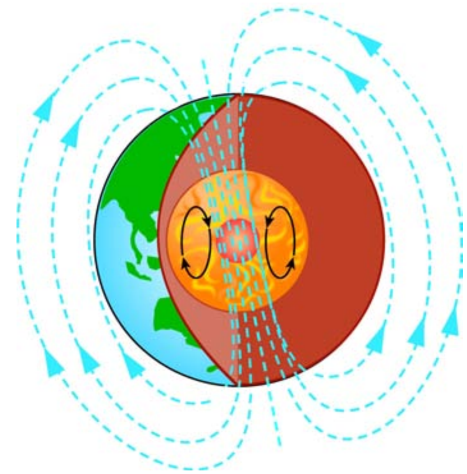
Chapter 16 Magnetism

Have you ever used a compass? A compass is very handy when you are on an open body of water with no land in sight, and you are trying to make sure you are headed in the right direction. It is also a good idea to have a compass with you if you are hiking. Some automobiles now come equipped with a built-in compass, and some even use more sophisticated global positioning system technology, which uses satellites rather than magnetic fields to determine direction.

How does a compass work? A simple compass is really nothing more than a lightweight magnet, in the shape of a pointer, that is mounted on a very low-friction pivot point. Earth, with its molten iron and nickel core, acts as though a giant magnet was buried deep inside, with the south pole end of the magnet located at the geographic North Pole. When you hold a compass in your hand, (and there is no other magnet nearby), the small pivoting magnet in the compass will be attracted by the geographic North Pole of Earth, and it will "point" north.

In this chapter, you will learn how magnets and magnetic fields work, and you will explore the source of magnetism. As with electricity, the source of magnetism can be traced back to atoms!



Key Questions

- ✓ How can a magnet be strong enough to lift a car?
- ✓ What is the biggest magnet on Earth?
- ✓ How does a compass work?

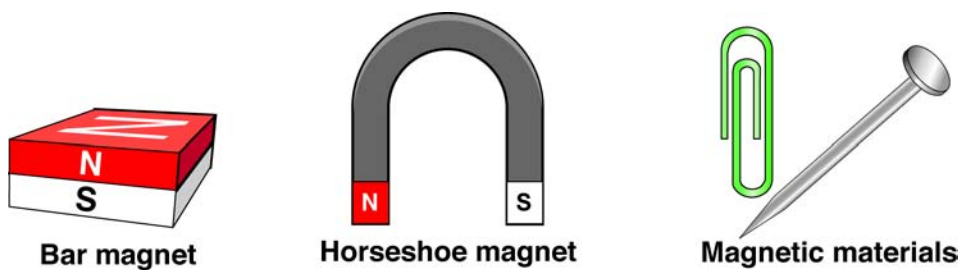
16.1 Properties of Magnets

Magnetism has fascinated people since the earliest times. We know that magnets stick to refrigerators and pick up paper clips or pins. They are also found in electric motors, computer disk drives, burglar alarm systems, and many other common devices. This chapter explains some of the properties of magnets and magnetic materials.

What is a magnet?

Magnets and magnetic materials If a material is **magnetic**, it has the ability to exert forces on magnets or other magnetic materials. A magnet on a refrigerator is attracted to the steel in the refrigerator's door. A *magnet* is a material that can create magnetic effects by itself. *Magnetic materials* are affected by magnets but do not actively create their own magnetism. Iron and steel are magnetic materials that can also be magnets.

Permanent magnets A **permanent magnet** is a material that keeps its magnetic properties, even when it is not close to other magnets. Bar magnets, refrigerator magnets, and horseshoe magnets are good examples of permanent magnets.



Poles All magnets have two opposite **magnetic poles**, called the north pole and south pole. If a magnet is cut in half, each half will have its own north and south poles (Figure 16.1). It is impossible to have only a north or south pole by itself. The north and south poles are like the two sides of a coin. You cannot have a one-sided coin, and you cannot have a north magnetic pole without a south pole.

Vocabulary

magnetic, permanent magnet, magnetic poles, magnetic field, magnetic field lines

Objectives

- ✓ Recognize that magnetic poles always exist in pairs.
- ✓ Decide whether two magnetic poles will attract or repel.
- ✓ Describe the magnetic field and forces around a permanent magnet.

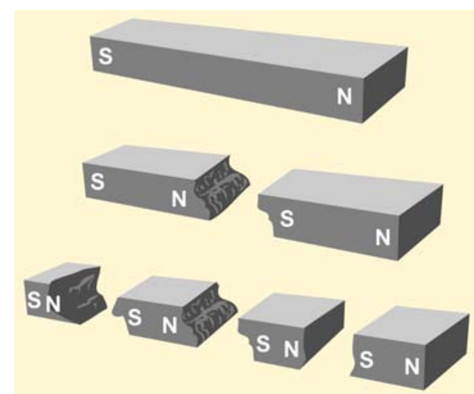
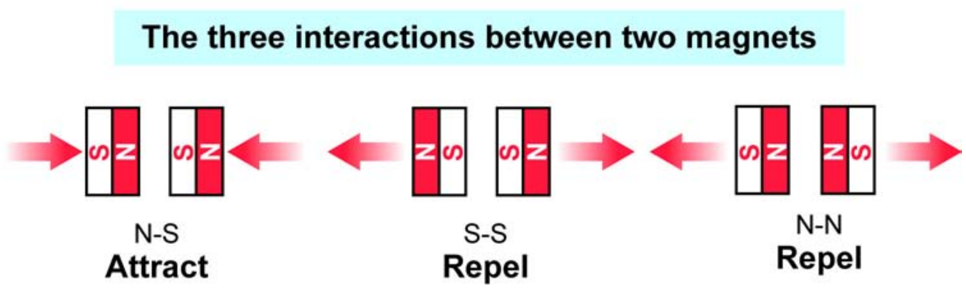


Figure 16.1: *If a magnet is cut in half, each half will have both a north pole and a south pole.*

The magnetic force

Attraction and repulsion

When near each other, magnets exert forces. Two magnets can either attract or repel. Whether the force between two magnets is attractive or repulsive depends on which poles face each other. If two opposite poles face each other, the magnets attract. If two of the same poles face each other, the magnets repel.



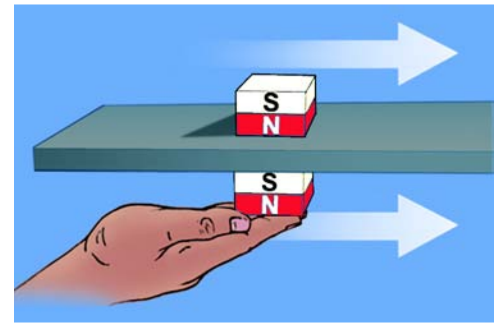


Figure 16.2: *The force between two magnets depends on how the poles are aligned.*

Most materials are transparent to magnetic forces

Magnetic forces can pass through many materials with no apparent decrease in strength. For example, one magnet can drag another magnet even when there is a piece of wood between them (Figure 16.2). Plastics, wood, and most insulating materials are transparent to magnetic forces. Conducting metals, such as aluminum, also allow magnetic forces to pass through, but may change the forces. Iron and a few metals near it on the periodic table have strong magnetic properties. Iron and iron-like metals can block magnetic forces and are discussed later in this chapter.

Using magnetic forces

Magnetic forces are used in many applications because they are relatively easy to create and can be very strong. There are large magnets that create forces strong enough to lift a car or even a moving train (Figure 16.3). Small magnets are everywhere; for example, some doors are sealed with magnetic weatherstripping that blocks out drafts. There are several patents for magnetic zippers and many handbags, briefcases, and cabinet doors close with magnetic latches. Many everyday devices rely on magnetic forces to make objects attract or repel one another. You could also use electric forces, but large-scale electric forces are harder to create and control than magnetic forces. Electrical forces tend to be much more important on the atomic level.

