Fig. 36-1 Which interaction has the greater strength—the gravitational attraction between the scrap iron and the earth, or the magnetic attraction between the magnet and the scrap iron?

36.1 Magnetic Poles

Magnets exert forces on one another. They are similar to electric charges, for they can both attract and repel without touching one another, depending on which ends of the magnets are held near one another. Like electric charges also, the strength of their interaction depends on the distance of separation of the two magnets. Whereas electric charges produce electrical forces, regions called **magnetic poles** produce magnetic forces.

If you suspend a bar magnet from its center by a piece of string, it will act as a compass. The end that points northward is called the *north-seeking pole*, and the end that points southward is called the *south-seeking pole*. More simply, these are called the *north* and *south poles*. All magnets have both a north and a south pole. For a simple bar magnet these are located at the two ends. The common horseshoe magnet is a bar magnet that has been bent, so its poles are also at its two ends.

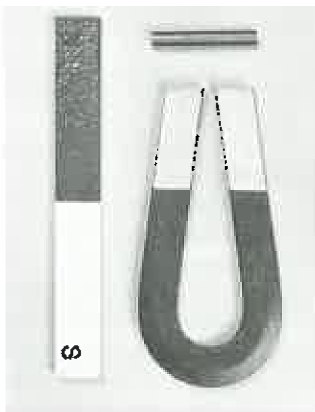

Fig. 36-2 Common magnets.

If the north pole of one magnet is brought near the north pole of another magnet, they repel. The same is true of a south pole

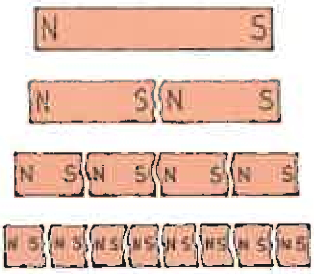

Fig. 36-3 Break a magnet in half and you have two magnets. Break these in half and you have four magnets, each with a north and south pole. Keep breaking the pieces further and further and you find the same results. Magnetic poles exist in pairs.

near a south pole. If opposite poles are brought together, however, attraction occurs.*

Like poles repel; opposite poles attract.

Magnetic poles behave similarly to electric charges in some ways, but there is a very important difference. Whereas electric charges can be isolated, magnetic poles cannot. Electrons and protons are entities by themselves. A cluster of electrons need not be accompanied by a cluster of protons, and vice versa. But a north magnetic pole never exists without the presence of a south pole, and vice versa. The north and south poles of a magnet are like the head and tail of the same coin.

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

▶ **Question**

Does every magnet necessarily have a north and south pole?

36.2 Magnetic Fields

Place a sheet of paper over a bar magnet and sprinkle iron filings on the paper. The filings will tend to trace out an orderly pattern of lines that surround the magnet. The space around a magnet, in which a magnetic force is exerted, is filled with a **magnetic field**. The shape of the field is revealed by *magnetic field lines*. Magnetic field lines spread out from one pole, curve around the magnet, and return to the other pole.

▶ **Answer**

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

* The force of interaction between magnetic poles is given by $F \sim pp'/d^2$, where p and p' represent magnetic pole strengths, and d represents the separation distance between them. Note the similarity of this relationship with Coulomb's law.

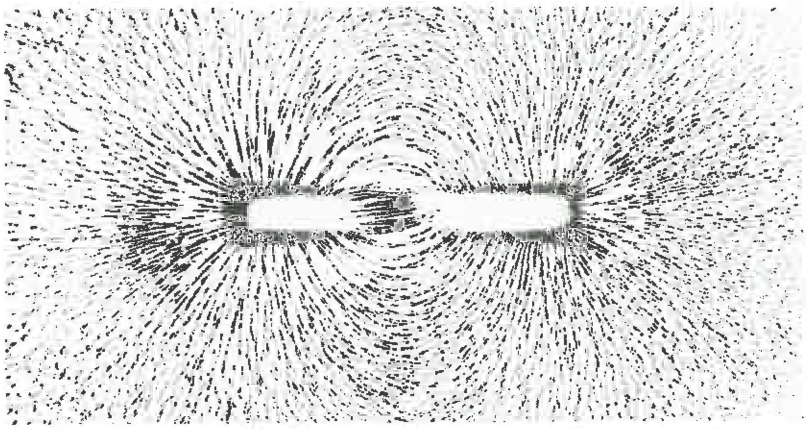

Fig. 36-4 Iron filings trace out a pattern of magnetic field lines in the space surrounding the magnet.

The direction of the field outside the magnet is from the north to the south pole. Where the lines are closer together, the field strength is greater. We see the magnetic field strength is greater at the poles. If we place another magnet or a small compass anywhere in the field, its poles will tend to line up with the magnetic field.

