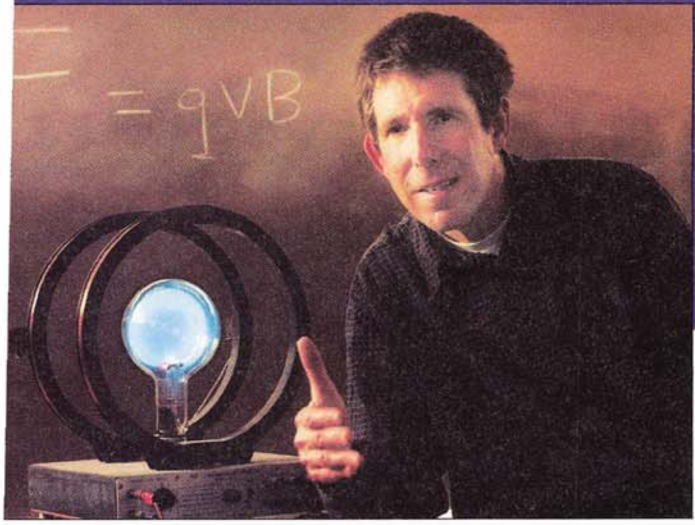


Ken Ganezer shows the bluish-green glow of electrons circling the magnetic field lines inside a Thompson tube.

CHAPTER 24

Magnetism

THE Physics Place — Magnetism

THE Physics Place — Oersted's Discovery

Youngsters are fascinated with magnets, largely because they act at a distance. One can move a nail with a nearby magnet even when a piece of wood is in between. Likewise, a neurosurgeon can guide a pellet through brain tissue to inoperable tumors, pull a catheter into position, or implant electrodes while doing little harm to brain tissue. The use of magnets grows daily.

The term *magnetism* comes from the name Magnesia, a coastal district of ancient Thessaly, Greece, where certain stones were found by the Greeks more than 2000 years ago. These stones, called *lodestones,* had the unusual property of attracting pieces of iron. Magnets were first fashioned into compasses and used for navigation by the Chinese in the twelfth century.

In the sixteenth century, William Gilbert, Queen Elizabeth's physician, made artificial magnets by rubbing pieces of iron against lodestone, and he suggested that a compass always points north and south because the Earth has magnetic properties. Later, in 1750, John Michell, an English physicist and astronomer, found that magnetic poles obey the inverse-square law, and his results were confirmed by Charles Coulomb. The subjects of magnetism and electricity developed almost independently of each other until 1820, when a Danish physicist named Hans Christian Oersted discovered, in a classroom demonstration, that an electric current affects a magnetic compass.[1] He saw confirming evidence that magnetism was related to electricity. Shortly thereafter, the French physicist André Marie Ampere proposed that electric currents are the source of all magnetic phenomena.

In days gone by, Dick Tracy comic strips, in addition to predicting the advent of cell phones, featured the heading, "He who controls magnetism controls the universe."

Insights

Magnetic Forces

In Chapter 22, we discussed the forces that electrically charged particles exert on one another: The force between any two charged particles depends on the magnitude of the charge on each and their distance of separation, as specified in Coulomb's law. But Coulomb's law is not the whole story when the charged particles are moving with respect to each other. The force between electrically charged particles depends also, in a complicated way, on their motion. We find that,

[1]We can only speculate about how often such relationships become evident when they "aren't supposed to" and are dismissed as "something wrong with the apparatus." Oersted, however, had the insight—characteristic of a good scientist—to see that nature was revealing another of its secrets.

in addition to the force we call *electrical,* there is a force due to the motion of the charged particles that we call the **magnetic force.** The source of magnetic force is the motion of charged particles, usually electrons. Both electrical and magnetic forces are actually different aspects of the same phenomenon of electromagnetism.

Magnetic Poles

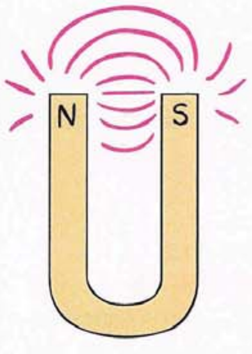


FIGURE 24.1
A horseshoe magnet.

The forces that magnets exert on one another are similar to electrical forces, for they can both attract and repel without touching, depending on which ends of the magnets are held near one another. Like electrical forces also, the strength of their interaction depends on the separation distance between the two magnets. Whereas electric charge is central to electrical forces, regions called *magnetic poles* give rise to magnetic forces.

