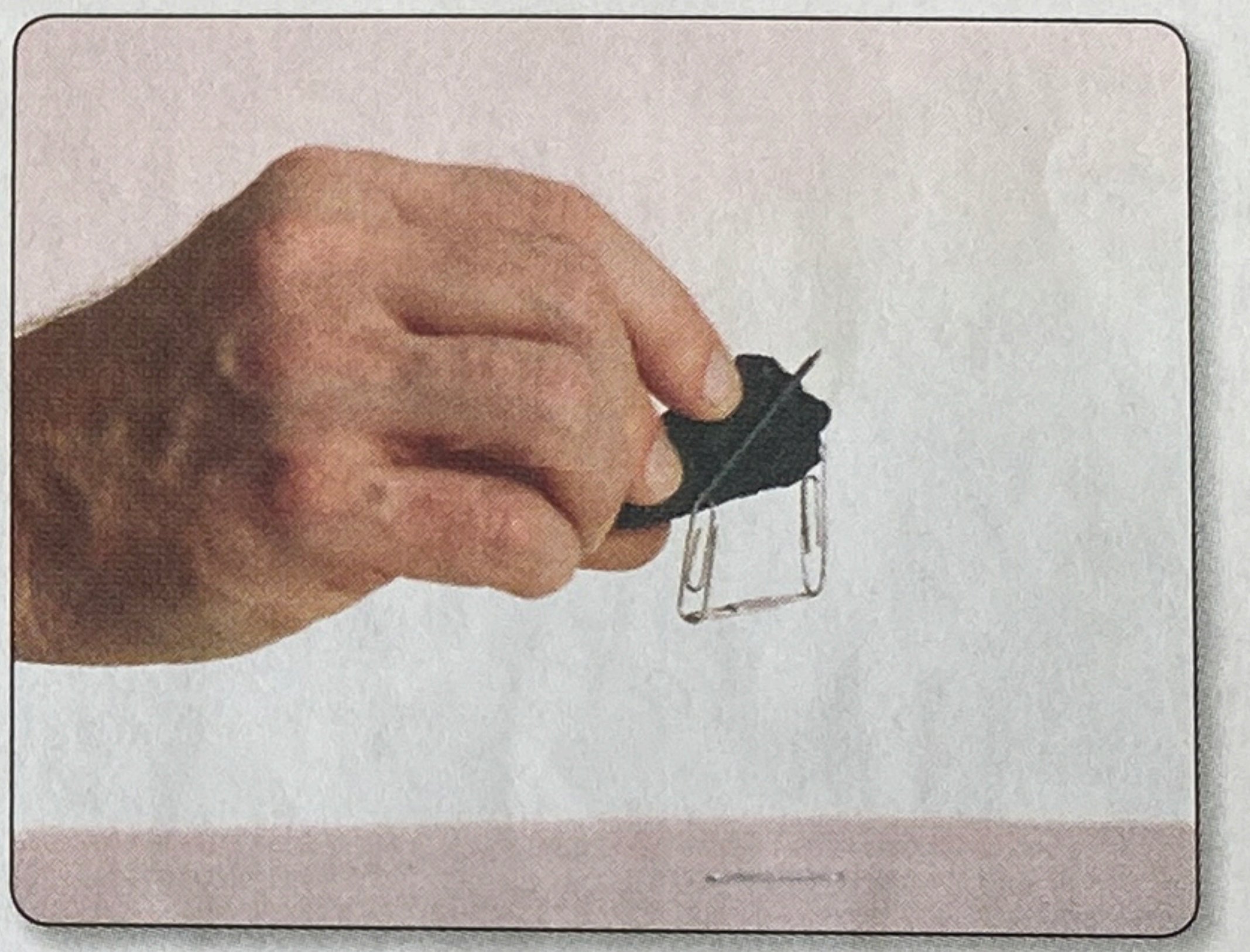
Magnetism

21

DOMINION MODELING

Understanding the Electron

In the 1800s, many physicists thought the atom was indivisible. Many also thought that a fluid or "ether" was responsible for carrying and transferring charge. English physicist Joseph John ("J.J.") Thomson was convinced otherwise. He suspected that the charge carriers were particles. In the 1890s, Thomson did a series of three experiments in which he clearly identified the presence of charged subatomic particles, electrons. In a bold move, he proved both that the atom could be divided and that these particles were charge carriers. He revolutionized the existing atomic model with this discovery, receiving the Nobel Prize in Physics in 1906. But how do the size and charge of electrons compare to other particles?