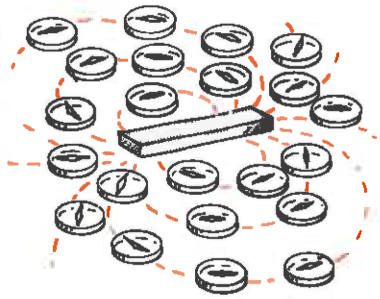

Fig. 36-5 Like the iron filings, the compasses line up with the magnetic field lines.

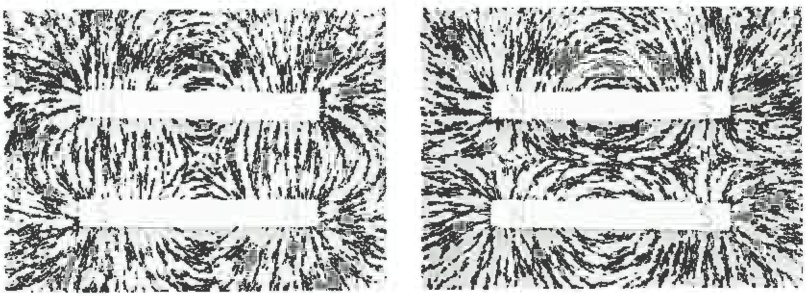

Fig. 36-6 The magnetic field patterns for a pair of magnets when (left) opposite poles are parallel to each other, and (right) like poles are parallel to each other.

36.3 The Nature of a Magnetic Field

Magnetism is very much related to electricity. Just as an electric charge is surrounded by an electric field, the same charge is also surrounded by a magnetic field if it is moving. This is due to "distortions" in the electric field caused by motion, and was explained by Albert Einstein in 1905 in his theory of special relativity. This text will not go into the details, except to acknowledge that a magnetic field is a relativistic byproduct of the electric field. Charges in motion have associated with them both an electric and a magnetic field. A magnetic field is produced by the motion of electric charge.*

Where is the motion of electric charges in a common bar magnet? Although the magnet as a whole may be stationary, it is composed of atoms whose electrons are in constant motion. Electrons behave as if they move in orbits about the atomic nuclei. This moving charge constitutes a tiny current and produces a magnetic field. More important, electrons spin about their own axes like tops. A spinning electron constitutes a charge in motion and thus creates another magnetic field. In most materials, the field due to spinning is predominant over the field due to orbital motion.

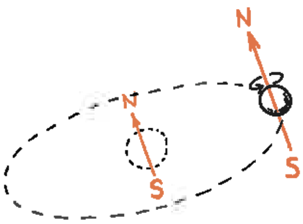

Fig. 36-7 Both the orbital motion and the spinning motion of every electron in an atom produce magnetic fields. These fields combine constructively or destructively to produce the magnetic field of the atom. The resulting field is greatest for iron atoms.

Every spinning electron is a tiny magnet. A pair of electrons spinning in the same direction makes up a stronger magnet. A pair of electrons spinning in opposite directions, however, has the opposite effect. The magnetic fields of each cancel the other. This is why most substances are not magnets. In most atoms, the various fields cancel each other because the electrons spin in opposite directions. In materials such as iron, nickel, and cobalt, however, the fields do not cancel each other entirely. Each iron atom has four electrons whose spin magnetism is uncanceled. Each iron atom, then, is a tiny magnet. The same is true to a lesser degree for the atoms of nickel and cobalt.**

36.4 Magnetic Domains

The magnetic field of individual iron atoms is so strong that interactions among adjacent iron atoms cause large clusters of them to line up with each other. These clusters of aligned atoms are called **magnetic domains**. Each domain is perfectly magnetized, and is made up of billions of aligned atoms. The domains are microscopic (Figure 36-8), and there are many of them in a crystal of iron.

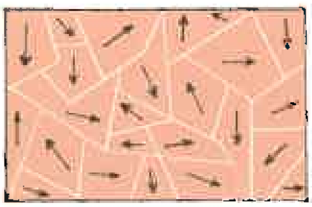

Fig. 36-8 A microscopic view of magnetic domains in a crystal of iron. Each domain consists of billions of aligned iron atoms.

* Interestingly enough, since motion is relative, the magnetic field is relative. For example, when a charge moves by you, there is a definite magnetic field associated with the moving charge. But if you move along with the charge so that there is no motion relative to you, you will find no magnetic field associated with the charge. Magnetism is relativistic.