If you suspend a bar magnet at its center by a piece of string, you'll have a compass. One end, called the *north-seeking pole,* points northward, and the opposite end, called the *south-seeking pole,* points southward. More simply, these are called the *north* and *south poles.* All magnets have both a north and a south pole (some have more than one of each). Refrigerator magnets, popular in recent years, have narrow strips of alternating north and south poles. These magnets are strong enough to hold sheets of paper against a refrigerator door, but they have a very short range because the north and south poles cancel. In a simple bar magnet, a single north pole and a single south pole are located at opposite ends. A common horseshoe magnet is simply a bar magnet that has been bent into a U shape. Its poles are also at its two ends (Figure 24.1).

When the north pole of one magnet is brought near the north pole of another magnet, they repel.[2] The same is true of a south pole near a south pole. If opposite poles are brought together, however, attraction occurs. We find that

Like poles repel each other; opposite poles attract.

This rule is similar to the rule for the forces between electric charges, where like charges repel one another and unlike charges attract. But there is a very important difference between magnetic poles and electric charges. Whereas electric charges can be isolated, magnetic poles cannot. Negatively charged electrons and positively charged protons are entities by themselves. A cluster of electrons need not be accompanied by a cluster of protons, and vice versa. But a north magnetic pole never exists without the presence of a south pole, and vice versa.

If you break a bar magnet in half, each half still behaves as a complete magnet. Break the pieces in half again, and you have four complete magnets. You can continue breaking the pieces in half and never isolate a single pole.[3] Even when your piece is one atom thick, there are two poles, which suggests that atoms themselves are magnets.

A magstripe on a credit card contains millions of tiny magnetic domains held together by a resin binder. Data are encoded in binary code, with zeros and ones distinguished by the frequency of domain reversals. It's quite amazing how quickly your name pops up when an airline reservationist swipes your card.

Insights

[2]The force of interaction between magnetic poles is given by $F \sim \frac{p_1 p_2}{d^2}$, where p_1 and p_2 represent magnetic pole strengths and d represents the separation distance between the poles. Note the similarity of this relationship to Coulomb's law.

[3]Theoretical physicists have speculated for more than 70 years about the possible existence of discrete magnetic "charges," called *magnetic monopoles*. These tiny particles would carry either a single north or a single south magnetic pole and would be the counterparts to the positive and negative charges in electricity. Various attempts have been made to find monopoles, but none has proved successful. All known magnets always have at least one north pole and one south pole.

CHECK YOURSELF

Does every magnet necessarily have a north and south pole?

Magnetic Fields

If you sprinkle some iron filings on a sheet of paper placed on a magnet, you'll see that the filings trace out an orderly pattern of lines that surround the magnet. The space around the magnet contains a **magnetic field.** The shape of the field is revealed by the filings, which align with the magnetic field lines that spread out from one pole and return to the other. It is interesting to compare the field patterns in Figures 24.2 and 24.4 with the electric field patterns in Figure 22.19 back in Chapter 22.

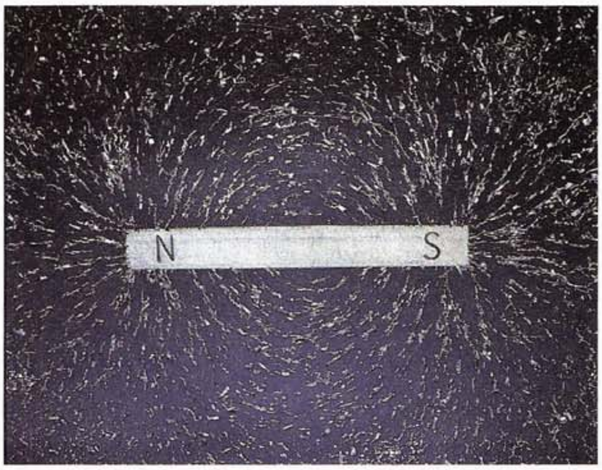


FIGURE 24.2
Interactive Figure

Top view of iron filings sprinkled around a magnet. The filings trace out a pattern of *magnetic field lines* in the space surrounding the magnet. Interestingly, the magnetic field lines continue inside the magnet (not revealed by the filings) and form closed loops.