21-1 A sample of lodestone

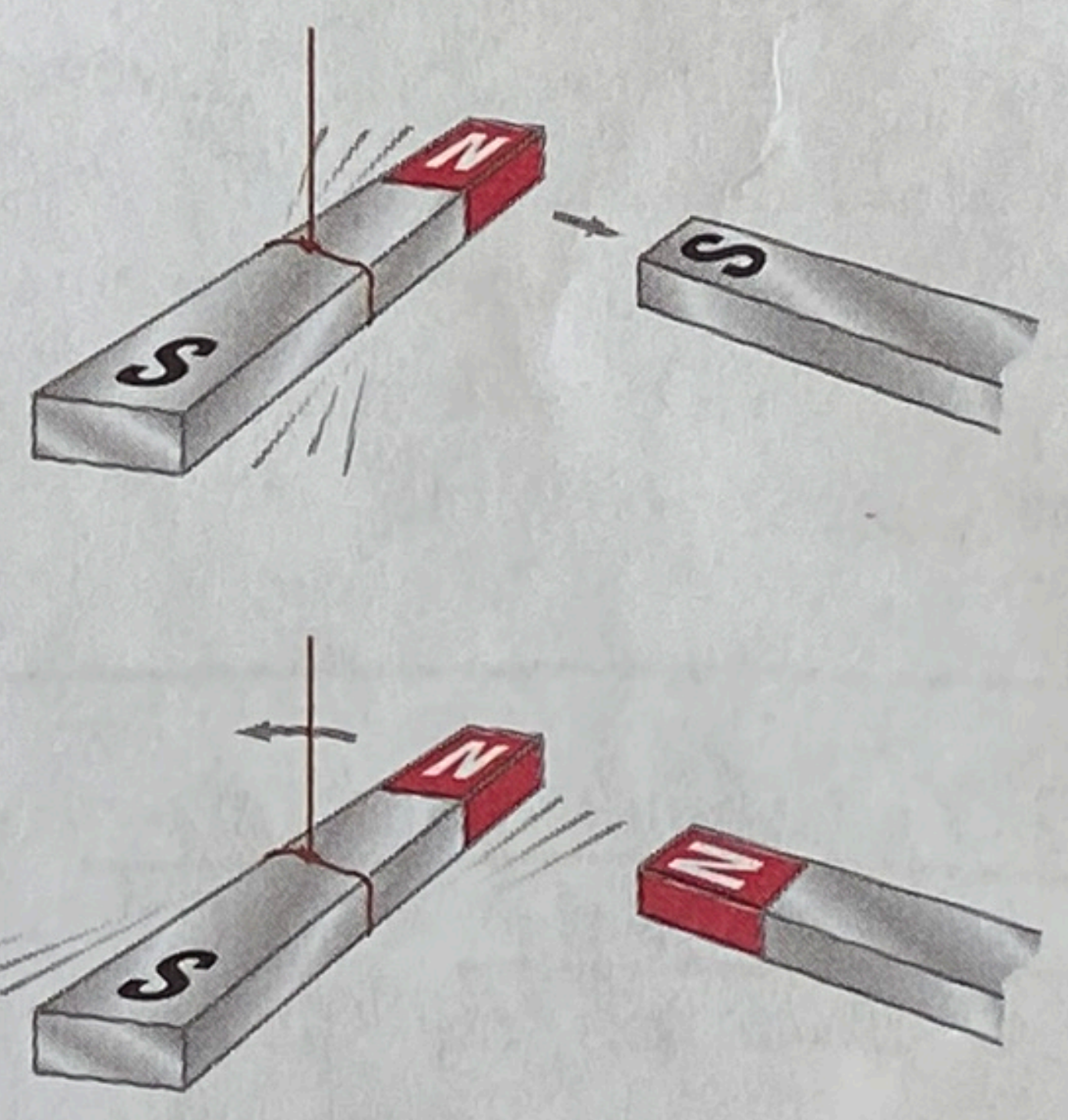
21A DESCRIBING MAGNETISM

21.1 Historical Background

Before the time of Christ, people knew that certain stones would attract other similar stones and some metals. The Romans called such stones *magnets* after the city of Magnesia, where legend says that natural magnets were first found. During the fourth century BC, the Chinese discovered that a natural magnet suspended by a string would rotate until it aligned in a more-or-less north-south orientation. As early as the tenth century AD, Chinese sailors were navigating using stone magnets, which the Europeans called **lodestones** ("leading stones"). By the end of the twelfth century, the navigational compass, equipped with a magnetized metal needle, was in common use.

