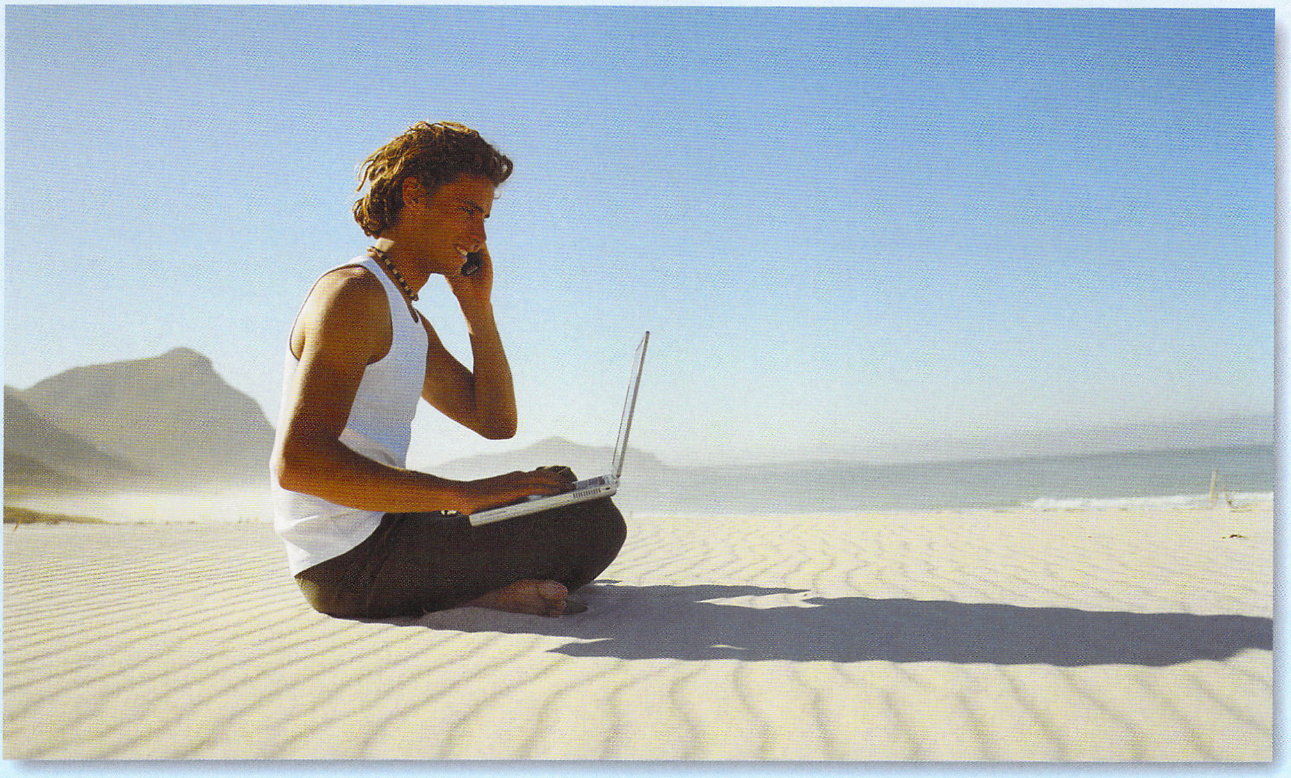
24 Electric and Magnetic Properties of Materials

KEY IDEA

The electric and magnetic properties of materials depend on the behavior of electrons in the chemical bonds that hold the material together.



PHYSICS AROUND US . . . Electricity on the Go

Portable electronics are the newest big thing. Advances in technology have changed computers from the size of a large room to a small laptop that you can fit inside a briefcase. Television sets used to be good-sized pieces of furniture; now they're so small and light that you can fit them in your car to entertain passengers. Large turntables and high-fidelity systems have been replaced by CD players with headphones so you can listen to music as you walk; telephones fit in your pocket and don't need wires; cameras don't need film but can download pictures right to your computer. All this new technology has come about from advances in materials science.

We have talked about how atomic structure and molecular forces determine the physical properties of materials, including strength and chemical reactivity. In light of this knowledge, you may not be surprised to learn that atomic and molecular bonding also affects the electric and magnetic properties of substances. What makes some materials conduct electricity while others do not? What kinds of materials allow us to pack so many electrical functions into such a small space? The answers to questions such as these all boil down to understanding the behavior of electrons in chemical bonds.

ELECTRIC PROPERTIES OF MATERIALS

Almost every aspect of our technological civilization depends on electricity, so scientists have devoted a good deal of attention to materials that are useful in electric systems. If the job at hand is to send electric energy from a power plant to a distant city, for example, then we need a material that can carry the electric energy without much loss. On the other hand, if the job is to put a covering over a wall switch so that we are not endangered by electric shock when we turn on a light, then we want a material that does not conduct electricity at all. In other words, several different kinds of materials contribute to any electric device.

Conductors

Any material capable of carrying electric current—that is, any material through which electric charges can flow freely—is called an **electrical conductor,** as discussed in Chapter 18. Metals, such as the copper that carries electricity through the building in which you are now sitting, are the most common conductors, but many other materials also conduct electricity. For example, salt water contains ions of sodium (Na^+) and chlorine (Cl^-), which are free to move if they become part of an electric circuit. We can find out if a material conducts electricity by making it part of an electric circuit and seeing if current flows through it.

The arrangement of a material's electrons determines its ability to conduct electricity. Recall that in the case of metals some electrons are bonded fairly loosely and are shared by many atoms. If you connect a copper wire across the terminals of a battery, these electrons are free to move in response to the battery's voltage. They flow from the negative pole toward the positive pole of the battery.

As we have seen in Chapter 18, the motion of electrons in electric currents is seldom smooth. Under normal circumstances, electrons moving through a metal collide continuously with the much heavier ions in that metal. In each of those collisions, electrons lose some of the energy they have gained from the battery, and that energy is converted to the faster vibration of ions, which we perceive as heat. In Chapter 18, we call this phenomenon **electrical resistance.** Even very good conductors have some electrical resistance.

The electrical conductor with which you are most likely to come into contact is copper. For example, the wires that carry electricity around most homes, schools, and office buildings are made of copper. Copper is an excellent conductor of electricity and is relatively inexpensive, so it is widely used for ordinary household and commercial circuits, as well as in most appliances. For some uses, such as the power lines that carry electricity overland from power plants to cities, aluminum is often used. Aluminum is not as good a conductor as copper, so more electric energy is lost to heat in these wires, but the low cost and light weight of aluminum more than makes up for that loss. In a few instances where cost is no object (in some circuits in satellites, for example), engineers occasionally use gold, which, while much more expensive than copper, is also a better conductor.