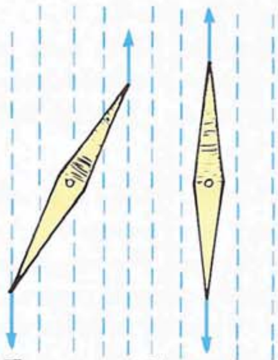


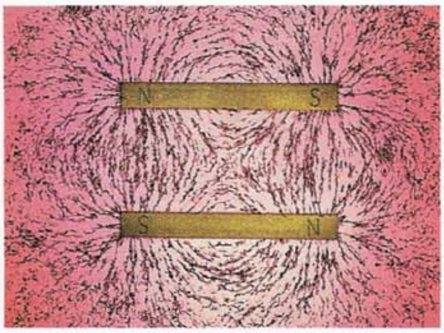
FIGURE 24.3
When the compass needle is not aligned with the magnetic field (left), the oppositely directed forces on the needle produce a pair of torques (called a *couple*) that twist the needle into alignment (right).

The direction of the field outside a magnet is from the north pole to the south pole. Where the lines are closer together, the field is stronger. The concentration of iron filings at the poles of the magnet in Figure 24.2 shows the magnetic field strength is greater there. If we place another magnet or a small compass anywhere in the field, its poles line up with the magnetic field.

Magnetism is very much related to electricity. Just as an electric charge is surrounded by an electric field, the same charge is also surrounded by a magnetic field if it is moving. This magnetic field is due to the "distortions" in the electric field caused by motion and was explained by Albert Einstein in 1905 in his special theory of relativity. We won't go into the details except to acknowledge that a magnetic field is a relativistic by-product of the electric

CHECK YOUR ANSWER

Yes, just as every coin has two sides, a "head" and a "tail." Some "trick" magnets have more than one pair of poles, but, nevertheless, poles always occur in pairs.



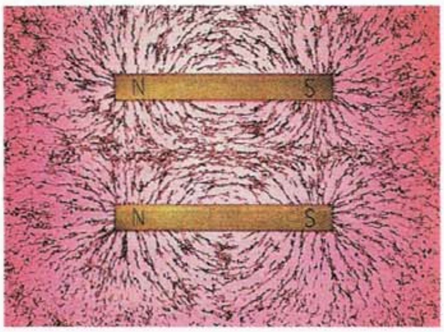


FIGURE 24.4
The magnetic field patterns for a pair of magnets. (a) Opposite poles are nearest each other, and (b) like poles are nearest each other.

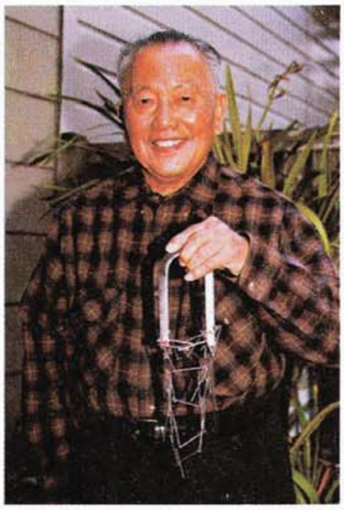


FIGURE 24.5
Wai Tsan Lee shows iron nails that have become induced magnets.

field. Charged particles in motion have associated with them both an electric field and a magnetic field. A magnetic field is produced by the motion of electric charge.[4]

If the motion of electric charges produces magnetism, where is this motion in a common bar magnet? The answer is, in the electrons of the atoms that make up the magnet. These electrons are in constant motion. Two kinds of electron motion contribute to magnetism: electron spin and electron revolution. Electrons spin about their own axes like tops, and they also revolve about the atomic nucleus. In most common magnets, electron spin is the chief contributor to magnetism.

Every spinning electron is a tiny magnet. A pair of electrons spinning in the same direction makes up a stronger magnet. A pair of electrons spinning in opposite directions, however, work against each other. The magnetic fields cancel. This is why most substances are not magnets. In most atoms, the various fields cancel one another because the electrons spin in opposite directions. In such materials as iron, nickel, and cobalt, however, the fields do not cancel each other entirely. Each iron atom has four electrons whose spin magnetism is uncancelled. Thus, each iron atom is a tiny magnet. The same is true, to a lesser extent, for the atoms of nickel and cobalt. Most common magnets are made from alloys containing iron, nickel, and cobalt in various proportions.[5]

Magnetic Domains

The magnetic field of an individual iron atom is so strong that interactions among adjacent atoms cause large clusters of them to line up with one another. These clusters of aligned atoms are called **magnetic domains.** Each domain is made up of billions of aligned atoms. The domains are microscopic (Figure 24.6), and there are many of them in a crystal of iron. Like the alignment of iron atoms within domains, domains themselves can align with one another.