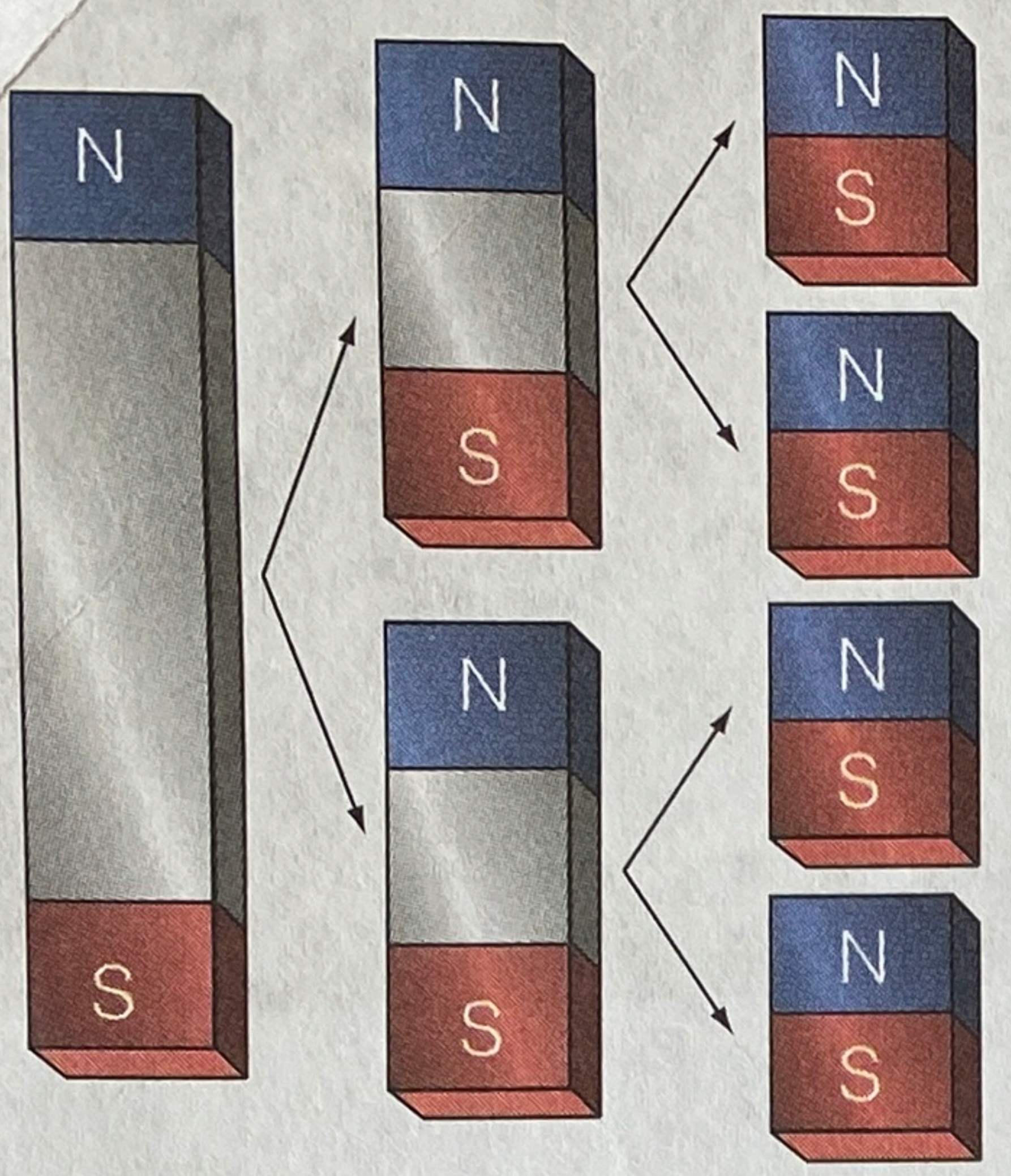
In the thirteenth century, Petrus Peregrinus de Maricourt performed several experiments to learn more about lodestones. He discovered that two regions at the opposite ends of a lodestone, which he called **poles**, had greater attraction for metals than the surface between them. He also discovered that there were two kinds of poles, north and south. Poles of the same kind repelled each other, while poles of different kinds attracted each other. This principle is called the **law of magnetic poles**. This property is very similar to the law of charges. There are two kinds of electrical charge, positive and negative. Like charges repel, whereas opposite charges attract. Early natural philosophers believed that static electricity and magnetism had much in common.