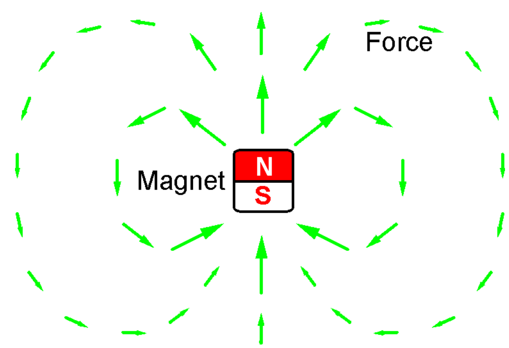
Figure 16.3: *Powerful magnets are used to lift discarded cars in a junkyard.*

The magnetic field

How to describe magnetic forces? Two magnets create forces on each other at a distance much larger than the size of the magnets. How do you describe the force everywhere around a magnet? One way is with a formula, like Newton's Law of Universal Gravitation. Unfortunately, magnetic forces are more complex than gravity because magnets can attract and repel. Gravity can only attract. Also, magnets all have two poles. That means part of the same magnet feels an attracting force and part feels a repelling force. While there *are* formulas for the magnetic force, they are complicated and usually used with computers.

The test magnet A convenient way to show the magnetic force around a magnet is with a drawing. The standard drawing shows the force acting on the north pole of an imaginary test magnet. The test magnet is so small that it does not affect the magnetic force. Also, since the test magnet is imaginary, we can let it have only a north pole. Having only one pole makes it easier to visualize the direction of the magnetic force (Figure 16.4).

Drawing the force The diagram shows a drawing of the magnetic force around a magnet. The force points away from the north pole because a north pole would be repelled from a north pole. The force points toward the south pole because a north pole magnet would be attracted.



The magnetic field The drawing shows what physicists call the **magnetic field**. A *field* in physics is a quantity that has a value at all points in space. A magnet creates a field because it creates a force on other magnets at all points around itself. The interaction between two magnets really occurs in two steps. First, a magnet creates a magnetic field. Then the magnetic field creates forces on other magnets. In the drawing the field is represented by the arrows.

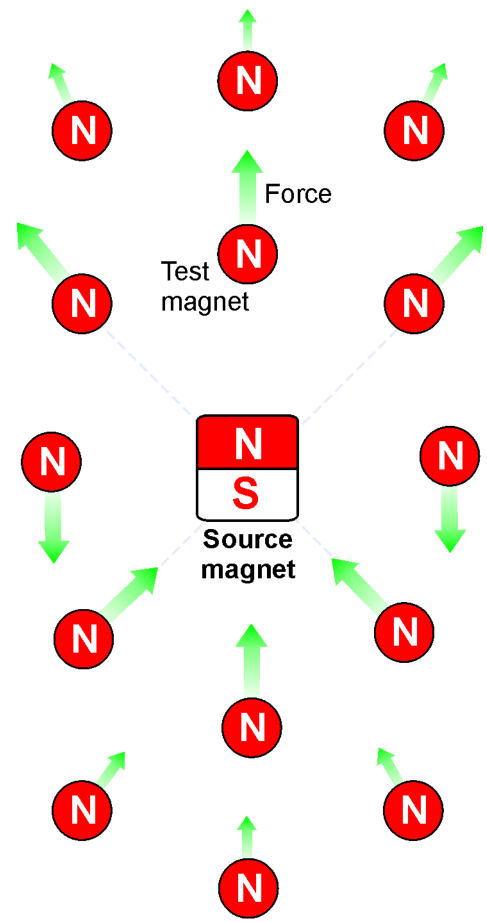


Figure 16.4: *The force on an imaginary north magnetic pole (test magnet) near a source magnet.*

Drawing the magnetic field

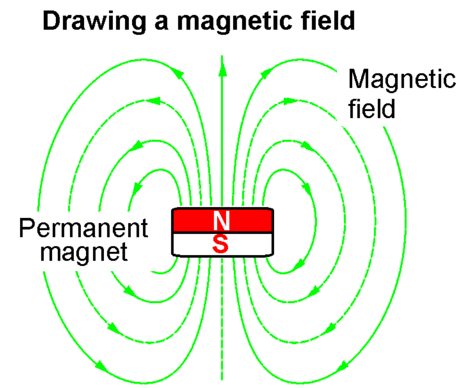
Describing magnetic force The magnetic field is a *force field*, because it represents a force at all points in space. Every magnet creates a magnetic field in the space around it. The magnetic field then creates forces on other magnets. The idea of fields is relatively new and very important in physics. In chapter 18 you learn about other kinds of fields.

Field lines The magnet that creates a field is called the *source magnet*. In the standard drawing of a magnetic field, the arrows we drew on the previous page are connected together into **magnetic field lines**. Magnetic field lines point in the direction of the force on an imaginary north pole test magnet. Magnetic field lines always point away from a north pole and toward a south pole.

Magnetic field lines always point away from a magnet's north pole and toward its south pole.

Understanding magnetic field lines A field line must start on a north pole and finish on a south pole. You cannot just "stop" a field line anywhere. In the drawing in Figure 16.5 notice that the field lines spread out as they get farther away from the source magnet. If field lines are close together, the force is stronger. If field lines are farther apart, the force is weaker. The field lines spread out because the force from a magnet gets weaker as distance from the magnet increases.

Reading a magnetic field drawing Figure 16.5 shows you how to "read" a magnetic field drawing. Magnet A will feel a net attracting force toward the source magnet. The north pole of magnet A feels a repelling force, but is farther away than the south pole. Since the south pole of magnet A is closest, the net force is attracting. Magnet B feels a twisting (torque) force because its north pole is repelled and its south pole is attracted with approximately the same strength.



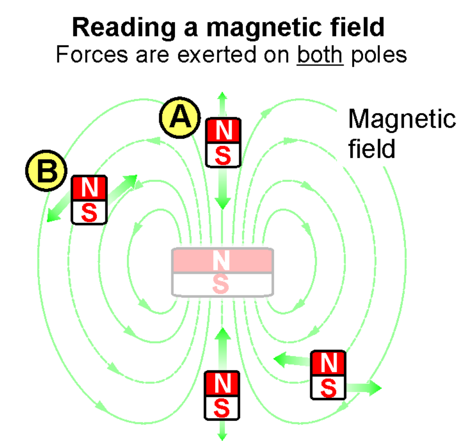


Figure 16.5: *The magnetic field is defined in terms of the force exerted on the north pole of another magnet.*

16.1 Section Review

1. Is it possible to have a magnetic south pole without a north pole? Explain your answer.
2. Describe the interaction between each set of magnetic poles: two north poles; a north and south pole; two south poles.
3. What does the direction of magnetic field lines tell you?

16.2 The Source of Magnetism

It seems strange that magnets can attract and repel each other but can only *attract* objects such as steel paper clips and nails. The explanation for this lies inside atoms. Magnetism is created by moving charges, either in an electric current or in the atoms that make up a material. This section takes a closer look at how magnetism is created.

Vocabulary

electromagnet, right-hand rule, diamagnetic, paramagnetic, ferromagnetic, magnetic domain, soft magnet, hard magnet

Objectives

- ✓ Learn how to build a simple electromagnet and change its strength.
- ✓ Use the right-hand rule to locate an electromagnet's poles.
- ✓ Explain the source of magnetism in materials.

Electromagnets

A coil of wire

Electromagnets are magnets created by electric current flowing in wires. A simple electromagnet is a coil of wire wrapped around an iron core (Figure 16.6). When the coil is connected to a battery, current flows and a magnetic field appears around the coil, just as if the coil were a permanent magnet. The iron core concentrates and amplifies the magnetic field created by the current in the coil.

The poles of an electromagnet

The north and south poles of an electromagnet are at each end of the coil. Which end is the north pole depends on the direction of the electric current. When the fingers of your right hand curl in the direction of current, your thumb points toward the magnet's north pole. This method of finding the magnetic poles is called the **right-hand rule**.

Advantages of electromagnets

Electromagnets have some big advantages over permanent magnets. You can switch an electromagnet on and off by switching the current on and off. You can switch an electromagnet's north and south poles by reversing the direction of the current in the coil. The strength of an electromagnet's field can be changed by changing the amount of current in the coil. Electromagnets can also be much stronger than permanent magnets because they can use large currents.

One use for an electromagnet

Electromagnets are used in many devices around your house. One example is a toaster. The switch you press down both turns on the heating circuit and sends current to an electromagnet. The electromagnet attracts a spring-loaded metal tray to the bottom of the toaster. When a timer signals that the bread is done toasting, the electromagnet's current is cut off. This releases the spring-loaded tray, which pops the bread out of the toaster.