[4]Interestingly, since motion is relative, the magnetic field is relative. For example, when a charge moves by you, there is a definite magnetic field associated with the moving charge. But, if you move along with the charge so that there is no motion relative to you, you'll find no magnetic field associated with the charge. Magnetism is relativistic. In fact, it was Albert Einstein who first explained this when he published his first paper on special relativity, "On the Electrodynamics of Moving Bodies." (More on relativity in Chapters 35 and 36.)

[5]Electron spin contributes virtually all of the magnetic properties in magnets made from alloys containing iron, nickel, cobalt, and aluminum. In the rare earth metals, such as gadolinium, the orbital motion is more significant.

PRACTICING PHYSICS

Most iron objects around you are magnetized to some degree. A filing cabinet, a refrigerator, or even cans of food on your pantry shelf, have north and south poles induced by Earth's magnetic field. If you bring a magnetic compass near the tops of iron or steel objects in your home, you will find that the north pole of the compass needle points to the tops of these objects, and the south pole of the compass needle points to the bottoms. This shows that the objects are magnets, having a south pole on top and a north pole on the bottom. Turn cans of food that have been in a vertical position upside down and see how many days it takes for the poles to reverse themselves!

FIGURE 24.6
A microscopic view of magnetic domains in a crystal of iron. Each domain consists of billions of aligned iron atoms. The blue arrows pointing in different directions tell us that these domains are not aligned.

Not every piece of iron, however, is a magnet. This is because the domains in ordinary iron are not aligned. Consider a common iron nail: The domains in the nail are randomly oriented. Many of them are induced into alignment, however, when a magnet is brought nearby. (It is interesting to listen with an amplified stethoscope to the clickity-clack of domains undergoing alignment in a piece of iron when a strong magnet approaches.) The domains align themselves much as electrical charges in a piece of paper align themselves in the presence of a charged rod. When you remove the nail from the magnet, ordinary thermal motion causes most or all of the domains in the nail to return to a random arrangement. If the field of the permanent magnet is very strong, however, the nail may retain some permanent magnetism of its own after the two are separated.

Permanent magnets are made by simply placing pieces of iron or certain iron alloys in strong magnetic fields. Alloys of iron differ; soft iron is easier to magnetize than steel. It helps to tap the iron to nudge any stubborn domains into alignment. Another way of making a permanent magnet is to stroke a piece of iron with a magnet. The stroking motion aligns the domains in the iron. If a permanent magnet is dropped or heated, some of the domains are jostled out of alignment and the magnet becomes weaker.

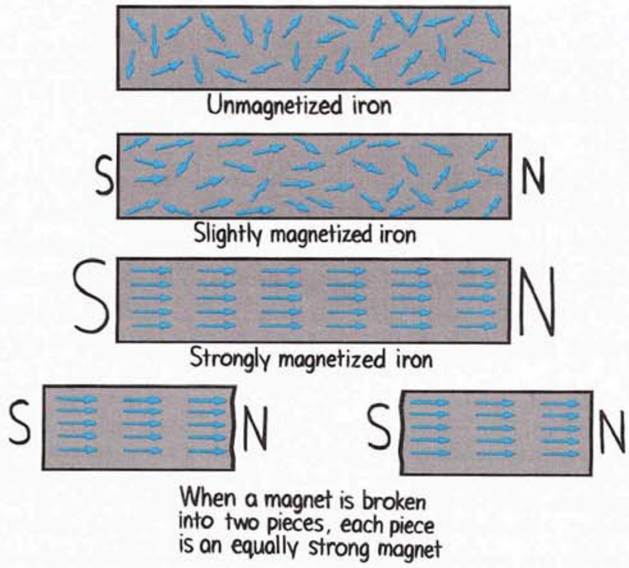


FIGURE 24.7
Interactive Figure
Pieces of iron in successive stages of magnetization. The arrows represent domains; the head is a north pole and the tail is a south pole. Poles of neighboring domains neutralize each other's effects, except at the two ends of a piece of iron.

MAGNETIC THERAPY*

Back in the eighteenth century, a celebrated "magnetizer" from Vienna, Franz Mesmer, brought his magnets to Paris and established himself as a healer in Parisian society. He healed patients by waving magnetic wands above their heads.