** Most common magnets are made from alloys containing iron, nickel, cobalt, and aluminum in various proportions. In these the electron spin contributes virtually all the magnetic properties. In the rare-earth metals, such as gadolinium, the orbital motion is more significant.

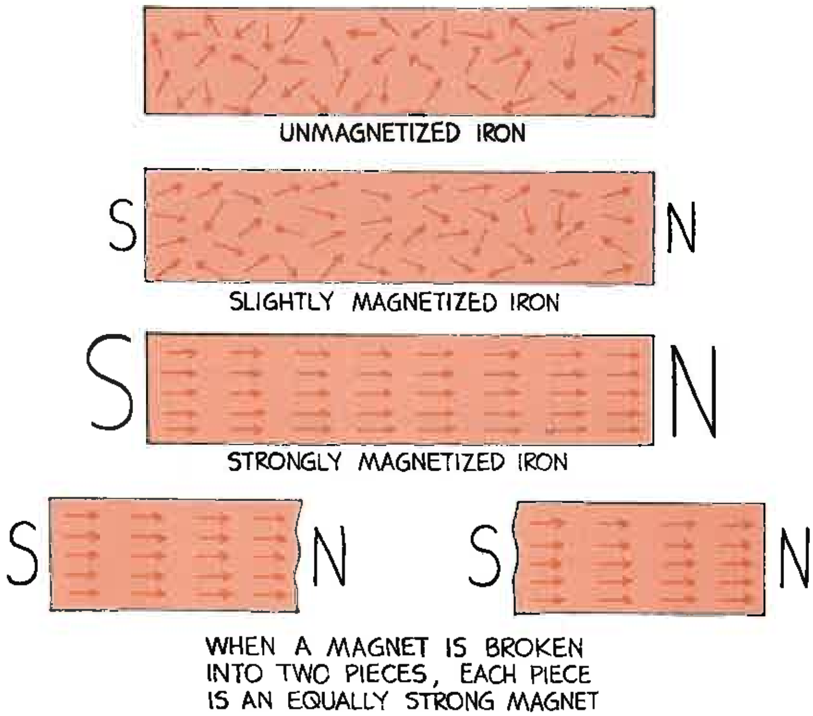

Fig. 36-9 A piece of iron in successive stages of magnetism. The arrows represent domains, where the head is a north pole and the tail a south pole. Poles of neighboring domains neutralize each other's effects, except at the ends.

The difference between a piece of ordinary iron and an iron magnet is the alignment of domains. In a common iron nail, the domains are randomly oriented. When a strong magnet is brought nearby, two effects take place. One is a growth in size of domains that are oriented in the direction of the magnetic field. This growth is at the expense of domains that are not aligned. The other effect is a rotation of domains as they are induced into alignment. The domains become aligned much as electric charges in a piece of paper are aligned in the presence of a charged rod. When you remove the nail from the magnet, ordinary thermal motion causes most or all of the domains in the nail to return to a random arrangement.

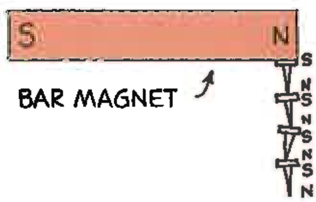

Fig. 36-10 The iron nails become induced magnets.

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

▶ Questions

1. How can a magnet attract a piece of iron that is not magnetized?
2. The iron filings sprinkled on the paper that covers the magnet in Figure 36-4 were not initially magnetized. Why, then, do they line up with the magnetic field of the magnet?

36.5 Electric Currents and Magnetic Fields

A moving charge produces a magnetic field. Many charges in motion—an electric current—also produce a magnetic field. The magnetic field that surrounds a current-carrying conductor can be demonstrated by arranging an assortment of magnetic compasses around a wire (Figure 36-11) and passing a current through it. The compasses line up with the magnetic field produced by the current and show it to be a pattern of concentric circles about the wire. When the current reverses direction, the compasses turn completely around, showing that the direction of the magnetic field changes also.

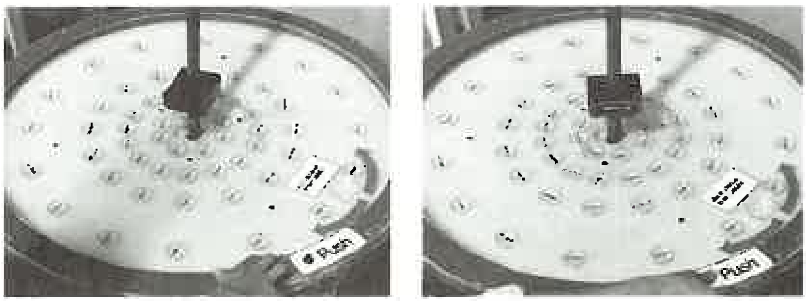

Fig. 36-11 (Left) When there is no current in the wire, the compasses align with the earth's magnetic field. (Right) When there is a current in the wire, the compasses align with the stronger magnetic field about the wire. The magnetic field about the wire forms concentric circles.