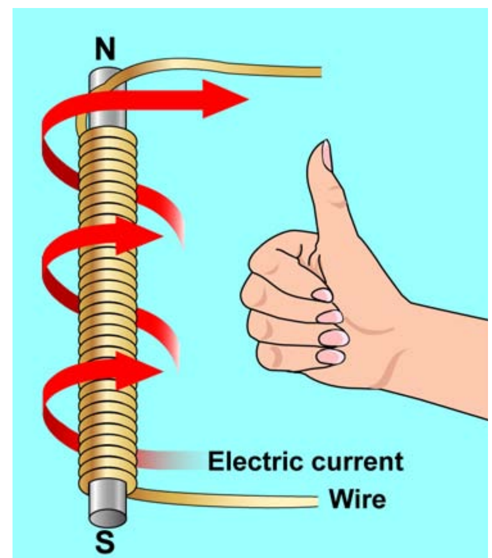


Figure 16.6: *If the fingers of your right hand curl in the direction of the current, your thumb points toward the north pole.*

Building an electromagnet

Wire and a nail You can easily build an electromagnet from a piece of wire and an iron nail. Wrap the wire snugly around the nail many times and connect a battery as shown in Figure 16.7. When there is current in the wire, the nail and coil become magnetic. Use the right-hand rule to figure out which end of the nail is the north pole and which is the south pole. To switch the poles, reverse the connection to the battery, making the current go the opposite direction.

Increase the electromagnet's strength There are two ways you can make the electromagnet's field stronger:

1. You can add a second battery to increase the current.
2. You can add more turns of wire around the nail.

Field is proportional to current The strength of the magnetic field is directly proportional to the amount of current flowing around the nail. If you double the current, the strength of the magnetic field doubles.

Why adding turns of wire works Adding turns of wire increases the field because the magnetism in your electromagnet comes from the *total* amount of current flowing *around* the nail (Figure 16.8). If there is 1 ampere of current in the wire, each loop of wire adds 1 ampere to the total amount of current flowing around the nail. Ten loops of 1 ampere each make 10 total amperes. By adding more turns, you use the same current over and over to create more magnetism.

Resistance Of course, every gain has its cost. By adding more turns in order to strengthen the magnetism, you also increase the resistance of your coil. Increasing the resistance lowers the current a little and generates more heat. A good electromagnet design is a balance between having enough turns to make the magnet strong and not making the resistance too high.

Factors affecting the field The magnetic field of a simple electromagnet depends on three factors:

- The amount of electric current in the wire.
- The amount and type of material in the electromagnet's core.
- The number of turns in the coil.

In more sophisticated electromagnets, the shape, size, and material of the core, and the winding pattern of the coil are specially designed to control the strength and shape of the magnetic field.

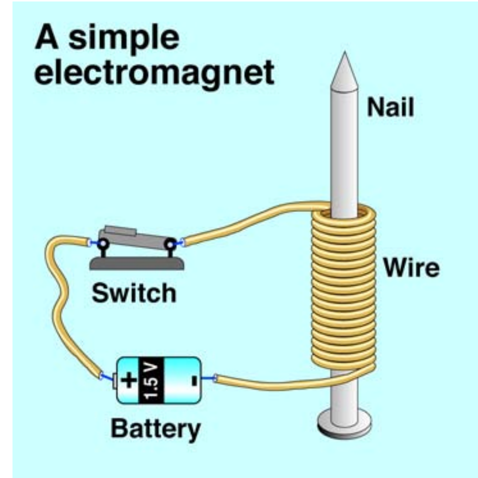


Figure 16.7: *Making an electromagnet from a nail, wire, and a battery.*

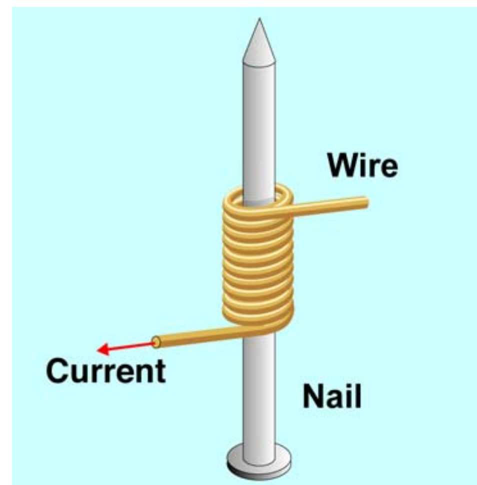


Figure 16.8: *Adding turns of wire increases the total current flowing around the electromagnet. The total current in all the turns is what determines the strength of the electromagnet.*

Magnetism in materials

Electric currents cause all magnetism

Once scientists discovered that electric current can make magnetism, they soon realized that *all magnetism comes from electric currents*. Each electron in an atom behaves like a small loop of current forming its own miniature electromagnet. All atoms have electrons, so you might think that all materials would be magnetic. In reality, we find great variability in the magnetic properties of materials. That variability comes from the arrangement of electrons in different atoms.

Diamagnetic materials

In many elements the magnetic fields of individual electrons in each atom cancel with each other. This leaves the whole atom with zero net magnetic field. Materials made of these kinds of atoms are called **diamagnetic**. Lead and diamond are examples of diamagnetic materials. Holding a magnet up to lead or diamond produces no effect. If you try hard enough, you can see magnetic effects in diamagnetic materials but it takes either a *very strong* magnetic field or very sensitive instruments.

Paramagnetic materials

Aluminum is an example of a **paramagnetic** material. In an atom of aluminum the magnetism of individual electrons does not cancel completely. This makes each aluminum atom into a tiny magnet with a north and a south pole. However, the atoms in a piece of aluminum are randomly arranged, so the alignment of the north and south poles changes from one atom to the next. Even a tiny piece of aluminum has trillions of atoms. Solid aluminum is "nonmagnetic" because the total magnetic field averages to zero over many atoms (top of Figure 16.9).

Magnetic fields in paramagnetic materials

We classify paramagnetic materials as "nonmagnetic." However, they do show weak magnetic activity that can be detected using sensitive instruments. If you hold the north pole of a permanent magnet near aluminum, it attracts the south poles of aluminum atoms nearby. Some atoms change their alignments (Figure 16.9). A weak overall magnetic field is created in the aluminum, so it weakly attracts the external magnet. When the permanent magnet is pulled away, the atoms go back to their random arrangement and the magnetic field disappears.

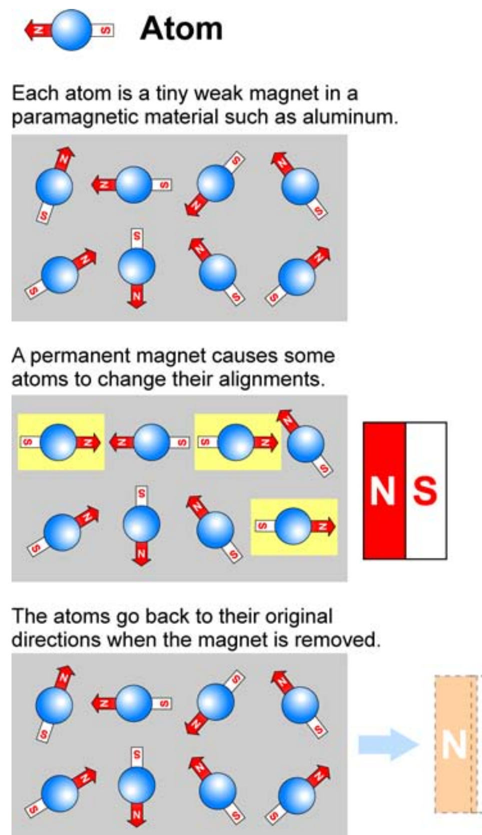


Figure 16.9: *Atoms in a paramagnetic material such as aluminum are tiny magnets. A piece of aluminum is not magnetic because the atoms are arranged in random directions. However, weak magnetic effects can be created because a permanent magnet can temporarily change the orientation of the atom-size magnets near the surface.*

Ferromagnetic materials

Ferromagnetism

A small group of **ferromagnetic** metals have very strong magnetic properties. The best examples of ferromagnetic materials are iron, nickel, and cobalt. Like paramagnetic atoms, the electrons in a ferromagnetic atom do not cancel each other's magnetic fields completely. Each atom is therefore a tiny magnet. The difference is that individual atoms of ferromagnetic materials do *not* act randomly like atoms in paramagnetic materials. Instead, atoms align themselves with neighboring atoms in groups called **magnetic domains**. Because atoms in a domain are aligned with each other the magnetic fields of individual atoms add up. This gives each magnetic domain a relatively strong overall magnetic field.