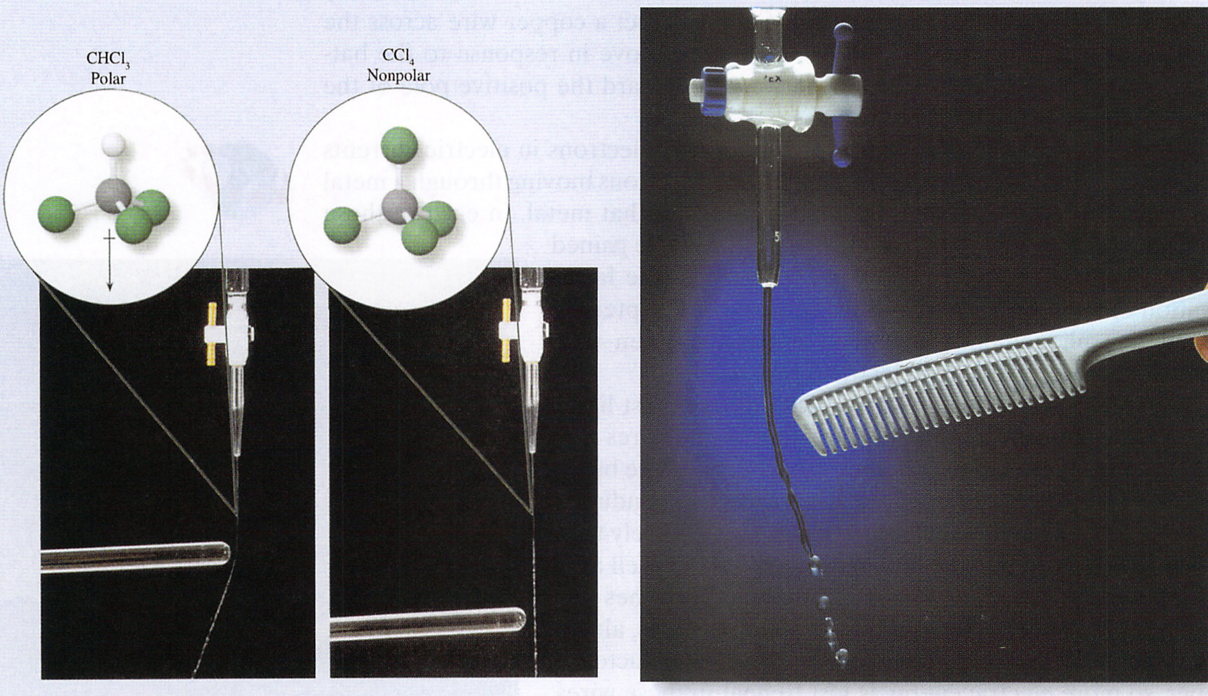
Power lines are often made of aluminum to conduct large amounts of electricity cheaply.

Develop Your Intuition: Electrical Attraction of Liquids

Liquid carbon tetrachloride, which in the past was used for dry cleaning clothing, is a symmetrical molecule. It contains four chlorine atoms surrounding a carbon atom. If you hold an electrically charged rod next to a thin stream of carbon tetrachloride, nothing happens. Suppose you try the same thing with chloroform, which used to be used as an anesthetic in hospitals. This molecule has the same structure as carbon tetrachloride, but with one of the chlorine atoms replaced with hydrogen, so it is no longer symmetrical. Now if you hold a charged rod next to a thin stream of chloroform, the liquid bends toward the rod. Why? What is happening? What do you think would happen if you held the charged rod next to a thin stream of water?

Because the chloroform molecule is not symmetrical, it is slightly polar (see Chapter 16). The electrically charged rod attracts charges of the opposite sign and repels charges of the same sign. The molecules turn so that the ends attracted to the rod are closer to it and feel a stronger force than the other ends of the molecules do. As a result, the stream of polar molecules is deflected toward the rod. This does not happen with the symmetrical molecules of carbon tetrachloride, so the stream of liquid passes the rod undeflected.

Water is a polar molecule, as we discussed in Chapter 16. As you might expect, then, a stream of water is deflected toward a charged rod.



(*a*) Chloroform (*b*) Carbon tetrachloride (*c*) Water

An electrically charged rod can deflect a stream of liquid composed of polar molecules, such as chloroform (*a*) and water (*c*), whereas a nonpolar liquid such as carbon tetrachloride (*b*) is not affected.

Insulators

Many materials incorporate chemical bonds in which few electrons are free to move in response to the push of an electric field. For example, in rocks, ceramics, and many biological materials such as wood and hair, the electrons are bound tightly to one or more atoms by ionic or covalent bonds (see Chapter 23). It takes considerable energy to pry electrons loose from those atoms—energy that is normally much greater than the energy supplied by a battery or an electric outlet. These materials do not conduct electricity unless they are subjected to an extremely high voltage that can pull the electrons loose. If they are made part of an electric circuit, no electricity flows through them. We call these materials **electrical insulators.**

The primary use of insulators in electric circuits is to channel the flow of electrons and to keep people from touching wires that are carrying current (Figure 24-1). For example, the shields on your light switches and household power outlets and the casings for most car batteries are made from plastic, a reasonably good insulating material that has the added advantages of low cost and flexibility. Similarly, electrical workers use protective rubber boots and gloves when working on dangerous power lines. In the case of high-power lines, glass or ceramic components are used to isolate the current because of their superior insulating ability.

Semiconductors

Many materials in nature are neither good conductors nor perfect insulators. We call such materials **semiconductors.** As the name implies, a semiconductor carries electricity but does not carry it very well. Typically, the resistance of silicon—