▶ Answers

1. Domains in the unmagnetized piece of iron are induced into alignment by the magnetic field of the nearby permanent magnet. See the similarity of this with Figure 32-12 back in Chapter 32. Like the pieces of paper, pieces of iron will jump to a strong magnet when it is brought nearby. But unlike the paper, they are not repelled. Can you think of the reason why?
2. Domains align in the individual filings, causing them to act like tiny compasses. The poles of each "compass" are pulled in opposite directions, producing a torque that twists each filing into alignment with the external magnetic field.

If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop (Figure 36-12). If the wire is bent into another loop, overlapping the first, the concentration of magnetic field lines inside the double loop is twice as much as in the single loop. It follows that the magnetic field intensity in this region is increased as the number of loops is increased. The magnetic field intensity is appreciable for a current-carrying coil of wire with many loops.

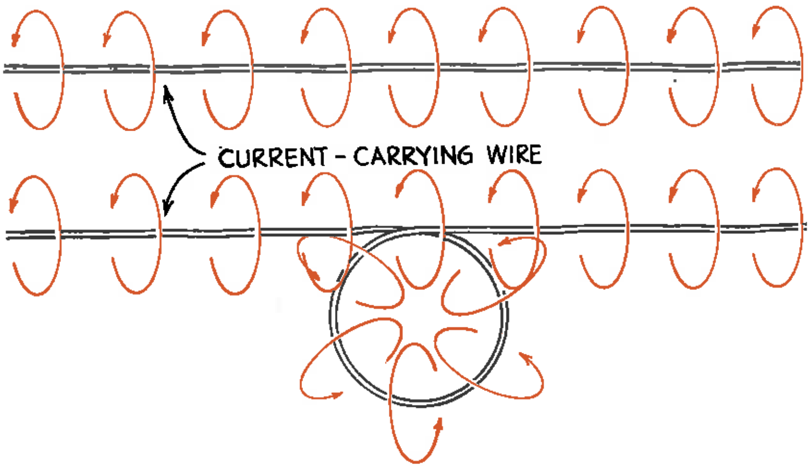

Fig. 36-12 Magnetic field lines about a current-carrying wire crowd up when the wire is bent into a loop.

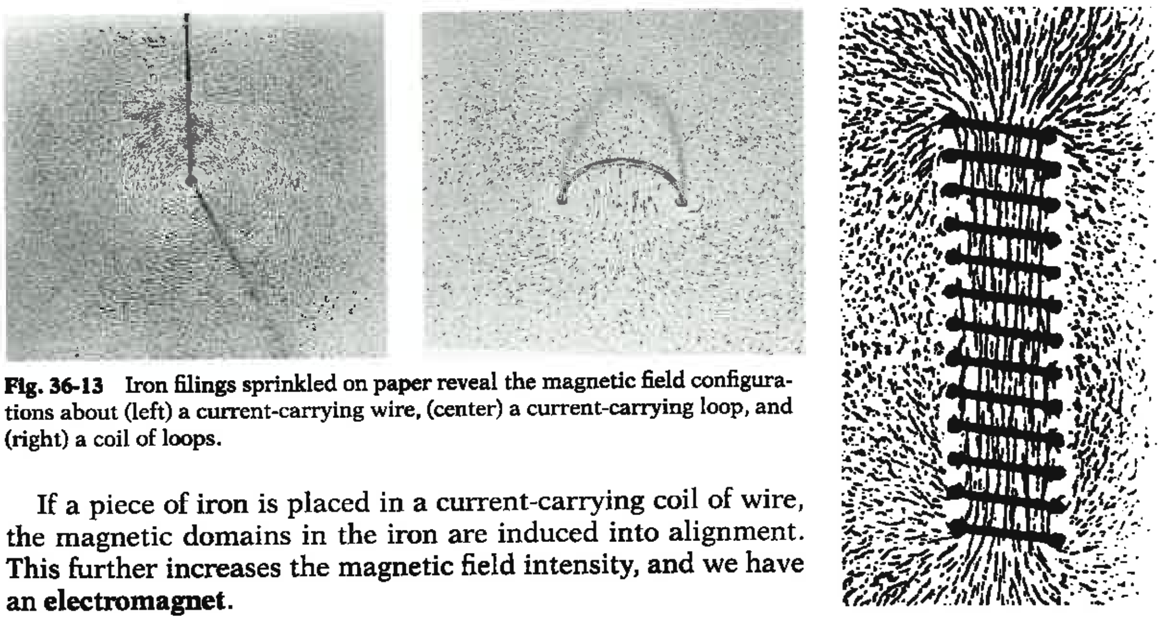

Fig. 36-13 Iron filings sprinkled on paper reveal the magnetic field configurations about (left) a current-carrying wire, (center) a current-carrying loop, and (right) a coil of loops.