Why all steel is not magnets

Each domain may contain millions of atoms but the overall size of a domain still small by normal standards. There are hundreds of domains in a steel paper clip. The domains in a steel paper clip are randomly arranged, so their magnetic fields cancel each other out (top of Figure 16.10). That is why a paper clip does not produce a magnetic field all the time.

Aligning domains

Ferromagnetic materials have strong magnetism because domains can grow very quickly by "adopting" atoms from neighboring domains. When a magnet is brought near a steel paper clip, magnetic domains that attract the magnet grow and domains that repel the magnet shrink. The paper clip quickly builds a magnetic field that attracts the magnet, no matter which pole is used (Figure 16.10). When the magnet is pulled away the domains tend to go back to their random orientation and the magnetism goes away.

Hard and soft magnets

Permanent magnets are created when the magnetic domains become so well aligned that they stay aligned even after the external magnet is removed. A steel paper clip can be *magnetized* (aligned magnetic domains) to make a weak permanent magnet by rubbing it with another magnet or with a strong magnetic field. Steel is a **soft magnet** because it is easy to magnetize but loses its magnetization easily too. Heat, shock, and other magnets can demagnetize steel. Materials that make better permanent magnets are called **hard magnets**. The domains in hard magnets tend to remain aligned for a long time. Strong electromagnets are used to magnetize hard magnets.

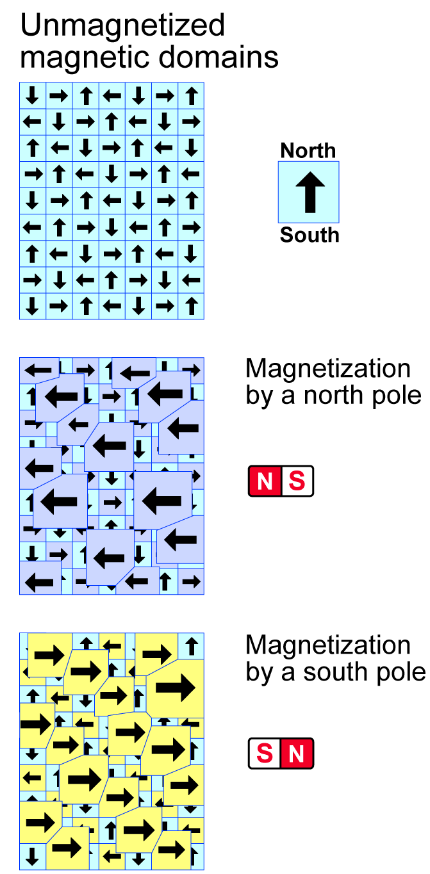


Figure 16.10: *A permanent magnet temporarily magnetizes a section of a paper clip.*

Magnetism in solids

High temperature destroys magnetism

Permanent magnets are created when atoms arrange themselves so they are magnetically aligned with each other. Anything that breaks the alignment destroys the magnetism, so "permanent" magnets are not necessarily permanent. In chapter 7 you learned that atoms are always moving due to temperature. Temperature is the enemy of magnetism because temperature creates disorder between atoms. All permanent magnets become demagnetized if the temperature gets too hot. The best magnetic materials are able to retain their magnetism only up to a few hundred degrees Celsius. A permanent magnet can also be demagnetized by strong shocks or other (stronger) magnets.

Liquids and gases

Permanent magnetism only exists in solids. There are no liquid or gaseous permanent magnets. Liquids or gases cannot be permanent magnets because the atoms have too much thermal energy to stay aligned with each other.

Materials for permanent magnets

The strongest permanent magnets are made from ceramics containing nickel and cobalt, or the rare earth metal neodymium. Using these materials, it is possible to manufacture magnets that are very small but also very strong and harder to demagnetize than steel magnets.

Soft magnets

Soft magnets are easy to magnetize with other magnets. You can see both the magnetization and demagnetization of paper clips or small iron nails using a magnet (Figure 16.11). If you use the north end of a bar magnet to pick up a nail, the nail becomes magnetized with its south pole toward the magnet. Because the nail itself becomes a magnet, it can be used to pick up other nails. If you separate that first nail from the bar magnet, the entire chain demagnetizes and falls apart.

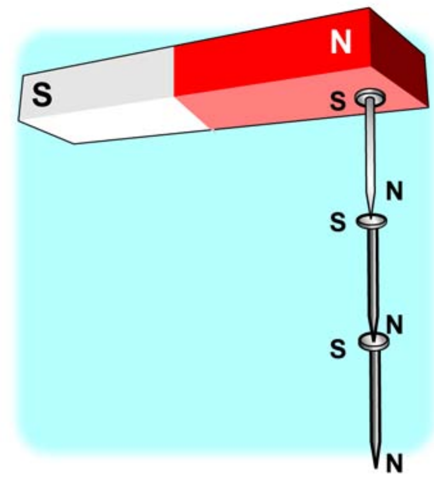


Figure 16.11: *Iron nails become temporarily magnetized when placed near a magnet.*

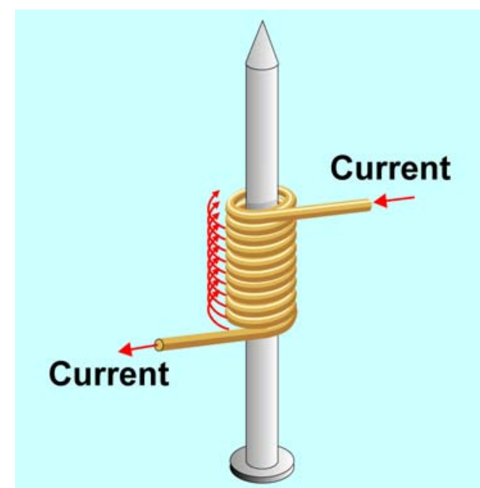


Figure 16.12: *Can you determine the location of the north and south poles of this electromagnet?*

16.2 Section Review

1. Use the right-hand rule to find the north and south poles in Figure 16.12.
2. List two ways to increase the strength of the electromagnet in Figure 16.12.
3. How is magnetism in an electromagnet related to magnetism in a permanent magnet?
4. Explain what happens when a ferromagnetic material is made into a permanent magnet.
5. Are permanent magnets truly permanent? Explain.

16.3 Earth's Magnetic Field

The biggest magnet on Earth is the planet itself. Earth has a magnetic field that has been useful to travelers for thousands of years. Compasses, which contain small magnets, interact with the Earth's magnetic field to indicate direction. Certain animals, including migratory birds, can feel the magnetic field of Earth and use their magnetic sense to tell which direction is north or south.

Discovering and using magnetism

Lodestone As early as 500 B.C. people discovered that some naturally occurring materials had magnetic properties. The Greeks observed that one end of a suspended piece of *lodestone* pointed north and the other end pointed south, helping sailors and travelers find their way. This discovery led to the first important application of magnetism: the **compass** (Figure 16.13).

The Chinese "south pointer" The invention of the compass was also recorded in China in 220 B.C. Writings from the Zheng dynasty tell stories of how people would use a "south pointer" when they went out to search for jade, so that they wouldn't lose their way home. The pointer was made of lodestone. It looked like a large spoon with a short, skinny handle. When balanced on a plate, the "handle" aligned with magnetic south.

The first iron needle compass By 1088 A.D., iron refining had developed to the point that the Chinese were making a small needlelike compass. Shen Kua recorded that a needle-shaped magnet was placed on a reed floating in a bowl of water. Chinese inventors also suspended a long, thin magnet in the air, realizing that the magnet ends were aligned with geographic north and south. Explorers from the Sung dynasty sailed their trading ships all the way to Saudi Arabia using compasses among their navigational tools. About 100 years later a similar design appeared in Europe and soon spread through the civilized world.

Compasses and exploration By 1200, explorers from Italy were using a compass to guide ocean voyages beyond the sight of land. The Chinese also continued exploring with compasses, and by the 1400s were traveling to the east coast of Africa. The compass, and the voyages it made possible, led to many interactions among cultures.