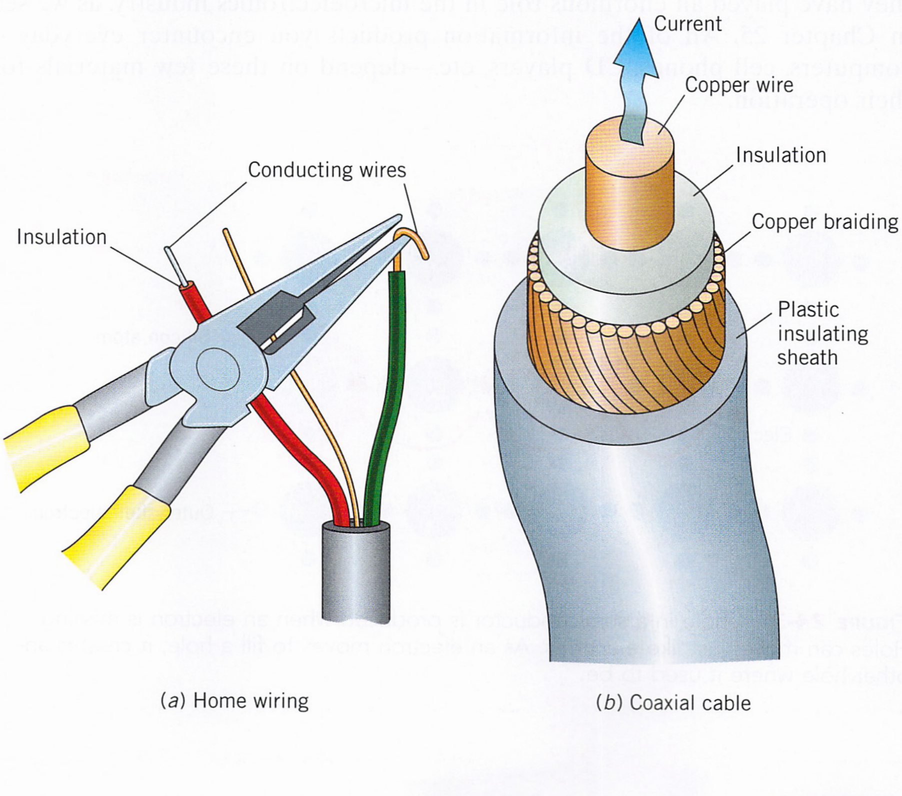


FIGURE 24-1. (*a*) Ordinary household electrical wiring consists of a conducting metal core surrounded by an insulating layer of plastic. The wire without insulation does not normally carry current but is present as a safety feature. (*b*) A coaxial cable, which is used to carry information in the form of a varying electric current, includes an inner wire and insulation with a surrounding mesh of copper wire and insulation. This outer layer reduces interference from outside sources of electricity.

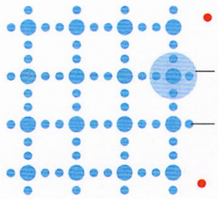


FIGURE 24-2. (a) A normal silicon crystal displays a regular pattern of silicon atoms. Some of its electrons are shaken loose by atomic vibrations; these electrons are free to move around and conduct electricity.

a common semiconductor—is a million times higher than the resistance of a conductor such as copper. Nevertheless, silicon is not an insulator because some of its electrons do flow in response to an applied voltage. Why should this be?

In a silicon crystal (Figure 24-2), all the electrons are taken up in the covalent bonds that hold each silicon atom to its neighbors. At low temperatures, these electrons are locked into bonds and we would expect the material to be an insulator. However, these bonds are relatively weak, so at room temperature the ordinary vibrations of the silicon atoms shake a few of the covalent bonding electrons loose. Think of the electrons as picking up a little of the vibrational energy of the atoms. These *conduction electrons* are free to move around the crystal. If the silicon is made part of an electric circuit, a modest number of conduction electrons are free to move through the solid.

When a conduction electron is shaken loose, it leaves behind a defect in the silicon crystal—the absence of an electron. This missing electron is called a *hole*. Just as electrons move in response to electric charges, so too can holes (see Figure 24-3). An electron can jump from one bond to fill a hole, leaving another hole in its original position. Then another electron can jump to that hole, and so on.

The motion of holes in semiconductors is similar to what you see in a traffic jam on a crowded expressway. A space opens up between two cars, after which one car moves up to fill the space, then another car moves up to fill that space, and so on. You could describe this sequence of events as the successive motion of cars. But you could just as easily (in fact, from a mathematical point of view, more easily) say that the space between cars—the hole—moves backward down the line. In the same way, you can either describe the effects of the successive jumping of electrons from one atom to another or talk about the hole moving through the material.

Although there are relatively few semiconducting materials in nature, they have played an enormous role in the microelectronics industry, as we see in Chapter 25. All of the information products you encounter everyday—computers, cell phones, CD players, etc.—depend on these few materials for their operation.

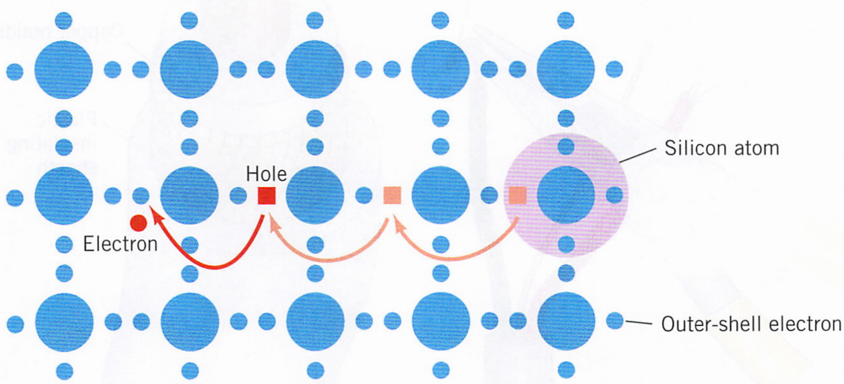


FIGURE 24-3. A hole in a semiconductor is produced when an electron is missing. Holes can move, just like electrons. As an electron moves to fill a hole, it creates another hole where it used to be.

Superconductors

Some materials cooled to extremely low temperatures, sometimes within a few degrees of absolute zero, exhibit a property known as **superconductivity**—the complete absence of any electrical resistance. Below some very cold critical temperature, electrons in these materials are able to move without surrendering any of their energy to the atoms. This phenomenon, discovered in the Netherlands in 1911, was not understood until the 1950s. Today, superconducting technologies provide the basis for a billion-dollar-a-year industry worldwide. The principal reason for this success is that once a material becomes superconducting and is kept cool, current can flow in it forever. This behavior means that if you take a loop of superconducting wire and hook it up to a battery to get the current flowing, the current continues to flow even if you take the battery away.

In Chapter 17, we learned that current flowing in a loop creates a magnetic field. If we make an electromagnet out of superconducting material and keep it cold, the magnetic field is maintained at no energy cost except for the refrigeration. Indeed, superconductors provide strong magnetic fields much more cheaply than any conventional copper-wire electromagnet because they don't heat up from electrical resistance. Superconducting magnets are used extensively in many applications where very high magnetic fields are essential—for example, in particle accelerators (see Chapter 27) and in magnetic resonance imaging systems for medical diagnosis (see Connection: Magnetic Resonance Imaging, page 520). Perhaps they will eventually be used in everyday transportation.

How is it that a superconducting material can allow electrons to pass through without losing energy? The answer in at least some cases has to do with the kind of electron–ion interactions that occur. At very low temperatures, heavy ions in a material don't vibrate very much and can be thought of as being more or less fixed in one place. As a fast-moving electron passes between two positive ions, the ions are attracted to the electron and start to move toward it. By the time the ions respond, however, the electron is long gone. Nevertheless, when the ions move close together, they create a region in the material with a more positive electric charge than normal. This region attracts a second electron and pulls it in. Thus the two electrons can move through the superconducting material somewhat like the way two bike racers move down a track, with the front rider overcoming air resistance so that the second rider can ride in the quieter air behind the leader (a strategy called "drafting").