The ancient city of Magnesia was located in the coastal region of what is now Thessaly in Greece on the western shore of the Aegean Sea.



21-2 Opposite poles attract, whereas like poles repel.

Petrus Peregrinus de Maricourt (thirteenth century) was a French scholar and scientist.



21-3 Breaking a magnet in half repeatedly just produces smaller dipole magnets.

21.2 Description of the Magnetic Field

Magnetic poles come in north-south pairs. Realizing that long magnets have little magnetic force at the center of their lengths, early experimenters tried to isolate a magnetic pole by breaking a magnet in half. They invariably got shorter, weaker magnets, each with a north and a south pole. No matter how small the magnetic pieces are made, two poles are always present. No example of a single, isolated magnetic pole has ever been observed. This is a significant difference from electrical charges.

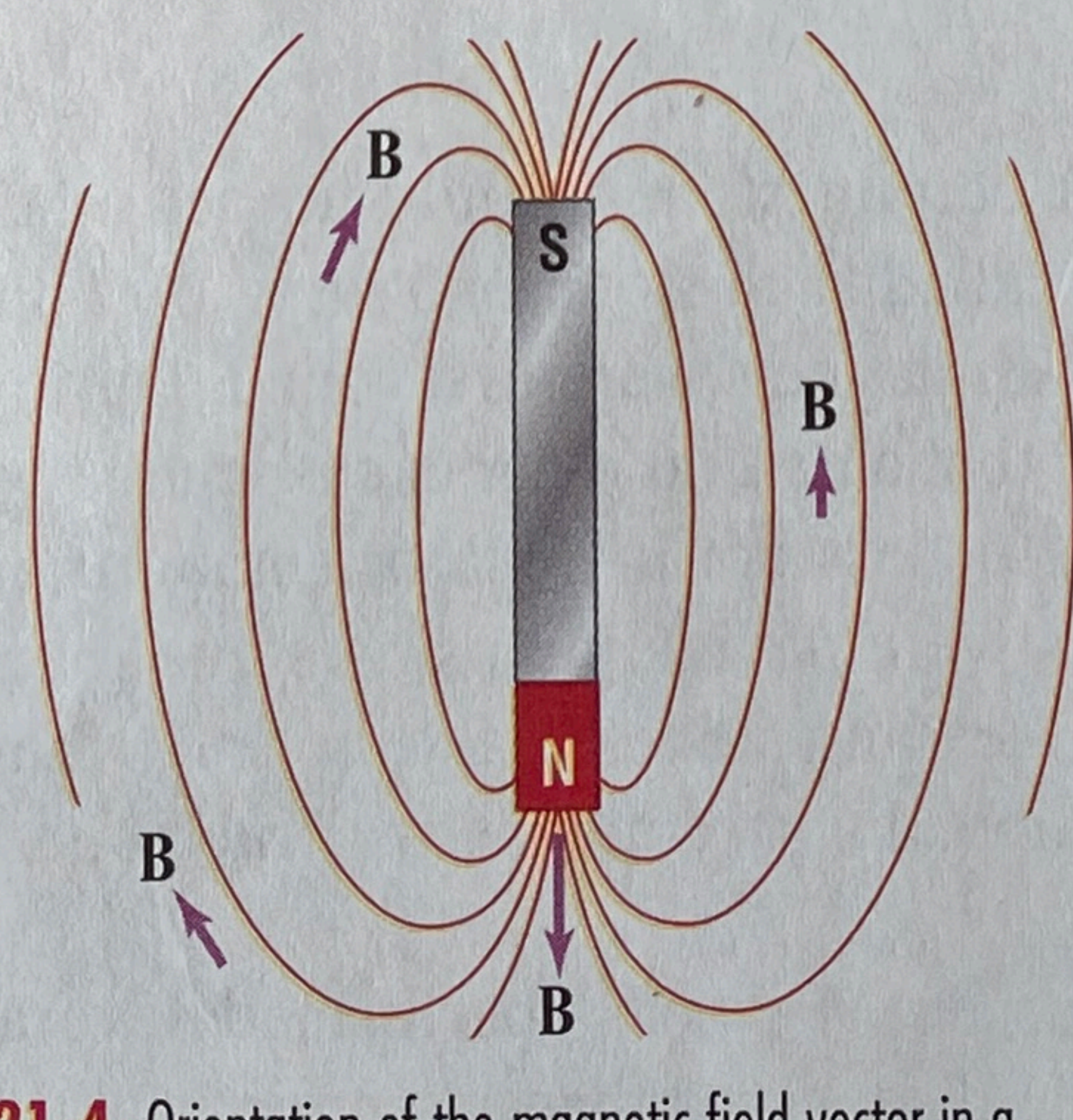
A magnet with two poles is called a *dipole*, while one with a single magnetic pole would be called a *monopole.* While no monopole magnet has been found, electric monopoles are common. The negative and positive unit charges (e) on electrons and protons produce monopole charges.