At that time, Benjamin Franklin, the world's leading authority on electricity, was visiting Paris as a U.S. representative. He suspected that Mesmer's patients did benefit from his ritual, but only because it kept them away from the bloodletting practices of other physicians. At the urging of the medical establishment, King Louis XVI appointed a royal commission to investigate Mesmer's claims. The commission included Franklin and Antoine Lavoisier, the founder of modern chemistry. The commissioners designed a series of tests in which some subjects thought they were receiving Mesmer's treatment when they weren't, while others received the treatment but were led to believe they had not. The results of these blind experiments established beyond any doubt that Mesmer's success was due solely to the power of suggestion. To this day, the report is a model of clarity and reason. Mesmer's reputation was destroyed, and he retired to Austria.

Now some two hundred years later, with increased knowledge of magnetism and physiology, hucksters of magnetism are attracting even larger followings. But there is no government commission of Franklins and Lavoisiers to challenge their claims. Instead, magnetic therapy is another of the untested and unregulated "alternative therapies" given official recognition by Congress in 1992.

Although testimonials about the benefits of magnets are many, there is no scientific evidence whatever for magnets boosting body energy or combating aches and pains. None. Yet millions of therapeutic magnets are sold in stores and catalogs. Consumers are buying magnetic bracelets, insoles, wrist and knee bands, back and neck braces, pillows, mattresses, lipstick, and even water. They are told that magnets have powerful effects on the body, mainly increasing blood flow to injured areas. The idea that blood is attracted by a magnet is bunk, for the type of iron that occurs in blood doesn't respond to a magnet. Furthermore, most therapeutic magnets are of the refrigerator type, with a very limited range. To get an idea of how quickly the field of these magnets drops off, see how many sheets of paper one of these magnets will hold on a refrigerator or any iron surface. The magnet will fall off after a few sheets of paper separate it from the iron surface. The field doesn't extend much more than one millimeter, and it wouldn't penetrate the skin, let alone into muscles. And even if it did, there is no scientific evidence that magnetism has any beneficial effects on the body at all. But, again, testimonials are another story.

Sometimes an outrageous claim has some truth to it. For example, the practice of bloodletting in previous centuries was, in fact, beneficial to a small percentage of men. These men suffered the genetic disease (*hemochromatosis,* excess iron in the blood—women being less afflicted partly due to menstruation). Although the number of men who benefited from bloodletting was small, testimonials of its success prompted the widespread practice that killed many.

No claim is so outrageous that testimonials can't be found to support it. Claims that the Earth is flat or claims for the existence of flying saucers are quite harmless and may amuse us. Magnetic therapy may likewise be harmless for many ailments, but not when it is used to treat a serious disorder in place of modern medicine. Pseudoscience may be promoted to intentionally deceive or it may be the result of flawed and wishful thinking. In either case, pseudoscience is very big business. The market is enormous for therapeutic magnets and other such fruits of unreason.

Scientists must keep open minds, must be prepared to accept new findings, and must be ready to be challenged by new evidence. But scientists also have a responsibility to inform the public when they are being deceived and, in effect, robbed by pseudoscientists whose claims are without substance.

*Adapted from *Voodoo Science: The Road from Foolishness to Fraud,* by Robert L. Park; Oxford University Press, 2000.

We each need a *knowledge filter* to tell the difference between what is true and what seems to be true. The best knowledge filter ever invented is science.

Insights

CHECK YOURSELF

How can a magnet attract a piece of iron that is not magnetized?

Electric Currents and Magnetic Fields

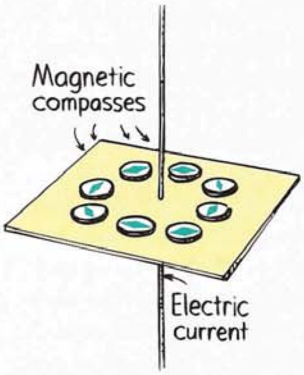


FIGURE 24.8
The compasses show the circular shape of the magnetic field surrounding the current-carrying wire.

Since a moving charge produces a magnetic field, it follows that a current of charges also produces a magnetic field. The magnetic field that surrounds a current-carrying conductor can be demonstrated by arranging an assortment of compasses around a wire (Figure 24.8) and passing a current through it. The compass needles line up with the magnetic field produced by the current and they show the field to be a pattern of concentric circles about the wire. When the current reverses direction, the compass needles turn around, showing that the direction of the magnetic field changes also. This is the effect that Oersted first demonstrated in the classroom.