At the very low temperatures at which a material becomes superconducting, electrons hook up in pairs, and the pairs start to interlock like links of a complex tangled matrix. While individual electrons are very light, the whole collection of interlocked electrons in a superconductor is quite massive. If one electron encounters an ion, the electron can't easily be deflected. In fact, to change the velocity of any electron, which you would have to do to get energy from it, you would have to change the velocity of all the electrons. Because this can't be done, no energy is given up in such collisions and electrons simply move through the material together. If the temperature is raised, however, the ions vibrate more vigorously and are no longer able to perform the delicate minuet required to produce the electron pairs. Thus, above the critical temperature, superconductivity breaks down.

Connection

Searching for New Superconductors

Until the mid-1980s, all superconducting materials had to be cooled in liquid helium, an expensive and cumbersome refrigerant that boils at a few degrees above absolute zero. The reason was that none of these materials was capable of sustaining superconductivity above about 20 kelvins. Acting on a hunch, scientists K. Alexander Müller and J. Georg Bednorz of IBM's Zurich, Switzerland, research laboratory began a search for new superconductors. Traditional superconductors are metallic, but Bednorz and Müller decided instead to focus on oxides—chemical compounds, such as most rocks and ceramics, in which oxygen participates in ionic bonds. It was an odd choice, because oxides make the best electrical insulators, although a few unusual oxides do conduct electricity.

Working with little encouragement from their peers and with no formal authorization from their employers, the scientists spent many months mixing chemicals, baking them in an oven, and testing for superconductivity. The breakthrough came on January 27, 1986, when a small black wafer of baked chemicals was found to become superconducting at greater than 30 degrees above absolute zero—a temperature that shattered the old record and ushered in the era of "high-temperature" (although still extremely cold) superconductors. Their compound of copper, oxygen, and other elements seemed to defy all conventional wisdom, and this discovery began a frantic race to study and improve the novel material.

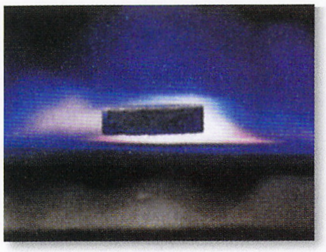


FIGURE 24-4. A magnet floats magically above a black disk made from a new high-temperature superconductor. The clouds in the background form above the cold liquid-nitrogen refrigerant.

Today, many scientists are attempting to synthesize new oxides closely related to those first described by Bednorz and Müller, while others struggle to devise practical applications for these new materials. Some recently developed compounds superconduct at temperatures as high as 160 degrees above absolute zero (Figure 24-4). It may soon be possible to make commercially useful electric devices out of these materials.

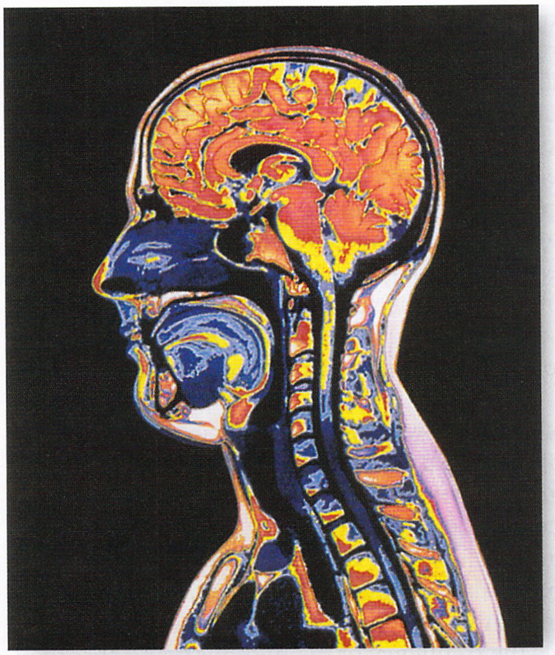
Perhaps equally important, high-temperature superconductors have taken superconductivity from the domain of a few specialists and brought it into classrooms around the world. As a new generation of scientists grows up with these new superconductors, new questions will be asked and exciting new ideas and inventions are sure to be found. As the Connection: Magnetic Resonance Imaging section illustrates, the main commercial use of superconductors to date has been the production of magnets for use in medicine. In the future, the use of superconductors in the next generation of interurban trains (see the Connection: Maglev Trains, page 522) could also become very important. ●