Vocabulary

compass, magnetic declination, gauss

Objectives

- ✓ Explain how a compass responds to a magnetic field.
- ✓ Describe the cause of Earth's magnetism.
- ✓ Recognize the difference between Earth's magnetic and geographic poles.
- ✓ Explain how a compass is used to indicate direction.

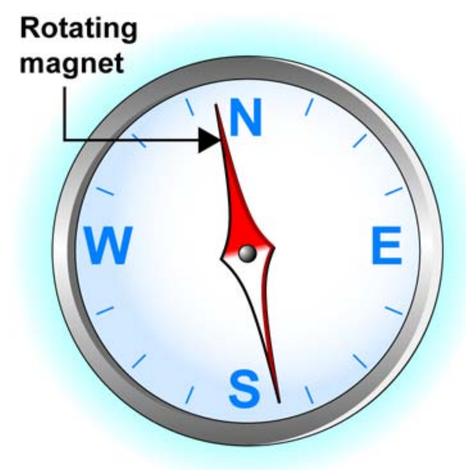


Figure 16.13: *A compass is made of a small bar magnet that is able to rotate.*

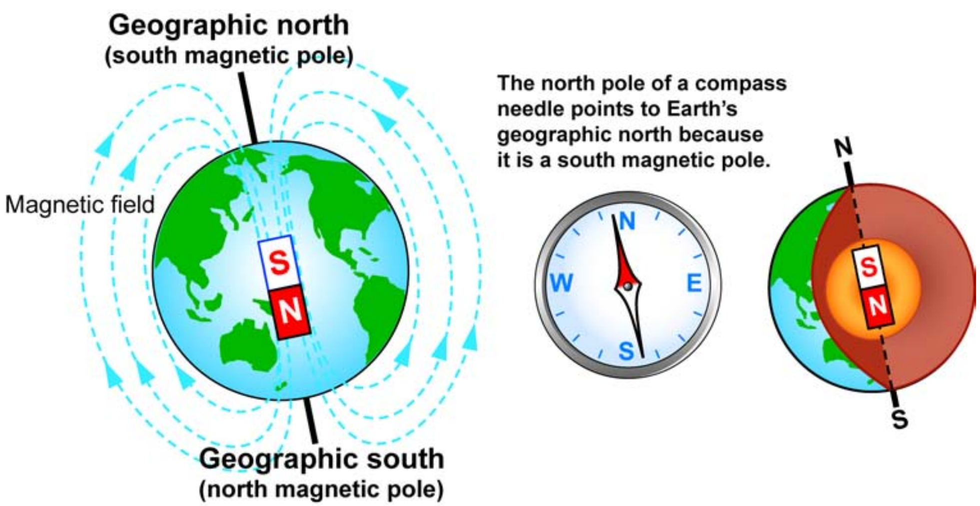
How does a compass work?

A compass is a magnet

A compass needle is a magnet that is free to spin. The needle spins until it lines up with any magnetic field that is present. (Figure 16.14). The north pole of a compass needle always points toward the south pole of a permanent magnet. This is in the direction of the magnetic field lines. Because the needle aligns with the local magnetic field, a compass is a great way to "see" magnetic field lines.

North and south poles

The origin of the terms "north pole" and "south pole" of a magnet comes from the direction that a magnetized compass needle points. The end of the magnet that pointed toward geographic north was called the magnet's north pole and the opposite pole was called south. The names were decided long before people truly understood how a compass needle worked.



Geographic and magnetic poles

The true *geographic* north and south poles are where the Earth's axis of rotation intersects its surface. Earth's *magnetic* poles are defined by the planet's magnetic field. When you use a compass, the north-pointing end of the needle points toward a spot near (but not exactly at) Earth's geographic north pole. That means the *south magnetic pole* of the planet is near the north geographic pole. The Earth has a planetary magnetic field that acts as if the core of the planet contained a giant magnet oriented like the diagram above.

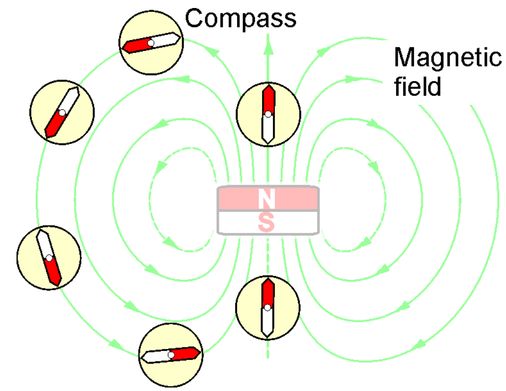


Figure 16.14: *A compass needle lines up with a magnetic field.*

Some animals have biological compasses

Many animals, including species of birds, frogs, fish, turtles, and bacteria, can sense the planet's magnetic field. Migratory birds are the best known examples. Magnetite, a magnetic mineral made of iron oxide, has been found in bacteria and in the brains of birds. Tiny crystals of magnetite may act like compasses and allow these organisms to sense the small magnetic field of Earth. Samples of magnetite are common in rock collections or kits.

Magnetic declination and "true north"

Magnetic declination

Because Earth's geographic north pole (true north) and magnetic south pole are not located at the exact same place, a compass will not point *directly* to the geographic north pole. Depending on where you are, a compass will point slightly east or west of true north. The difference between the direction a compass points and the direction of true north is called **magnetic declination**. Magnetic declination is measured in degrees and is indicated on topographical maps.

Finding true north with a compass

Most good compasses contain an adjustable ring with a degree scale and an arrow that can be turned to point toward the destination on a map (Figure 16.15). The ring is turned the appropriate number of degrees to compensate for the declination. Suppose you are using a compass and the map shown below and you want to travel directly north. You do not simply walk in the direction of the compass needle. To go north, you must walk in a direction 16 degrees west of the way the needle points.

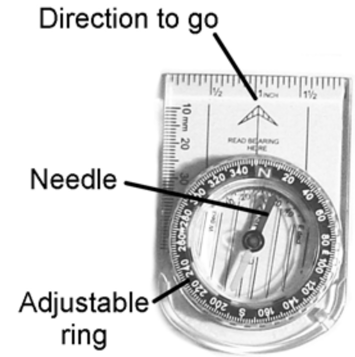
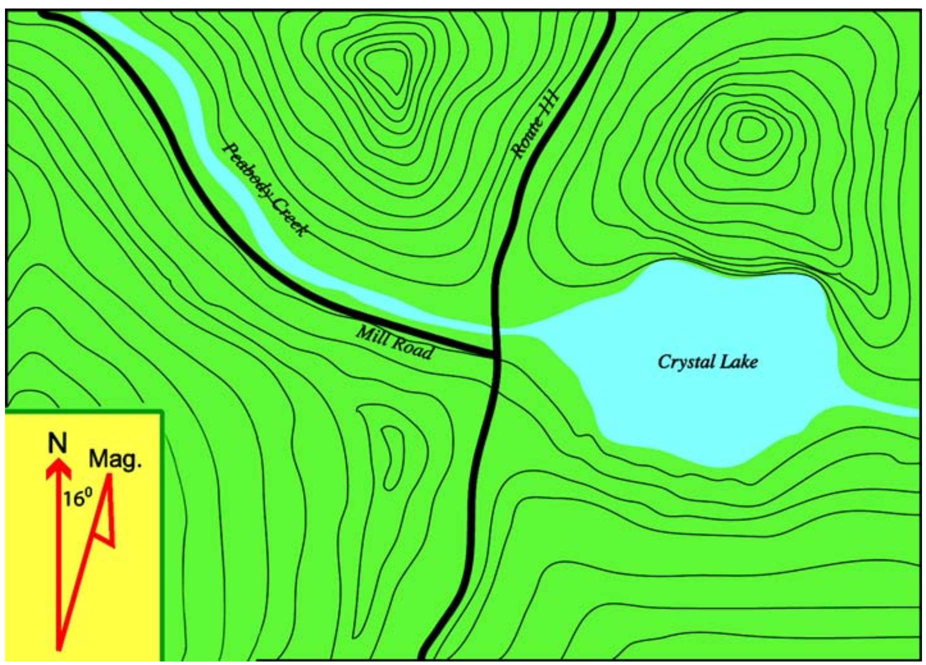


Figure 16.15: *Most compasses have an adjustable ring with a degree scale and an arrow that can be turned to a point toward the destination on a map.*