If a piece of iron is placed in a current-carrying coil of wire, the magnetic domains in the iron are induced into alignment. This further increases the magnetic field intensity, and we have an **electromagnet**.

Powerful electromagnets, some cooled to temperatures low enough for them to become superconducting, are used for research purposes. These magnets are used to control charged particle beams in high-energy accelerators. More impressively, electromagnets can levitate and propel high-speed trains.

Fig. 36-14 Conventional trains vibrate as they ride on rails at high speeds. This Japanese magnetically levitated train is capable of vibration-free high speeds, even in excess of 200 km/h.

36.6 Magnetic Forces on Moving Charged Particles

A charged particle at rest will not interact with a static magnetic field. But if the charged particle *moves* in a magnetic field, the magnetic character of its motion becomes evident. It experiences a deflecting force.* The force is greatest when the particle moves in a direction perpendicular to the magnetic field lines. At other angles, the force is less; it becomes zero when the particle moves parallel to the field lines. In any case, the direction of the force is always perpendicular to both the magnetic field lines and the velocity of the charged particle (Figure 36-15). So a moving charge is deflected when it crosses magnetic field lines but not when it travels parallel to the field.

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

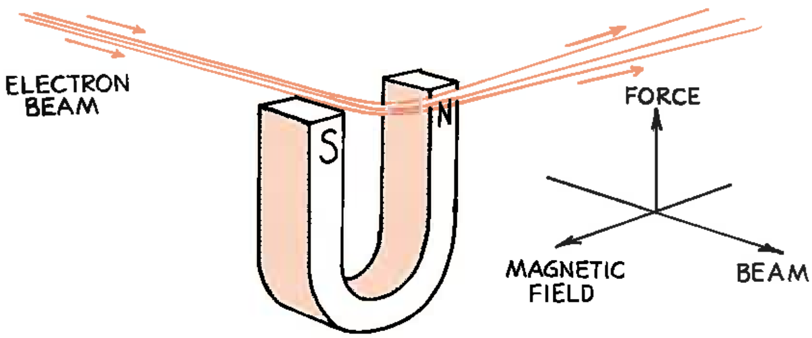

Fig. 36-15 A beam of electrons is deflected by a magnetic field.

This sideways deflecting force is very different from the forces that occur in other interactions, such as the force of gravitation between masses, the electrostatic force between charges, and the force between magnetic poles. The force that acts on a moving charged particle does not act in a direction between the sources of interaction, but instead acts perpendicular to both the magnetic field and the electron beam.

It's nice that charged particles are deflected by magnetic fields, for this fact is employed to spread electrons onto the inner surface of a TV tube and provide a picture. More importantly, charged particles from outer space are deflected by the earth's magnetic field. The harmful cosmic rays bombarding the earth's surface would be much more intense otherwise.

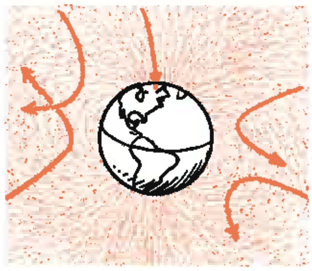

Fig. 36-16 The magnetic field of the earth deflects many charged particles that make up cosmic radiation.

36.7 Magnetic Forces on Current-Carrying Wires

Simple logic tells you that if a charged particle moving through a magnetic field experiences a deflecting force, then a current of charged particles moving through a magnetic field also experiences a deflecting force. If the particles are trapped inside a wire when they respond to the deflecting force, the wire will also move (Figure 36-17).

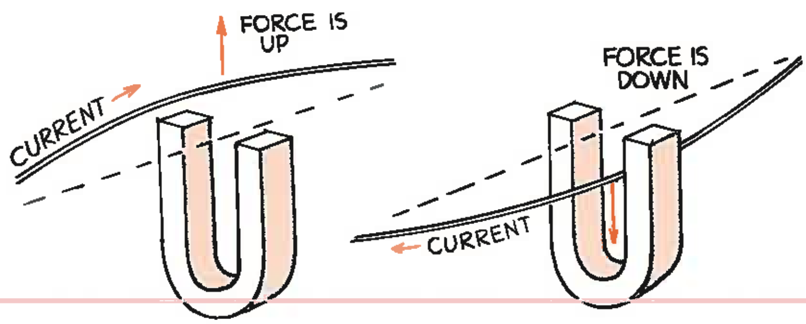

Fig. 36-17 A current-carrying wire experiences a force in a magnetic field. (Can you see that this is a simple extension of Figure 36-15?)