Connection

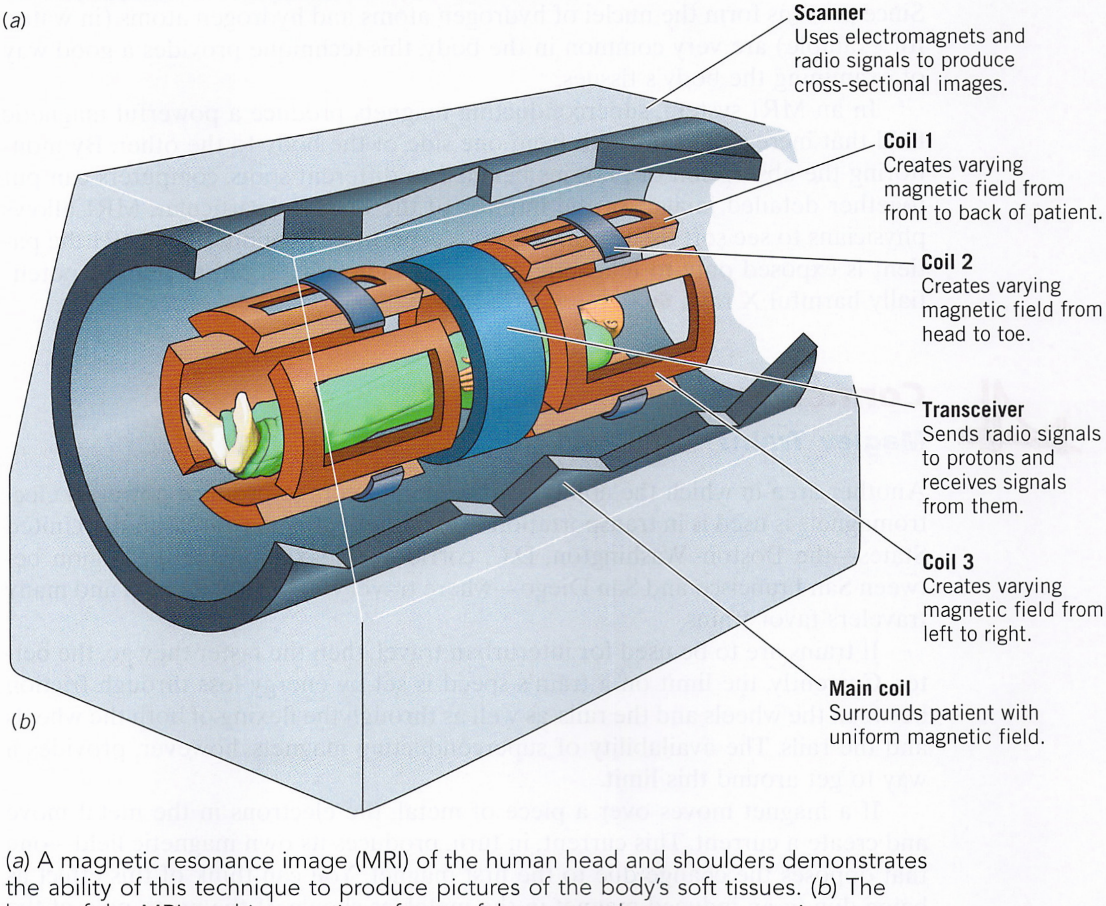
Magnetic Resonance Imaging

The ability to produce strong magnetic fields has led to an important advance in the ability of physicians to diagnose illness. Called "magnetic resonance imaging" (MRI), this procedure allows the physician to obtain a detailed image of the interior of your body in a noninvasive way. The development of superconducting magnets has helped make MRI more widespread as a diagnostic tool.

To understand how MRI works, you need to recall what we have learned in Chapter 17—that moving electric charges can produce magnetic fields. If you think of a charged particle such as the proton as rotating, then it, too, constitutes



(a)



(b)

(*a*) A magnetic resonance image (MRI) of the human head and shoulders demonstrates the ability of this technique to produce pictures of the body's soft tissues. (*b*) The heart of the MRI machine consists of powerful magnets that create a varying magnetic field. This field interacts with molecules in your body.

a moving electric charge. Consequently, the proton has its own dipole magnetic field and we can think of each proton as being like a tiny bar magnet. If the proton is in an external magnetic field, then it turns out that the laws of quantum mechanics (see Chapter 22) require that this magnet be oriented in only one of two ways. Roughly speaking, the north pole of the proton's "bar magnet" can line up with the external field (i.e., its north pole can point toward the north pole of the external magnet) or the proton's "bar magnet" can line up against that field. Physicists say that the proton must be either "spin up" or "spin down."

The orientation in which the proton's magnetic field is aligned with the external field has a slightly lower energy than the orientation in which it is aligned against that field. Under normal circumstances, therefore, there are slightly more protons in the spin up orientation (aligned with the external field) than in the spin down orientation.

Suppose we flood a region of the body with radio-frequency photons. Some protons in the body will absorb photons and flip from spin up to spin down. (For this to happen, the photon has to have precisely the right energy—the energy that corresponds to the difference between the energies of the spin up and spin down orientations.) By noting how much of this particular radiation is absorbed, scientists can tell how many protons there are in that particular region. If the strength of the external field changes, the amount of energy needed to make the proton flip changes as well, as does the frequency of the photons being absorbed. Since protons form the nuclei of hydrogen atoms and hydrogen atoms (in water, for example) are very common in the body, this technique provides a good way of examining the body's tissues.

In an MRI system, superconducting magnets produce a powerful magnetic field that increases in strength from one side of the body to the other. By monitoring the absorption of photons beamed to different spots, computers can put together detailed images of the interior of the body. In particular, MRI allows physicians to see soft tissue, which X rays cannot do. In addition, in MRI the patient is exposed only to magnetic fields and radio waves, rather than to potentially harmful X rays.

Connection

Maglev Trains

Another area in which the ability of superconductors to produce powerful electromagnets is used is in transportation. Today, there are many areas in the United States—the Boston–Washington, D.C. corridor, for example, or the region between San Francisco and San Diego—where travel volume is very high and many travelers favor trains.

If trains are to be used for interurban travel, then the faster they go, the better. Currently, the limit on a train's speed is set by energy loss through friction between the wheels and the rails, as well as through the flexing of both the wheels and the rails. The availability of superconducting magnets, however, provides a way to get around this limit.

If a magnet moves over a piece of metal, the electrons in the metal move and create a current. This current, in turn, produces its own magnetic field—one that opposes the change due to the first magnet. You can think of this effect as being due to an induced magnet in the metal, as shown. If the north pole of the original magnet is closest to the metal, then this induced magnet will have its north pole up. The repulsive force between the two magnets—one original and the other due to the movement of electrons in the metal—pushes upward on the original magnet. If the force is strong enough, it can actually balance the force of gravity and keep the magnet floating above the metal. This process is called *magnetic levitation,* or "maglev" for short.

The idea of a maglev train (see Figure 24-5) is that the interaction between the superconducting magnet in the train and in the metal rail results in an upward force through the levitation process, essentially floating the train a few inches above a metal track. Without the need for wheels to touch the track, the train is able to overcome present limits on speed. Speeds in excess of 300 mph are expected for maglev systems. A maglev train would leave the station on ordinary wheels, but as its speed increased the levitation force would eventually get large enough so that the train would take off and literally fly to its destination.

Another aspect of maglev train systems is that by controlling currents in the electromagnets on the train, you can induce opposite magnetic poles in the guide rail in front of each electromagnet. With this system, each electromagnet is pulled forward by the forces between the magnetic poles. By adjusting the timing of the polarity of magnets in the train, you can adjust the speed of the train. Or you

