclear energy, the subject of the final two chapters of the text, stands as one of the more promising solutions to the dilemma of decreasing fossil fuels.

CHAPTER SUMMARY

All magnets have two *poles,* called *north* poles and *south* poles. Poles interact with one another: Like poles repel and unlike poles attract. *Magnetic fields,* illustrated by the patterns of iron filings sprinkled around magnets, describe the strength of magnetic forces surrounding a magnet. The magnetic properties of matter are described in terms of *magnetic domains,* regions that behave as tiny magnets. *Permanent* and *temporary* magnets differ in the number of magnetic domains that remain when an external magnetic field is removed. Magnetic domains arise when atoms with a net magnetic field become aligned. Electrons, which are charges moving within atoms, give rise to magnetic fields. In most atoms the fields from individual electrons cancel each other, but the atoms of a few elements have net magnetic fields. These atoms form magnetic domains.

All moving charges produce magnetic fields. A current-carrying wire produces a cylindrical magnetic field around itself. The strength of the field depends on the amount of current flowing, and the direction depends on the direction in which the current moves. The magnetic field of a current-carrying coil is similar to that produced by a bar magnet. Current-induced magnetic fields can be added to the field created when the domains of a magnetic material line up to create an *electromagnet.* A magnetic field exerts a force on a moving charge. A current-carrying wire placed in a magnetic field moves in a direction perpendicular to the current and the field. Motors use the interaction between a current-carrying wire and an external magnetic field to convert electrical energy into kinetic energy.

Electromagnetic induction is the process by which a changing magnetic field produces an electric current. *Faraday's law* summarizes the relationship between the changing magnetic field and the induced voltage: The voltage induced across the two ends of a coil is directly proportional to the number of loops in the coil and the rate at which the magnetic field inside the coil changes. Generators use the motion of a coil in an external magnetic field to convert kinetic energy into electrical energy. A simple *generator* produces an *alternating current,* which changes direction with each half-rotation of the coil. *Transformers* use the principles of electromagnetic induction to increase or decrease the voltage that is delivered to them.

Electromagnetism describes the single model which unites electricity and magnetism. A changing electric field produces a magnetic field. A changing magnetic field produces an electric field. When propagated outward at the speed of light, these two fields support one another. This leads to the creation of electromagnetic waves, which include light, radio waves, and X rays.

ANSWERS TO SELF-CHECKS

20A. Each time the magnet is dropped, some of its magnetic domains can be knocked out of alignment. As more domains are knocked out of alignment, the strength of the magnet decreases.

20B. The strength of the electromagnet decreases. Aluminum has no natural magnetic properties. Consequently, even when it is placed in the magnetic field of the coil, it does not become magnetized. The total magnetic field produced is simply that produced by the coil alone.

20C. We can apply the right-hand rule. If we place the fingers of our right hand in the direction of the magnetic field and our thumb in the direction of the electric current, our palm points downward. The wire jumps downward.

20D. The kinetic energy produced by a motor depends on the strength of the two magnetic fields. If we place an iron core inside the current-carrying coil, then the coil will produce an even stronger magnetic field. This increases the strength of the motor.

20E. a. Yes, because the horseshoe magnet rotates, the two coils are surrounded by a changing magnetic field.
b. If we had only the arrangement shown in Figure 20-18, we could increase the induced voltage by rotating the magnet faster. If we could alter the arrangement, then we might use a stronger magnet or replace the coils with ones that had more turns.

20F. Since the voltage supplied to the calculator is less than the voltage supplied to the transformer, this is a step-down transformer. The secondary coil has fewer loops than the primary coil.

PROBLEMS AND QUESTIONS

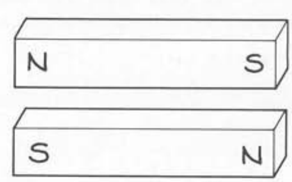
A. Review of Chapter Material

A1. Define each of the following:

Magnetic pole	Electromagnetic induction
Magnetic field	Faraday's law
Magnetic domain	Generator
Permanent magnet	Alternating current
Temporary magnet	Transformer
Electromagnet	Electromagnetism
Electric motor	

A2. How is our model of magnetism similar to our model of electric charge? How are the two models different?

A3. Sketch the magnetic field produced by the two magnets shown below.



A4. Use the concept of magnetic domains to explain the different behaviors of permanent and temporary magnets.

C6. A television picture is created by electrons, which cause light to be emitted when they hit the screen. In modern television sets, the motion of these electrons is controlled by magnetic fields. Describe how the coils of wire through which current flows can be used to control the location at which the electron strikes a television screen.

C7. Television pictures are created by moving electrons, which strike the screen. Color television screens are coated with a material that can very easily be magnetized permanently.

a. If you bring a permanent magnet near a television, the picture is distorted. Why?

b. When a magnet is brought near a color television, the distortion remains even after the magnet is removed. Why?

c. Sometimes permanent distortion occurs on a color television after a vacuum sweeper has been operated very close to it. Why?

C8. When a steel can sits in one place for a long time, it becomes magnetized. Use an analogy with the discussion of information stored in rocks on earth to explain why.

D. Activities

D1. Tear apart an old motor, generator, or relay. Identify as many parts as you can.

D2. Use a magnetic compass to identify permanent magnets in your environment.