If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop (Figure 24.9). If the wire is bent into another loop, overlapping the first, the concentration of magnetic field lines inside the loops is doubled. It follows that the magnetic field intensity in this region is increased as the number of loops is increased. The magnetic field intensity is appreciable for a current-carrying coil of many loops.

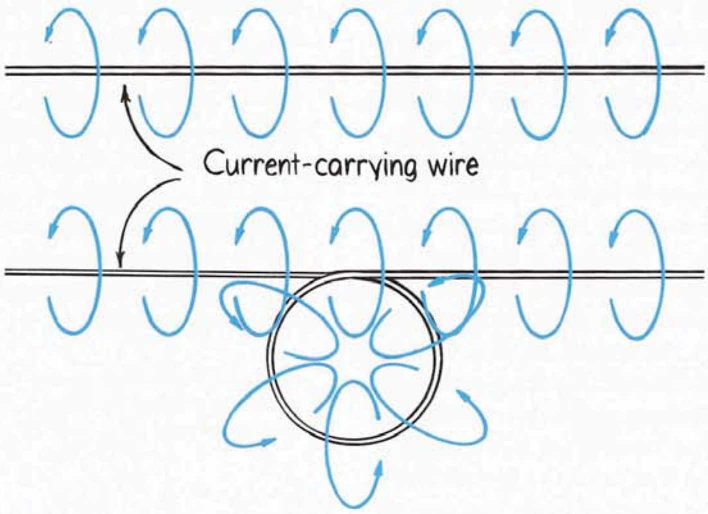


FIGURE 24.9
Magnetic field lines about a current-carrying wire crowd up when the wire is bent into a loop.

CHECK YOUR ANSWER

Domains in the unmagnetized piece of iron are induced into alignment by the magnetic field of the nearby magnet. See the similarity of this with Figure 22.13 back in Chapter 22. Like the pieces of paper that jump to the comb, pieces of iron will jump to a strong magnet when it is brought nearby. But, unlike the pieces of paper, they are not then repelled. Can you think of the reason why?

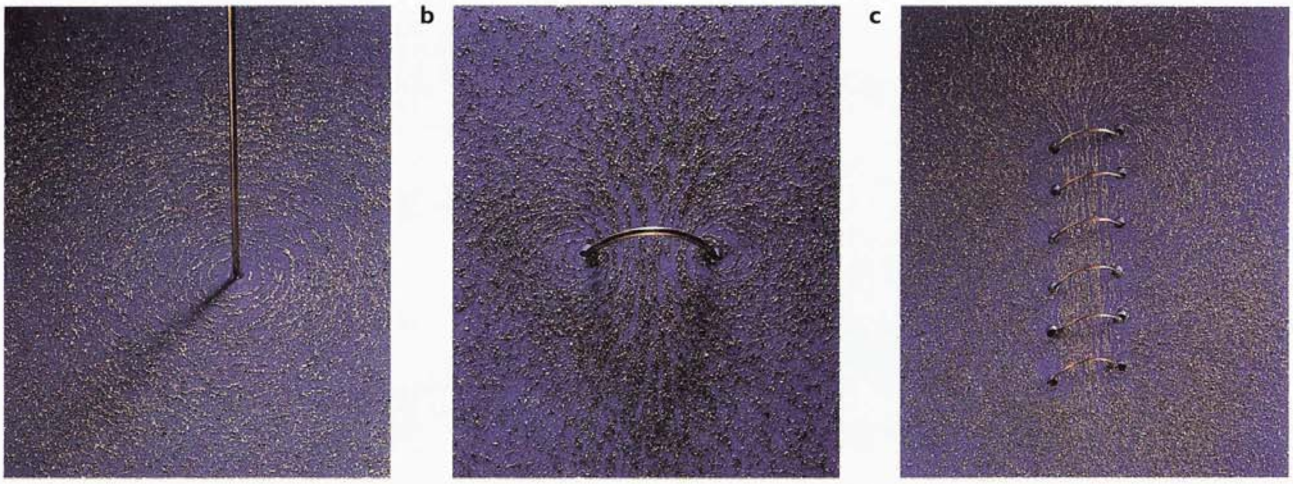
a
b
c


FIGURE 24.10
Iron filings sprinkled on paper reveal the magnetic field configurations about (a) a current-carrying wire, (b) a current-carrying loop, and (c) a current-carrying coil of loops.