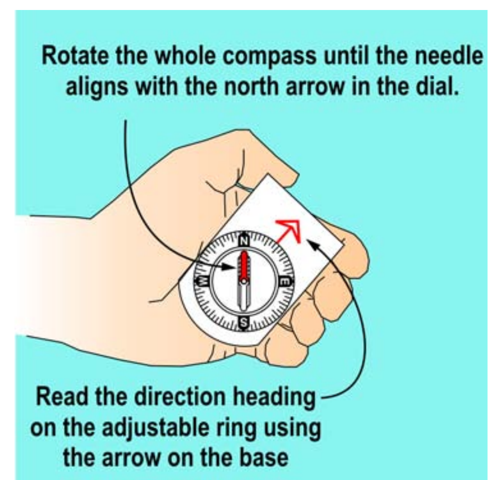


Figure 16.16: *Reading a direction heading (angle) from a compass*

The source of the Earth's magnetism

Earth's magnetic core While Earth's core is magnetic, we know it is not a solid permanent magnet. Studies of earthquake waves reveal that the Earth's core is made of hot, dense molten iron, nickel, and possibly other metals that slowly circulate around a solid inner core (Figure 16.17). Huge electric currents flowing in the molten iron produce the Earth's magnetic field, much like a giant electromagnet.

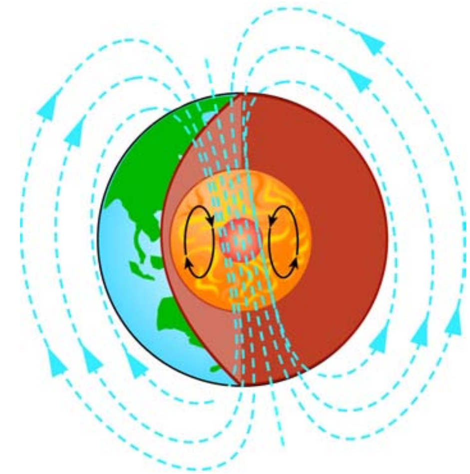


Figure 16.17: *Scientists believe moving charges in the molten core create Earth's magnetic field.*

The strength of Earth's magnetic field The magnetic field of Earth is weak compared to the field near the ceramic magnets you have in your classroom. For this reason you cannot trust a compass to point north if any other magnets are close by. The **gauss** is a unit used to measure the strength of a magnetic field. A small ceramic permanent magnet has a field between 300 and 1,000 gauss at its surface. By contrast, the magnetic field averages about 0.5 gauss at Earth's surface.

Reversing poles Historical data shows that both the strength of the planet's magnetic field and the location of the north and south magnetic poles change over time. Studies of magnetized rocks in Earth's crust provide evidence that the poles have reversed many times over the last tens of millions of years. The reversal has happened every 500,000 years on average. The last field reversal occurred roughly 750,000 years ago so Earth is overdue for another switch of the planet's north and south magnetic poles.

The next reversal Today, Earth's magnetic field is losing approximately 7 percent of its strength every 100 years. We do not know whether this trend will continue, but if it does, the magnetic poles will reverse sometime in the next 2,000 years. During a reversal, Earth's magnetic field would not completely disappear. However, the main magnetic field that we use for navigation would be replaced by several smaller fields with poles in different locations.

Movements of the magnetic poles The location of Earth's magnetic poles is always changing—slowly—even between full reversals. Currently, the magnetic south pole (to which the north end of a compass points) is located about 1,000 kilometers (600 miles) from the geographic north pole (Figure 16.18).

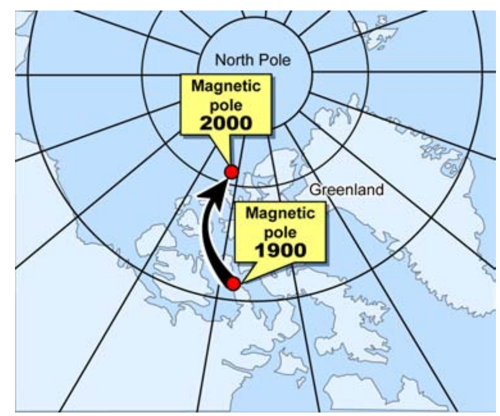


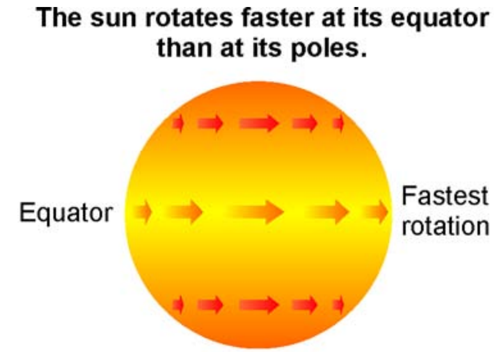
Figure 16.18: *The location of magnetic north changes over time. Magnetic north is where a compass needle points, and is actually Earth's magnetic south pole.*

Magnetism in stars and planets

Planets and moons Magnetism is created by moving electric charge. Like the Earth, other planets in the Solar System also have magnetic fields. In the case of Jupiter the magnetic field is very strong and was mapped by the Cassini spacecraft Smaller bodies like the Moon do not have much magnetic field. The Moon is too small and cold to have a hot, liquid core.

The sun's magnetic field Even stars have magnetic fields. Our most important star, the sun, has a strong magnetic field. Like Earth, the sun also rotates with a "day" of about 25 Earth days. Because the sun is not solid, different parts of the sun rotate at different rates. The sun rotates once every 25 days at its "equator" but takes 35 days to rotate once near its poles. The sun's uneven rotation twists the magnetic field lines. Every so often, the magnetic field lines become so twisted they "snap" and reconnect themselves. This sudden change causes huge solar storms where great eruptions of hot gas flare up from the sun's surface (Figure 16.19). The energy released by the sun's magnetic storms is great enough to disrupt radio and cell phone signals here on Earth. Magnetism also causes sunspots, regions of relative darkness on the sun's surface.

Energy for the Earth's field The electrical currents that create Earth's magnetic field would quickly stop flowing if energy were not constantly being added. As the Earth moves in its orbit around the sun, its magnetic field acts like a giant net, sweeping up free electrons and protons flowing out from the sun. These charged particles create an electrical current that flows in and out through the planet's poles. This current in turn feeds energy into the planet's core, driving the currents that maintain the Earth's magnetic field.



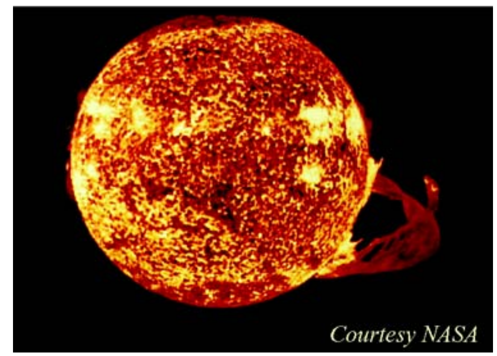


Figure 16.19: *The sun rotates unevenly because it is not solid, but a ball of hot gas. This twists the sun's magnetic field resulting in both sunspots and also huge magnetic storms (lower photo).*

16.3 Section Review

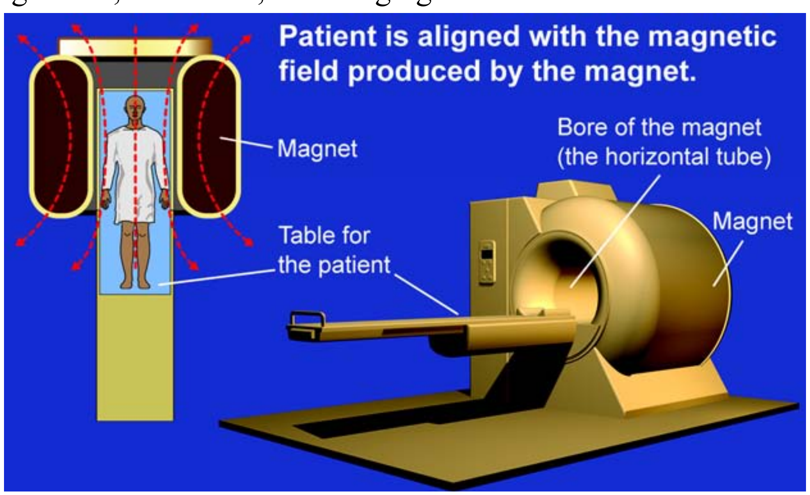
1. Describe one of the early compasses people used to indicate direction.
2. How does a compass respond when it is placed in the magnetic field of a bar magnet?
3. What is the cause of Earth's magnetism?
4. Is Earth's magnetic north pole at the same location as the geographic north pole?