If the direction of current is reversed, the deflecting force acts in the opposite direction. The force is maximum when the current is perpendicular to the magnetic field lines. The direction of force is along neither the magnetic field lines nor the direction of current. The force is perpendicular to both field lines and current. It is a sideways force.

So just as a current-carrying wire will deflect a magnetic compass, as discovered by Oersted in his high school classroom in 1820, a magnet will deflect a current-carrying wire. Both cases show different effects of the same phenomenon. This discovery created much excitement, for almost immediately people began harnessing this force for useful purposes—with great sensitivity in electric meters, and with great force in electric motors.

36.8 Meters to Motors

The simplest meter to detect electric current is shown in Figure 36-18. It consists of a magnetic needle on a pivot at the center of a number of loops of insulated wire. When an electric current passes through the coil, each loop produces its own effect on the needle so that a very small current can be detected. A current-indicating instrument is called a *galvanometer*.

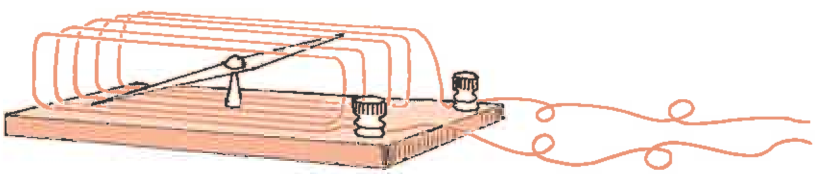

Fig. 36-18 A very simple galvanometer.

A more common design is shown in Figure 36-19. It employs more loops of wire and is therefore more sensitive. The coil is mounted for movement and the magnet is held stationary. The coil turns against a spring, so the greater the current in its loops, the greater its deflection.

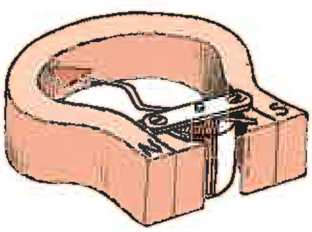

Fig. 36-19 A common galvanometer design.

A galvanometer may be calibrated to measure current (amperes), in which case it is called an *ammeter*. Or it may be calibrated to measure electric potential (volts), in which case it is called a *voltmeter*.

If the design of the galvanometer is slightly modified, you have an electric motor. The principal difference is that the current is made to change direction every time the coil makes a half revolution. After it has been forced to rotate one half revolution,

Fig. 36-20 Both the ammeter and the voltmeter are basically galvanometers. (The electrical resistance of the instrument is made to be very low for the ammeter, and very high for the voltmeter.)

it overshoots just in time for the current to reverse, whereupon it is forced to continue another half revolution, and so on in cyclic fashion to produce continuous rotation.

A simple dc motor is shown in bare outline in Figure 36-21. A permanent magnet is used to produce a magnetic field in a region where a rectangular loop of wire is mounted so that it can turn about an axis as shown. When a current passes through the loop, it flows in opposite directions in the upper and lower sides of the loop. (It has to do this because if charge flows into one end of the loop, it must flow out the other end.) If the upper portion of the loop is forced to the left, then the lower portion is forced to the right, as if it were a galvanometer. But unlike a galvanometer, the current is reversed during each half revolution by means of stationary contacts on the shaft. The parts of the wire that brush against these contacts are called *brushes*. In this way, the current in the loop alternates so that the forces in the upper and lower regions do not change directions as the loop rotates. The rotation is continuous as long as current is supplied.

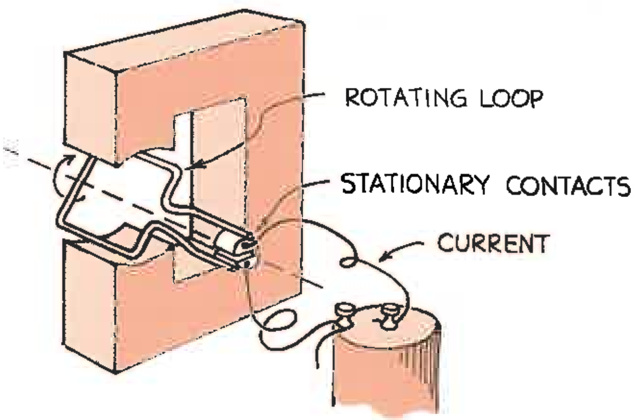

Fig. 36-21 A simplified dc motor.