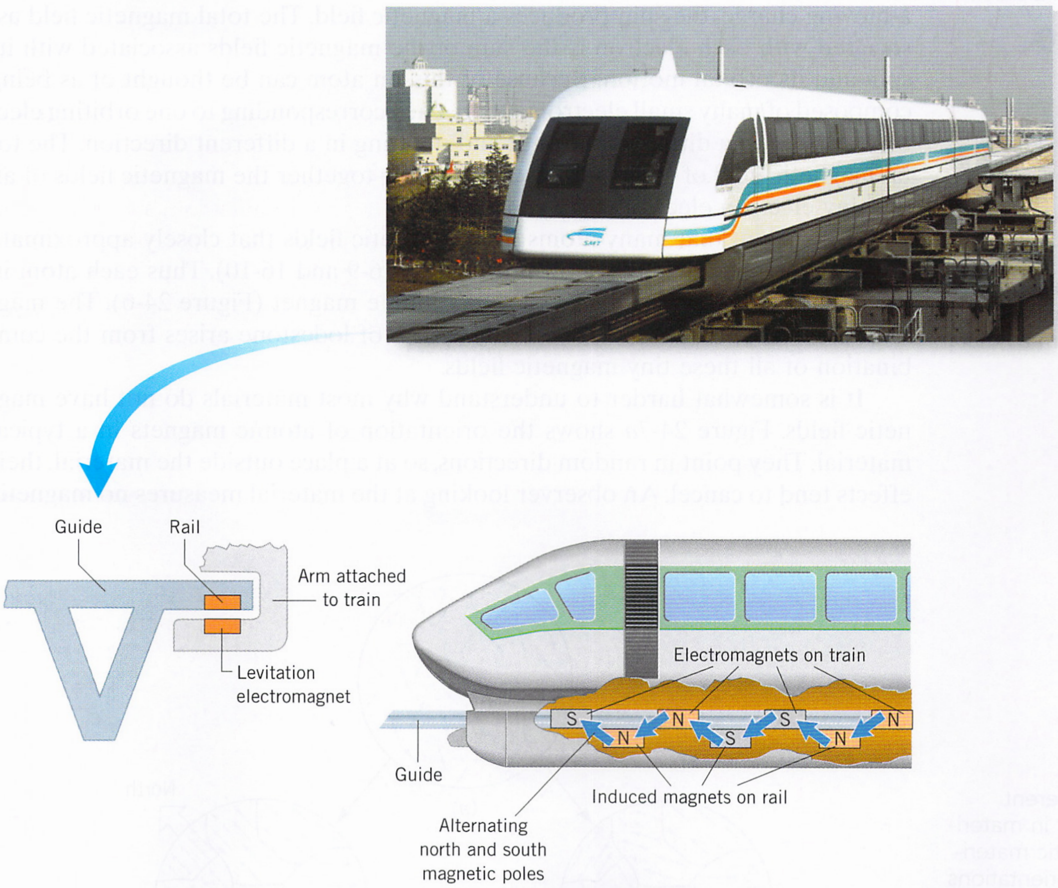


FIGURE 24-5. Superconducting magnets can magnetically levitate a train, while other magnets provide a push-pull effect that accelerates the train to speeds of hundreds of miles per hour. This superconductor technology has been used for commercial trains in the United States.

can reverse the polarity of the induced magnets in the rail so they are the same as the electromagnets, thus slowing the train down to a stop.

In 2002, the first permanent commercial maglev system in the world was installed at Virginia Commonwealth University in Richmond, Virginia. ●

MAGNETIC PROPERTIES OF MATERIALS

The magnets that lie at the heart of most electric motors and generators, although critical to almost everything we do, are not much evident in our everyday lives. Similarly, we are usually unaware of the magnets that drive our stereo speakers, telephones, and other audio systems. Even refrigerator magnets and compass needles are so common that we take them for granted. But why do some common materials, such as iron, display strong magnetism, while other substances seem to be unaffected by magnetic fields?

In Chapter 17, we learned that one of the fundamental laws of nature is that every magnetic field is due, ultimately, to the presence of electric currents. It turns out that every electron has a spin—that is, you can roughly picture an electron as spinning on an axis, like the Earth. Because the spinning electron constitutes a moving charge, the spin produces a magnetic field. The total magnetic field associated with each electron is the sum of the magnetic fields associated with its spin and its orbital motion. Because of this, an atom can be thought of as being composed of many small electromagnets, each corresponding to one orbiting electron, each with a different strength and pointing in a different direction. The total magnetic field of the atom arises by adding together the magnetic fields of all the tiny electron electromagnets.

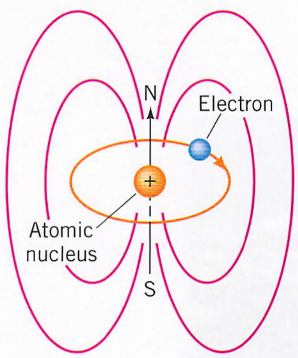


FIGURE 24-6. The dipole magnetic field of atoms takes the same form as that of larger magnets.

It turns out that many atoms have magnetic fields that closely approximate the dipole type (originally shown in Figures 16-9 and 16-10). Thus each atom in the material can be thought of as a tiny dipole magnet (Figure 24-6). The magnetic field of a solid material such as a piece of lodestone arises from the combination of all these tiny magnetic fields.

It is somewhat harder to understand why most materials do not have magnetic fields. Figure 24-7*a* shows the orientation of atomic magnets in a typical material. They point in random directions, so at a place outside the material, their effects tend to cancel. An observer looking at the material measures no magnetic

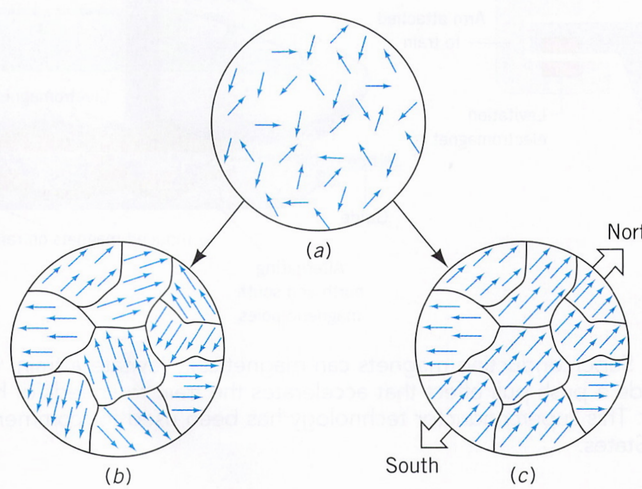


FIGURE 24-7. Different magnetic behavior in materials. (*a*) Nonmagnetic materials have random orientations of spins. (*b*) Ferromagnetic materials with randomly oriented domains are not magnetic. (*c*) A permanent magnet has more uniformly oriented atomic spins.

field, and a compass placed outside the material is not deflected. This explains how materials made up of tiny magnets can, as a whole, be nonmagnetic.

Nevertheless, given the fact that atoms are inherently magnetic, it should come as no surprise that materials often display magnetic properties, either in isolation or when they are immersed in an external magnetic field. There are, in fact, three important classes of material magnetism: **ferromagnetism,** *paramagnetism,* and *diamagnetism.*

Ferromagnetism

In a few materials, including iron, cobalt, and nickel metals, the angular momentum vectors associated with the electrons in the atoms line up with one another. This effect imposes a kind of order on the atoms. As a result, the atomic magnets associated with these atoms line up as well (Figure 24-7*b*). Typically, all the atoms in a region that measures about a thousand atoms on a side are aligned in this way. Such a region is called a *ferromagnetic domain.*

In a normal piece of iron, atoms within a specific domain all line up pointing in the same direction, but the orientations of the domains are random. You do not measure a magnetic field in this material because the magnetic fields due to different domains cancel one another out. However, in special cases, such as when iron cools from very high temperature in the presence of a strong magnetic field, some of the neighboring domains may line up and thus reinforce one another. Only when most of the magnetic domains line up (as shown in Figure 24-7*c*) do you get a material that exhibits a strong external magnetic field—the arrangement that occurs in permanent magnets.