What is an MRI Scanner?

Has anyone ever told you that you have a magnetic personality? Well, here's a machine with one—an MRI scanner. MRI stands for Magnetic Resonance Imaging—a device that uses magnetism and radio waves to scan all or part of a body that may be sick or injured.

Unlike X rays, which have been around for over 100 years, the MRI scanner is a relatively new medical diagnostic tool, having first been used in 1977. The first MRI scanners were very large and intimidating, extremely loud, and slow with a single scan taking several hours. Fortunately, these machines have come a long way. Although they still are still large and loud, they are faster, and produce better results in diagnosing illness and injury.

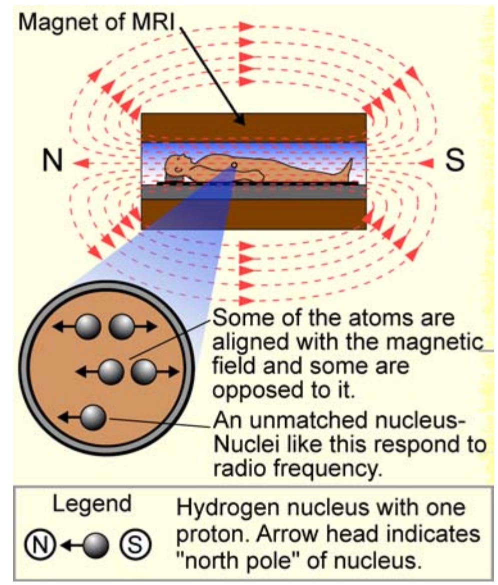
MRIs are especially valuable as diagnostic tools because they are non-invasive. In other words, information about a person's body can be obtained without probes or cutting tissue. You may be wondering how an MRI "sees" inside a sick or injured body. This device uses magnetism, radio waves, and a lot of computer power to create images. To understand how the MRI works, let's examine each concept represented in the name of this technology—magnetism, resonance, and imaging.



The role of magnetism

MRIs contain powerful magnets. The strength of common magnets such as ones found in motors or sound speakers ranges from a few hundred to a few thousand gauss. A *gauss* is a unit used to measure the strength of a magnetic field. The magnets in MRIs range from 5,000 to 20,000 gauss. Since 10,000 gauss equals 1 tesla, this translates to 0.5 to 2.0 tesla. In comparison, the strength of Earth's magnetic field is 0.3 to 0.5 gauss or 3×10^{-4} to 5×10^{-4} tesla.

There are two kinds of magnets used in an MRI. The main magnet creates a very strong magnetic field. The gradient magnets create a changing magnetic field.



The main magnet is used to temporarily "polarize" the nuclei of certain atoms in parts of the body. These atoms become tiny magnets in the body with a north and south pole. This process is similar to how an iron nail can be "magnetized" by rubbing a magnet along its length in one direction. Actually, all substances are capable of becoming internally "polarized" to some extent under the right conditions. This phenomenon is what makes an MRI work.

Some of the nuclei in a certain part of the body line up with the MRI magnetic field and some oppose it. Aligned and opposing nuclei cancel each other. Nuclei that are not cancelled are used to create the MRI image.

The role of the gradient magnets within the main magnet is to locate a particular area of the body to be imaged. The gradient magnets turn on and off quickly and cause changes in the magnetic field where a specific part of the body or a specific plane or "slice" of the body occurs. Unlike an X ray or CT scanner, which can only take scans of one plane at a time, the gradient magnets can take slices at virtually any angle. This not only produces a detailed picture of that slice, but image slices can be combined to form a two-dimensional (2-D) or three-dimensional (3-D) images.

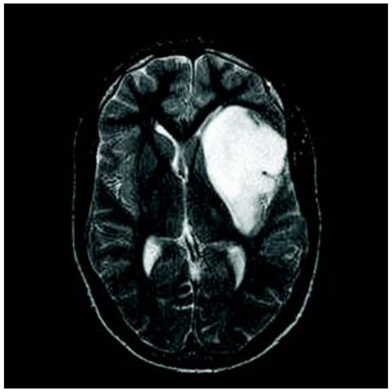
The role of resonance

The effects of the main magnet and the gradient magnets set up conditions for creating an MRI scanner image using resonance. Resonance describes how an object responds when it receives a pulse of energy at its natural frequency. At its natural frequency, the object oscillates easily or "resonates." For example, if you speak into the sound box of a piano, some of the frequencies that make up your voice will match the natural frequencies of some of the strings, and set them oscillating!

For an MRI, radio waves, oscillating at thousands or even millions of cycles per second, are first produced by the on/off oscillations of an electrical current through a series of coils. The frequency of these oscillations (in the radio frequency part of the electromagnetic spectrum, or RF) is set to match the natural frequency of the nuclei of common elements found in the body, like hydrogen, carbon, or calcium. When the nuclei of atoms in the body absorb this specific energy, they too (like the strings in the piano) vibrate as they absorb and release energy.

The nuclei that respond to the RF are unmatched. The energy they absorb causes them to resonate and change their alignment in the magnetic field. When the RF is turned off, the unmatched nuclei return to their positions and give off energy which is captured by the MRI and used to make the final image.

Making images



Energy signals that are released by the unmatched nuclei are received by the coils are recorded as bits of mathematical data. This data is used to map the density of the particular atoms responding to the RF signal. A computer assembles the data and creates such a map and sends it to either a screen or film. The result is a clear, detailed picture of a part or "slice" of the body.

MRIs are commonly used to visualize, diagnose, and evaluate many abnormalities anywhere in the body due to disease or injury. As MRIs become more advanced, we will be able to use this wonderful application of physics to learn more about how the brain functions, how serious diseases develop and grow within the body, and how best to treat injured bone, tissue, and cartilage.

Questions:

1. What is the role of the main magnet in an MRI? What is the role of the gradient magnets?
2. In MRI technology what is it that resonates with radio waves that helps produce an MRI scanner image?
3. Imagine you had a choice of getting an MRI, a CAT scan, or an X ray. Research and describe what each procedure involves. List the pros and cons of each procedure. Which is the least expensive? Which is the most expensive?
4. MRI scanners are very safe devices. However, they do produce very strong magnetic fields that powerfully attract metal objects. Research the precautions that MRI facilities use when the strong magnetic field is turned on.

Chapter 16 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

electromagnet	magnetic field	magnetic poles
right-hand rule	magnetic domains	diamagnetic
compass	magnetic declination	paramagnetic
soft magnet	permanent magnet	ferromagnetic
gauss		

Section 16.1

1. A _____ keeps its magnetic properties even when it is not near other magnets.
2. Every magnet has two _____.
3. A _____ is present in the region around a magnet.

Section 16.2

4. A(n) _____ is a magnet created by electric current in a wire.
5. You can use the _____ to figure out the locations of an electromagnet's poles.
6. A material that is _____ has the same number of electrons spinning in each direction, so there is no overall magnetic field.
7. In ferromagnetic materials, groups of atoms with the same magnetic alignment create _____.
8. _____ materials such as iron can create permanent magnets.
9. _____ materials are very weakly magnetic because electrons are randomly arranged.
10. A _____ quickly loses its magnetism when taken out of a magnetic field.

Section 16.3

11. The _____ is a unit used to measure the strength of magnetic fields.
12. A _____ is simply a permanent magnet that is free to spin.
13. The difference between the way a compass points and the direction of true north is called _____.

Reviewing Concepts

Section 16.1

1. What is a magnetic material able to do?
2. Suppose you stick a magnet on the door of your refrigerator. Is the magnet a magnetic material or a permanent magnet? Is the refrigerator door a magnetic material or permanent magnet? Explain.
3. Is it possible to have a south pole without a north pole or a north pole without a south pole? Explain.
4. What happens to a magnet if it is cut in half?
5. Two magnetic north poles _____ each other. Two south poles _____ each other. A north pole and a south pole _____ each other.
6. Can magnetic forces pass through non-magnetic materials?
7. List three uses for magnetism.
8. What describes the magnetic force in the space around a magnet?
9. Draw a bar magnet and sketch the magnetic field lines around it. Include arrows to show the direction of the lines.
10. Magnetic field lines outside a magnet point away from its _____ pole and toward its _____ pole.
11. What information can you get by looking at the spacing of magnetic field lines?
12. What happens to the strength of the magnetic field as you move away from a magnet?