Electromagnets

A current-carrying coil of wire is an **electromagnet.** The strength of an electromagnet is increased by simply increasing the current through the coil. Industrial magnets gain additional strength by having a piece of iron within the coil. Magnetic domains in the iron are induced into alignment, adding to the field. For extremely strong electromagnets, such as those used to control charged-particle beams in high-energy accelerators, iron is not used, because, beyond a certain point, all of its domains are aligned and it no longer adds to the field.

Electromagnets powerful enough to lift automobiles are a common sight in junkyards. The strength of these electromagnets is limited by heating of the current-carrying coils (due to electrical resistance) and saturation of magnetic-domain alignment in the core. The most powerful electromagnets, which do not have iron cores, use superconducting coils through which large electrical currents flow with ease.

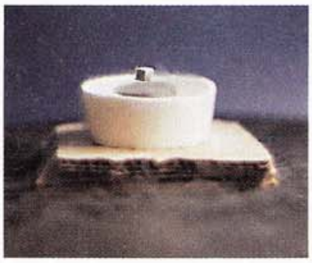


FIGURE 24.11
A permanent magnet levitates above a superconductor because its magnetic field cannot penetrate the superconducting material.

Superconducting Electromagnets

Recall, from Chapter 22, that there is no electrical resistance in a superconductor to limit the flow of electric charge and, therefore, no heating, even if the current is enormous. Electromagnets that utilize superconducting coils produce extremely strong magnetic fields—and they do so very economically because there are no heat losses (although energy is used to keep the superconductors cold). At the Fermi National Accelerator Laboratory (Fermilab), near Chicago, superconducting electromagnets guide high-energy particles around an accelerator 4 miles in circumference. Superconducting magnets can also be found in magnetic resonance imaging (MRI) devices in hospitals.

Another application to watch for is magnetically levitated, or "maglev," transportation. Figure 24.12 shows the scale model of a maglev system developed in the United States. The vehicle, called a magplane, carries superconducting

FIGURE 24.12
A magnetically levitated vehicle—a *magplane.* Whereas conventional trains vibrate as they ride on rails at high speeds, magplanes can travel vibration-free at high speeds because they make no physical contact with the guideway they float above.

coils on its underside. Moving along an aluminum trough, these coils generate currents in the aluminum that act as mirror-image magnets and repel the magplane. It floats a few centimeters above the guideway, and its speed is limited only by air friction and passenger comfort.

A maglev train built by German engineers is currently operating at speeds up to 460 km/h between downtown Shanghai and its airport. It covers some 30 km in less than eight minutes. A high-speed line is projected that will connect Shanghai with 1380-km distant Beijing, reducing the customary 14-hour trip by half. Watch for the proliferation of this relatively new technology.

Magnetic Force on Moving Charged Particles

A charged particle at rest will not interact with a static magnetic field. But if the charged particle is moving in a magnetic field, the magnetic character of a charge in motion becomes evident. It experiences a deflecting force.[6] The force is greatest when the particle moves in a direction perpendicular to the magnetic field lines. At other angles, the force is less, and it becomes zero when the particles move parallel to the field lines. In any case, the direction of the force is always perpendicular to the magnetic field lines and to the velocity of the charged particle (Figure 24.13). So a moving charge is deflected when it crosses through a magnetic field, but, when it travels parallel to the field, no deflection occurs.

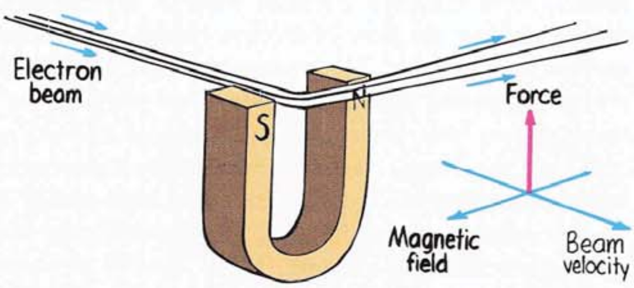


FIGURE 24.13
A beam of electrons is deflected by a magnetic field.

[6]When particles of electric charge q and velocity v move perpendicularly into a magnetic field of strength B, the force F on each particle is simply the product of the three variables: $F = qvB$. For nonperpendicular angles, v in this relationship must be the component of velocity perpendicular to B.