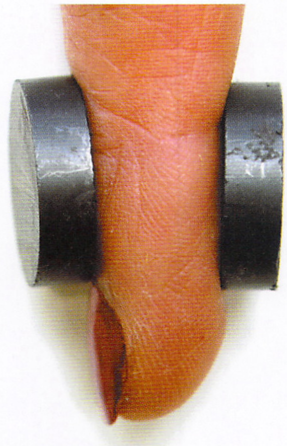
We can understand how ferromagnets form by thinking about a piece of very hot iron. Because of the high temperature, the atoms are moving around vigorously, and there is no chance for the atomic magnets to align and reinforce one another. As the temperature is lowered, however, the random motion slows down and the magnetic force can take over to influence the atoms' orientations. At high temperature, the effects of this force are overwhelmed by thermal motion, but at low temperature it creates a situation where atomic magnetic fields reinforce one another. The temperature where this transition takes place is called the *Curie point* of the metal, after the French physicist Pierre Curie (1859–1906).

This picture of permanent magnets explains many of their features. It explains, for example, how you can turn an ordinary piece of iron into a magnet by stroking it with another magnet. This process aligns some (but usually not all) of the domains in the direction of the stroking, so that they produce an external magnetic field. This description also explains why heating (or sometimes just hammering) a magnet can destroy its properties. Adding energy in this way jostles the domains, randomizing their directions so that their magnetic fields cancel.

Some alloys developed in recent years can produce very powerful permanent magnets after proper magnetization. These alloys contain smaller domains (and more of them than in most ferromagnetic materials) making it easier to align them.

Paramagnetism

In most materials, the atomic magnets are arranged randomly and their magnetic fields cancel one another out. However, in some materials, when an external magnetic field is applied, the atomic magnets line up in such a way as to reinforce that field. These materials, called "paramagnets," do not normally display magnetic properties, but will do so in the presence of a magnetic field.



(*a*)

(*b*)

(*a*) Magnets made from new alloys can attract one another from either side of your finger. (*b*) Using magnetic shoes to climb the side of a steel-hulled ship.

Pierre Curie spent the early part of his career exploring the nature of magnetic materials and, indeed, gave us most of our current understanding of that field. In his later career, he teamed with his wife, Marie Sklodowska Curie, in the study of radioactivity (see Chapter 26), for which they became the only husband and wife team to share a Nobel Prize (in 1903). Marie Curie went on to become the first person to win two Nobel Prizes (she received her second, in chemistry, in 1911).

Pierre Curie found that the extra magnetic field produced when atoms line up in a paramagnet is proportional to the applied magnetic field—that is, the stronger the external field, the more the atoms tend to line up. He also discovered that if the temperature of a paramagnet is raised, the extra magnetic field decreases. This happens because as the temperature goes up, the increased thermal motion of the atoms starts to destroy the alignment. These results are summarized in *Curie's law:*

1. In words:

The magnetization of a material increases as the magnetic field increases and decreases with temperature.

2. In an equation with words:

$$\text{Magnetization} = \text{Curie constant} \times \frac{\text{Magnetic field}}{\text{Temperature}}$$

3. In an equation with symbols:

$$M = C\,\frac{B}{T}$$

where M is the extra magnetic field, or magnetization, of the material, B is the applied magnetic field, T is the temperature (in kelvins), and C is a number known as Curie's constant. Curie's constant is always the same for a given material, but varies from one material to another.

Develop Your Intuition: Magnetic Attraction of Liquids

Oxygen becomes a liquid at a temperature of 90 kelvins and nitrogen becomes a liquid at 77 kelvins. If you were to pour a stream of liquid oxygen between the poles of a magnet, it would be attracted to the magnet just as if the oxygen were iron filings. However, a stream of liquid nitrogen would pass between the poles as if nothing had happened. How can we explain this different behavior?

(a) (b)

(a) Liquid oxygen poured between the poles of a magnet is attracted to the poles, building up a blockage suspended in the magnetic field. (b) Liquid nitrogen passes right between the poles of a magnet with no attraction.

Nitrogen and oxygen are right next to each other in the periodic table. Nitrogen contains five electrons in its outer shell and oxygen contains six. Careful counting of electrons in molecular nitrogen (N_2) shows that the electrons pair up in this molecule very neatly, with no unpaired electrons. Thus, the magnetic fields of pairs of electrons in nitrogen tend to cancel one another out, and the atom has no net magnetic field. But molecular oxygen (O_2) does not pair up nicely; it is left with two single electrons of the same spin that cannot pair up together. The result is that oxygen is paramagnetic and is attracted to the poles of a magnet.

Diamagnetism

In some materials (bismuth is one of the most common) the magnetic fields associated with the electrons cancel one another so that the atom has no net magnetic field. If such an atom is placed in a magnetic field, however, the motion of the electrons changes to oppose this field. Thus, the magnetic field generated in the material is in a direction opposite to the magnetic field that is imposed from the outside. Such a material is said to be a "diamagnet."

THINKING MORE ABOUT

High-Temperature Superconductors

The discovery of high-temperature superconductors in 1987 created a firestorm of sensationalistic news stories. Optimistic researchers predicted a new age of inexpensive energy, fast transportation, and futuristic applications in medicine, communications, and computer technology. Bold headlines estimated the advance to be worth billions of dollars, while *Time* magazine featured superconductors as their cover story. The government quickly poured tens of millions of dollars into superconductor research while many venture capitalists, hoping to profit from the discovery, invested large sums into new companies.

It didn't take long for the hype to turn into a more realistic assessment of daunting technological hurdles. All the new superconductors are ceramic materials, which are rigid and brittle. They behave very differently from the flexible metal used to conduct electricity in wire. Furthermore, all these materials prove to be rather unstable; for example, they tend to break down when exposed to water. Thus, in spite of the extraordinary ability of high-temperature superconductors to transmit electricity without loss, it has proven extremely difficult to shape them into reliable wires or useful

Superconductors in the news. (*Time*, May 1987).

devices. The dream of a multibillion-dollar industry has failed to materialize.

How should scientists handle the announcement of potentially exciting but unproven new discoveries? How should the press deal with futuristic speculations? Should the government respond quickly to fund research on potentially significant technologies?

Summary

The electric properties of materials depend on the kinds of constituent atoms and the bonds they form. For example, **electrical resistance**—a material's resistance to the flow of an electric current—depends on the mobility of bonding electrons. Metals, which are characterized by loosely bonded outer electrons, make excellent **electrical conductors,** while most materials with tightly held electrons in ionic and covalent bonds are good **electrical insulators.** Materials, such as silicon, that conduct electricity, but not very well, are called **semiconductors.** At very low temperatures, some compounds lose all resistance to electron flow and become **superconductors.**

Magnetic properties also arise from the collective behavior of atoms. While most materials are nonmagnetic, **ferromagnets** have domains in which electron spins are aligned with one another. In paramagnets, the magnetic dipoles associated with atoms line up to reinforce imposed magnetic fields. In diamagnetic materials, atomic electrons produce a magnetic field that opposes imposed fields.