The effect of a magnet on another magnet, metals, and moving electric charges is best described by a *magnetic field.* Like an electric field, a magnetic field is a convenient description of how the space surrounding a magnet is affected by it. A magnetic field line gives the direction that a (hypothetical) magnetic north monopole would travel if released along the line. Consequently, magnetic lines of force are curved arrows pointing toward south magnetic poles and away from north magnetic poles. If the imaginary magnetic monopole is replaced by a tiny dipole magnet that is suspended in a large magnetic field, the dipole will align itself so that it lies along the field with its north pole pointing in the direction of the arrows.

You can find the general shape of the magnetic field of a magnet easily. Simply sprinkle some iron filings onto a piece of paper and hold the paper over the magnet. The iron filings will become magnetized and align themselves along the magnetic field. Another way to map a magnetic field is to place a compass in it. The magnetized compass needle will point in the direction of the magnetic field. These methods are limited because they are able to portray only a two-dimensional cross section of the field surrounding a magnet. Like electric and gravitational fields, magnetic fields are three-dimensional.

Notice in Figure 21-4 that the magnetic field lines are closer together at a magnet's poles than anywhere else. The number of field lines passing through an area of space represents the strength of the field at a point. More lines indicate a stronger field. Both the strength and the direction of the magnetic field at a point are described by the **magnetic field vector (B)**, whose magnitude is called the *magnetic flux density.* The direction of **B** at any point in space is tangent to the magnetic field line through that point. The strength of the field, and therefore the magnitude of **B**, is measured in **teslas (T)**, the SI unit named after Nikola Tesla. One tesla is equal to one volt-second per square meter:

$$1\ \text{T} = 1\ \text{V}\cdot\text{s/m}^2$$



21-4 Orientation of the magnetic field vector in a magnetic field

Nikola Tesla (1856–1943) was a brilliant Serbian-American electrical engineer and inventor. He invented the methods for the practical production and use of alternating current that made the modern commercial power industry possible.

Another convenient unit of magnetism is the **gauss (G)**, often used in research involving small magnetic fields as well as in geophysics.

$$10^4\ \text{gauss} = 1\ \text{T}$$

The earth's total magnetic field strength at its surface varies between 0.3 G and 0.6 G, depending on the observer's location.

21.3 Magnetic Properties of Matter

When a material is placed within a magnetic field, the field will alter the material's magnetic character in a process called **magnetization**. Most materials lose this magnetic character when the field is removed, while others may retain some or even most of the magnetizing effect.

Materials differ in their responses to magnetic fields. A magnetic field passing through a material is usually not the same as in a vacuum. We saw this with electrical fields and capacitors. The dielectric constant κ is the ratio of the material's permittivity to the permittivity of free space (vacuum) (ε_0). The permittivity of a material is its ability to store energy in the electric field when an electrical potential difference is applied. The dielectric constant is a measure of how a material tends to concentrate electric field lines. In a similar way, scientists describe the way a material affects a magnetic field that is within it by a property called the material's *magnetic permeability* (μ). A more easily interpreted quantity is the material's **relative permeability (μ_r)**, which is defined as the ratio of the permeability of the material and the permeability of free space (μ_0):

$$\mu_r = \frac{\mu}{\mu_0} \qquad (21.1)$$

Relative permeability can be thought of as the ratio of the strength of a magnetic field within a material to the strength of the same field in a vacuum, though this is not strictly accurate for all materials under all conditions.

Materials can be classified by their magnetic properties according to the magnitude of their relative permeabilities. One group of materials is readily attracted to magnets. Their relative permeabilities are much greater than 1. Therefore, a magnetic field is much more concentrated within one of these materials than in a vacuum. These materials can be induced to become permanent magnets. A material with these properties, such as iron, nickel, cobalt, and certain alloys, is called **ferromagnetic**.