Larger motors, dc or ac, are usually made by replacing the permanent magnet by an electromagnet that is energized by the power source. Of course, more than a single loop is used. Many loops of wire are wound about an iron cylinder, called an *armature*, which then rotates when energized with electric current.

Needless to say, the advent of electric motors saw the replacement of enormous human and animal toil the world over. Electric motors have greatly changed the way that people live.

▶ **Question**

How is a galvanometer similar to a simple electric motor? How is each fundamentally different?

36.9 The Earth's Magnetic Field

A compass points northward because the earth itself is a huge magnet. The compass aligns with the magnetic field of the earth. The magnetic poles of the earth, however, do not coincide with the geographical poles, nor are they very close to the geographical poles. The magnetic pole in the Northern Hemisphere, for example, is located nearly 1800 kilometers from the geographical North Pole, somewhere in the Hudson Bay region of northern Canada. The other magnetic pole is located south of Australia (Figure 36-22). This means that compasses do not generally point to true north. The discrepancy between the orientation of a compass and true north is known as the *magnetic declination*.

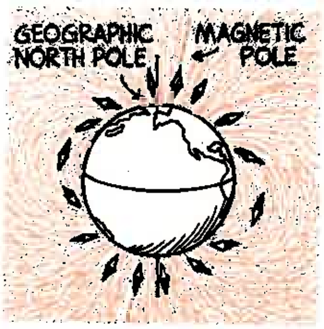

Fig. 36-22 The earth is a magnet.

It is not known exactly why the earth itself is a magnet. The configuration of the earth's magnetic field is like that of a strong bar magnet placed near the center of the earth. But the earth is not a magnetized chunk of iron like a bar magnet. It is simply too hot for individual atoms to remain aligned.

A better candidate for the earth's magnetic field are the currents in the molten part of the earth's core. About 2000 km below the outer rocky mantle (which itself is almost 3000 km thick) lies

▶ **Answer**

Both a galvanometer and a motor are similar in that they both employ coils positioned in a magnetic field. When a current passes through the coils, forces on the wires rotate the coils. The fundamental difference is that the maximum rotation of the coil in a galvanometer is one half turn, whereas in a motor the coil (armature) rotates through many complete turns. In the armature of a motor, the current is made to alternate with each half turn of the armature.

the molten part, which surrounds the solid center. Most earth scientists think that moving charges looping around within the earth create the magnetic field. Because of the earth's great size, the speed of moving charges would have to be less than one millimeter per second to account for the field.

Another candidate for the earth's magnetic field is convection currents that result from heat rising from the central core (Figure 36-23). Perhaps such convection currents combined with the rotational effects of the earth produce the earth's magnetic field. A firmer explanation awaits more study.

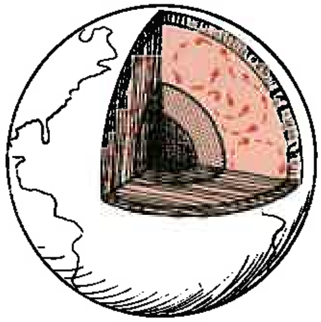

Fig. 36-23 Convection currents in the molten parts of the earth's interior may produce the earth's magnetic field.

Whatever the cause, the magnetic field of the earth is not stable, but has wandered throughout geological time. Evidence of this comes from analysis of the magnetic properties of rock strata. Iron atoms in a molten state tend to align themselves with the earth's magnetic field. When the iron solidifies, the direction of the earth's field is recorded by the orientation of the domains in the rock. The slight magnetism that results can be measured with sensitive instruments. As samples of rock from different strata formed throughout geologic time are tested, the magnetic field of the earth for different periods can be charted. The evidence from the rock shows that there have been times when the magnetic field of the earth has diminished to zero and then reversed itself.

More than twenty reversals have taken place in the past 5 million years. The most recent occurred 700 000 years ago. Prior reversals happened 870 000 and 950 000 years ago. Studies of deep sea sediments indicate that the field was virtually switched off for 10 000 to 20 000 years just over 1 million years ago. This was the time that modern humans emerged.

We cannot predict when the next reversal will occur because the reversal sequence is not regular. But there is a clue in recent measurements that show a decrease of over 5% of the earth's magnetic field strength in the last 100 years. If this change is maintained, we may well have another magnetic field reversal within 2000 years.

36 Chapter Review

Concept Summary

Magnetic forces are produced by north and south magnetic poles.

- Like poles repel; opposite poles attract.
- North and south poles always occur in pairs.