Key Terms

electrical conductor A material in which charges are free to move from place to place. (p. 515)

electrical insulator A material in which charges are not free to move from place to place. (p. 517)

electrical resistance The tendency of a material to resist the flow of electric charges through it. (p. 515)

ferromagnetism The magnetic properties of a material associated with the spontaneous alignment of domains of magnetic fields of its atoms. (p. 525)

semiconductor A material that is neither a good electrical conductor nor a good insulator. (p. 517)

superconductivity The property of having no electrical resistance. (p. 519)

Review

1. What aspects of your life depend on electricity and, hence, on the electric properties of materials?
2. What is an electrical conductor?
3. How does an electrical conductor actually transmit electricity? What particle is moving through the material, and exactly what allows a material that is a good conductor to be one?
4. Give several examples of materials that are good conductors.
5. Describe the origin of electrical resistance in a material. What is it, and how is heat generated due to it?
6. Do materials that are good conductors exhibit any electrical resistance?
7. Aluminum is often used in the main utility power lines that take electricity from power plants to cities, while copper is used to wire a home. Why is this? When might gold be preferred to conduct electricity?
8. What is the hallmark of a material that is an electrical insulator? What types of bonds does such a material generally have, and how does this affect the transmission of electricity?
9. Why is plastic commonly used as an insulator? What other materials are also used?
10. What is a semiconductor? How does it differ from a conductor or insulator?
11. How does the strength of silicon bonds help to account for its semiconducting properties? Where do the conducting electrons in silicon come from?
12. What is a hole in a semiconductor, and how does this facilitate the conduction of electricity?
13. What is so unusual about superconductors? Under what conditions do materials exhibit superconductivity?
14. Why does a superconducting magnet use less electric power than a traditional copper-wire electromagnet?

15. How does a superconducting material allow electrons to pass through it without losing energy? What is the role of low temperature and electron–ion interactions in this process?
16. What is magnetic resonance imaging (MRI)? How does it work?
17. What benefits does MRI offer to patients and physicians in comparison to X-rays photographs?
18. What is magnetic levitation?
19. Why are magnetic levitation trains more efficient than conventional diesel trains?
20. What is the role of electrons and electric current in producing magnetic fields at the atomic level?
21. What is ferromagnetism? What substance exhibits this?
22. What is a ferromagnetic domain? How are the atoms within a single domain oriented, and how do the many separate domains within a material line up when the material as a whole is magnetic? When it is nonmagnetic?
23. What is the Curie point of a metal?
24. What is paramagnetism? What must be present for a material to exhibit this property?
25. In a paramagnetic material, what is the strength of the magnetism in the material proportional to?
26. How does temperature affect the magnetic field of a paramagnetic field? What is Curie's law?
27. What is diamagnetism?

Questions

1. Metals are generally good conductors of electricity. Why is this the case? Can you relate this generality to the type of bonding that occurs in metals? Explain.
2. Take the point of view of an electron moving among other electrons and atoms in a material. Describe your motion in an insulator, a conductor, a superconductor, and a semiconductor.
3. How is it that salt water can conduct electricity? Should absolutely pure water conduct electricity? How about ice?
4. When you go in to have an MRI done, the technician always tells you to remove your watch, pens, and other metal objects from your pockets. Why is this request made?
5. How can a hole moving through a semiconductor be like an electric charge moving through the same material? Explain.
6. If all atoms have electrons that are in motion about an atom, why aren't all materials magnetic?
7. Compare the way that the motion of electrons in a diamagnetic material creates an opposing magnetic field with the way electrons in a copper wire accomplish the same end.
8. A normal piece of iron produces no external magnetic field. Suppose a piece of iron consisted of one very large domain instead of many small ferromagnetic domains. Would this piece of iron produce an external magnetic field? Why?
9. A paramagnetic material will acquire a magnetization if it is placed in an applied magnetic field. What happens to the magnetization of a paramagnetic material if the temperature of the material is doubled? What if the temperature and the applied magnetic field are simultaneously doubled?
10. Is air an electrical conductor or an insulator? Give an example of electrical conduction through air.
11. If the temperature of a semiconductor is increased, does its electrical resistance increase or decrease? Explain.
12. Based on Ohm's law (Chapter 18), how much current would you expect to run though a superconductor if the voltage across it were 100 volts? Is this possible? What do you think would really happen?
13. What is the significance of one material having a larger Curie constant than another?
14. The Pauli exclusion principle (Chapter 21) says that no two electrons can occupy the same energy state unless their spins point in opposite directions. Use the Pauli exclusion principle to argue that atoms with an even number of electrons tend to have small Curie constants.

Investigations

1. Shortly after the discovery of high-temperature superconductivity, many newspapers and TV shows ran features on how these new materials would change society. In what ways might superconductivity change society? Historically, what other new materials have caused significant changes in human societies?
2. Why does a magnet become demagnetized when you repeatedly hit it with a hammer? In what other ways can you destroy a permanent magnet? Why aren't permanent magnets permanent?
3. Compare the absorption of a photon that occurs in the MRI process to the absorption process that occurs in the Bohr atom.
4. Every year, one or two promising new materials capture public attention. Scan recent issues of *Science News* and

identify one such material. Who made it? How might it be used?

5. Imagine that you are a science fiction writer. Concoct a description of a new material with unique (but plausible) properties and describe how that material might change a society.

6. Seek out a licensed electrician and examine a new construction project where the wiring is installed yet still visible. Ask about all the precautions taken to avoid electrocution. What types of materials are their clothes, ladders, and tools made of? Trace the flow of electricity from the street, into the construction site, through the various appliances, and back out again. What materials are conductors, what provides resistance in the circuit, and where is insulation important?

7. Research the status of magnetic levitation trains like the one now operating in Japan. How does it operate? How fast might it go? When did such a train begin operating in North America?

8. Silicon is the best-known semiconducting material. What are some other semiconducting materials and compounds in use today? Who uses them, and why are they used instead of silicon?

9. The term magnetic resonance imaging (MRI) is now used instead of the original term nuclear magnetic resonance (NMR). Why do you think that happened? Can you think of other examples where technologies have been renamed or redescribed so that they are more palatable to the public? How about military technologies?

WWW Resources

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

1. **http://www.owlnet.rice.edu/~hkic/superconductors/** A site devoted to history, theory, and applications of superconductivity.

2. **http://www.ornl.gov/reports/m/ornlm3063r1/contents.html** *A Teacher's Guide to Superconductivity for High School Students,* from Oak Ridge National Laboratory.

3. **http://micro.magnet.fsu.edu/electromag/java/filamentresistance/index.html** A short and sweet animated applet demonstrating electron flow through a metal conductor from Florida State University.

4. **http://micro.magnet.fsu.edu/electromag/electricity/resistance.html** Complete tutorial on resistance from Florida State University.