Section 16.2

13. Explain the design of a simple electromagnet.
14. What is the purpose of the core of an electromagnet?
15. Explain how you can use the right-hand rule to determine the location of an electromagnet's poles.
16. What happens to an electromagnet's field if the current is increased?
17. What happens to an electromagnet's field if the direction of the current is reversed?

18. Describe two ways you could increase the strength of an electromagnet without increasing the current.
19. Why is it not always the best idea to increase an electromagnet's strength by simply increasing the current?
20. What advantages do electromagnets have over permanent magnets when used in machines?
21. Are diamagnetic materials magnetic? Why or why not?
22. Are paramagnetic materials magnetic? Why or why not?
23. What happens inside a paramagnetic material if a permanent magnet is brought close to it? What happens when the permanent magnet is removed?
24. List three ferromagnetic materials.
25. What are magnetic domains?
26. Which materials are more strongly magnetic, ferromagnetic or paramagnetic? Why?
27. Describe how to create a permanent magnet from a ferromagnetic material.
28. What is the difference between hard magnets and soft magnets?
29. Which is easier to magnetize, a hard magnet or a soft magnet? Once magnetized, which is easier to demagnetize?
30. List several ways to demagnetize a permanent magnet.

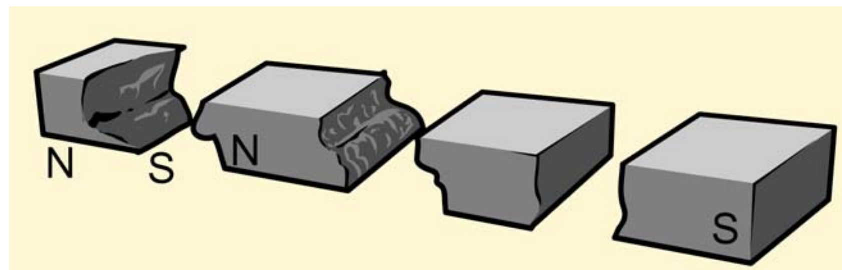
Section 16.3

31. For what purpose did people first use magnetism?
32. Describe the design of two early compasses.
33. Explain why the two ends of a magnet are called "north pole" and "south pole."
34. Is Earth's magnetic north pole at its geographic north pole? Explain.
35. Why does a compass point north?
36. Why is it important to know the magnetic declination in a region where you are using a compass to navigate?
37. How does the strength of Earth's field compare to the strength of the field of average permanent magnets?
38. What material is at the core of Earth?
39. What do scientists believe is the source of Earth's magnetism?
40. What has happened to the strength and location of Earth's magnetic field in the past?
41. If the current trend continues, how long do scientists think it will take for Earth's magnetic poles to reverse again?

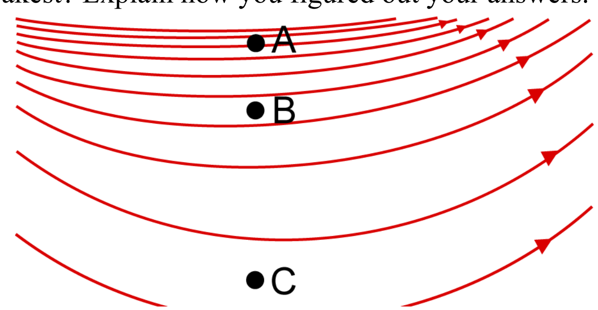
Solving Problems

Section 16.1

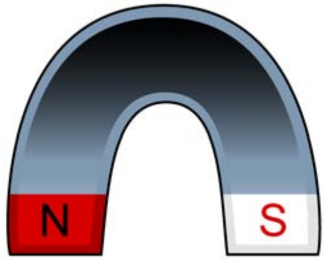
1. A student knocked a ceramic permanent magnet off her desk, and it shattered when it hit the floor. Copy the broken pieces and label the north and south poles on each one.



2. The diagram below shows the magnetic field in a region. The source of the field is not shown. At which of the labeled points in the diagram below is the magnetic field the strongest? At which point is it the weakest? Explain how you figured out your answers.

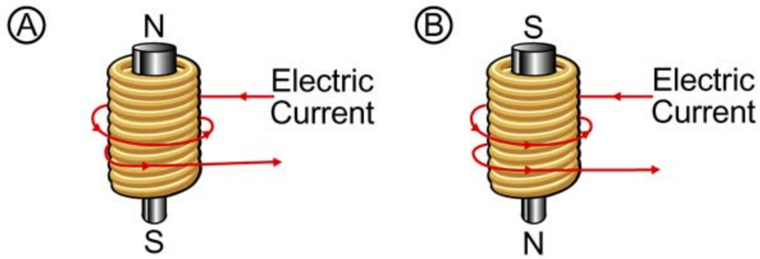


3. A horseshoe magnet is shown to the right. Copy the picture of the magnet and draw the magnetic field lines around it.



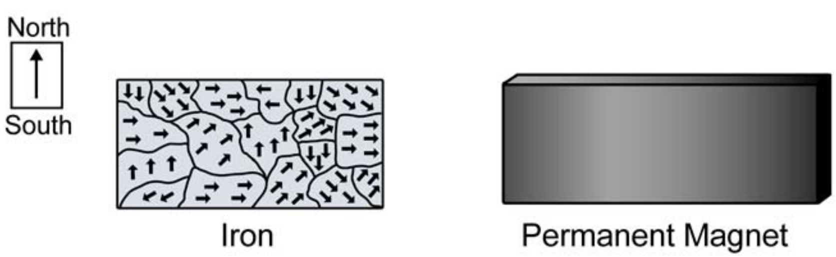
Section 16.2

4. Which picture below shows the correct location of the north and south poles of the electromagnet? Choose A or B and explain how you arrived at your choice.



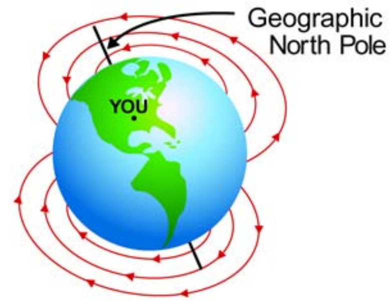
5. A permanent magnet attracts a steel pin as shown to the right. The pin has become a soft magnet. Copy the picture and then use what you know about magnetism to label the north and south poles of the pin.

6. A strong permanent magnet is brought near a piece of iron. Magnetic domains are created as shown below. Which pole of the permanent magnet is closest to the iron?



Section 16.3

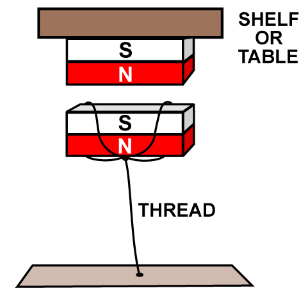
7. Suppose Earth's magnetic field were to change so it looks like the picture to the right. If you stand at the marked point, in which direction will your compass needle point? What is the approximate magnetic declination at this point?



Applying Your Knowledge

Section 16.1

1. A story dating back 2,300 years describes Ptolemy Philadelphos' attempt at using magnetism. He had the dome of a temple at Alexandria made of magnetite and tried to suspend a statue of himself in midair. The experiment failed. However, you can use magnetism to suspend a small magnet by building a device like the one shown here. The upper magnet is fixed to a shelf or table. The lower one is held down with a thread. See how far apart you can position the magnets and still have the lower one levitate.



Section 16.2

2. Magnetically levitated or "maglev" trains use electromagnets to raise the train cars above the tracks to reduce friction. Research to find out where maglev trains are used and how they work.

Section 16.3

3. You can easily build your own compass using a sewing needle, permanent magnet, piece of cork or styrofoam, and dish of water. Run the magnet many times along the length of the needle, always in the same direction. Float a piece of cork or styrofoam in a cup of water. Place the needle on top of it and give it a gentle spin. When it stops, it will be lined up with Earth's magnetic field.

4. Find out the magnetic declination where you live.