A magnetic field is produced by the motion of electric charge.

- In magnetic substances such as iron, the magnetic fields created by spinning electrons do not cancel each other out; large clusters of magnetic atoms align to form magnetic domains.
- In nonmagnetic substances, electron pairs within the atoms spin in opposite directions; there is no net magnetic field.

An electric current produces a magnetic field.

- Bending a current-carrying wire into coils intensifies the magnetic field.
- Placing a piece of iron into a current-carrying coil creates an electromagnet.

A charged particle may be deflected by a magnetic field.

- Deflection is greatest for particles moving perpendicular to the magnetic field, and zero for particles moving parallel to the field.

An electric current is also deflected by a magnetic field.

- The force is maximum when the current is perpendicular to the field.
- Galvanometers, ammeters, voltmeters, and electric motors are based on this effect.

The earth itself is a magnet; its magnetic poles are almost 2000 km from its geographical poles.

Important Terms

electromagnet (36.5)
magnetic domain (36.4)
magnetic field (36.2)
magnetic pole (36.1)

Review Questions

1. What do electric charges have in common with magnetic poles? (36.1)
2. What is a major difference between electric charges and magnetic poles? (36.1)
3. What is a magnetic field, and what is its source? (36.2)
4. Every spinning electron is a tiny magnet. Since all atoms have spinning electrons, why are not all atoms tiny magnets? (36.3)
5. What is so special about iron that makes each iron atom a tiny magnet? (36.3)
6. What is a magnetic domain? (36.4)
7. Why do some pieces of iron behave as magnets, and other pieces of iron do not? (36.4)
8. How can a piece of iron be induced into becoming a magnet? For example, if you place a paper clip near a magnet, it will itself become a magnet. Why? (36.4)
9. Why will dropping or heating a magnet weaken it? (36.4)
10. What is the shape of the magnetic field that surrounds a current-carrying wire? (36.5)
11. If a current-carrying wire is bent into a loop, why is the magnetic field stronger inside the loop than outside? (36.5)

12. What must a charged particle be doing in order to experience a magnetic force? (36.6)

13. With respect to an electric and magnetic field, how does the direction of a magnetic force on a charged particle differ from the direction of the electrical force? (36.6)

14. What role does the earth's magnetic field play in cosmic ray bombardment? (36.6)

15. How does the direction in which a current-carrying wire is forced when in a magnetic field compare to the direction that moving charges are forced? (36.7)

16. How do the concepts of force, field, and current relate to a galvanometer? (36.8)

17. Why is it important that the current in the armature of a motor periodically change direction? (36.8)

18. What is meant by magnetic declination? (36.9)

19. According to most geophysicists, what may be the probable causes of the earth's magnetic field? (36.9)

20. What are magnetic pole reversals, and what is the evidence that the earth's magnetic field has undergone pole reversals throughout its history? (36.9)

Think and Explain

1. What kind of force field surrounds a stationary electric charge? A moving electric charge?

2. Why can iron be made to behave as a magnet and wood not?

3. Since iron filings are not themselves magnets, by what mechanism do they align themselves with the field of a magnet, as shown in Figure 36-6?

4. A strong magnet and a weak magnet attract each other. Which magnet exerts the stronger force—the strong one or the weak one? (Could you have answered this way back in Chapter 5?)

5. Why will the magnetic field strength be further increased inside a current-carrying coil if a piece of iron is placed in the coil?

6. Magnetic fields can be used to trap plasmas in "magnetic bottles," but the plasma must be moving. Why?

7. A cyclotron is a device for accelerating charged particles in ever-increasing circular orbits to high speeds. The charged particles are subjected to both an electric field and a magnetic field. One of these fields increases the speed of the particles, and the other field holds them in a circular path. Which field performs which function?

8. A magnetic field can deflect a beam of electrons, but it cannot do work on them to speed them up. Why? (*Hint:* Consider the direction of the force relative to the direction in which the electrons move.)

9. In what direction relative to a magnetic field does a charged particle travel in order to experience maximum magnetic force? Minimum magnetic force?

10. Pigeons have multiple-domain magnetite magnets within their skulls that are connected with a large number of nerves to the pigeon's brain. How does this aid the pigeon in navigation? (Magnetic material also exists in the abdomens of bees; none, however, has been found in humans.)

11. What changes in cosmic ray intensity at the earth's surface would you expect during periods in which the earth's magnetic poles passed through a zero phase while undergoing reversals? (A widely held theory supported by fossil evidence, is that the periods of no protective magnetic field may have been as effective in changing life forms as X rays have been in the famous heredity studies of fruit flies.)