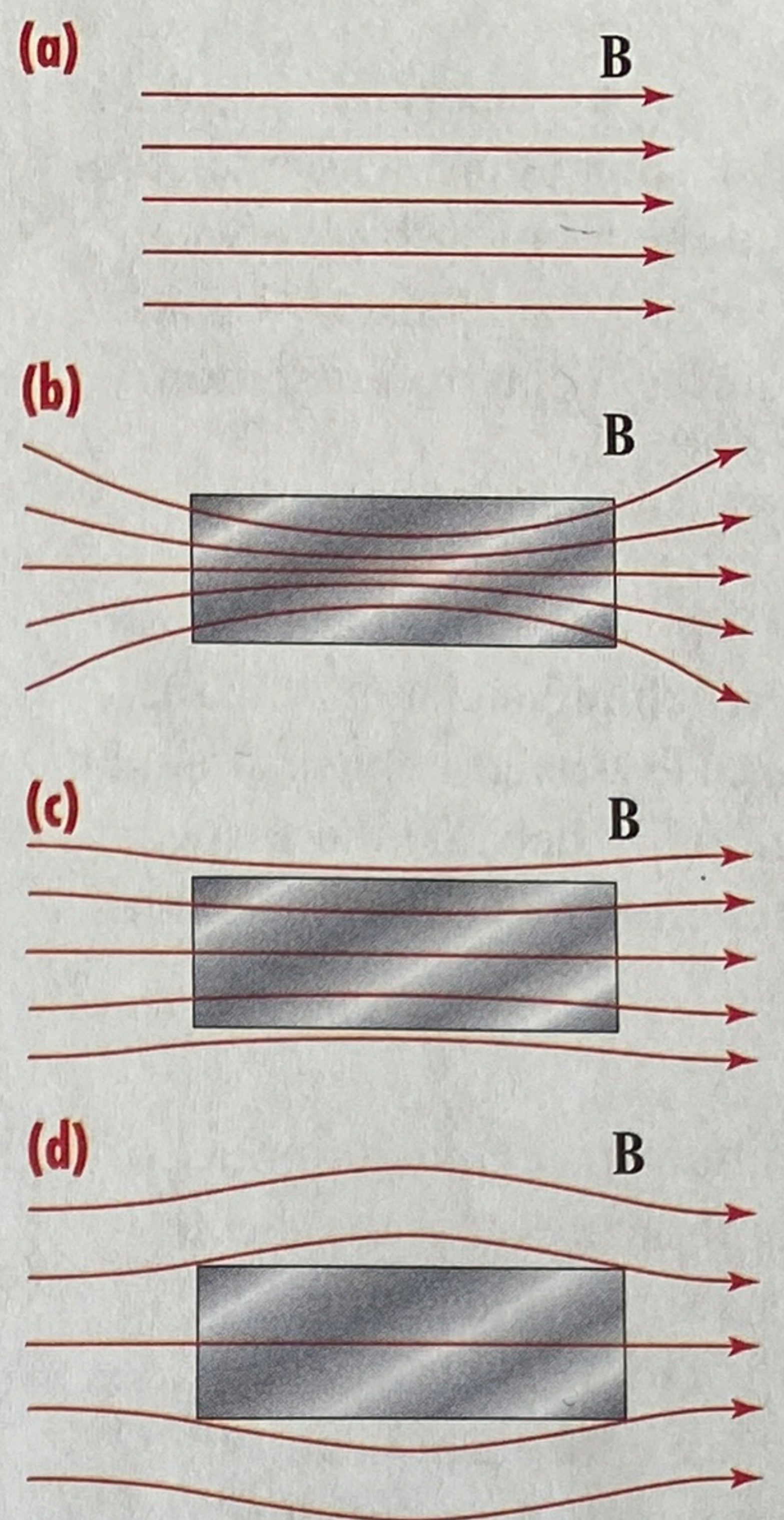
Another group of materials, **paramagnetic** materials, is not noticeably attracted to small magnets. The relative permeability of these materials is slightly greater than 1. The magnetic field in a paramagnetic material is only slightly more concentrated than it would be in a vacuum. Aluminum, platinum, and sodium are examples of paramagnetic materials.

TABLE 21-1

Relative Permeabilities

Material	μ_r
Ferromagnetic Materials	
Iron (Fe)	200–5000
78 Permalloy (22% Fe, 78% Ni)	5000–100 000
Supermalloy (5% Mo, 79% Ni, 16% Fe)	100 000–1 000 000
Paramagnetic Materials	
Aluminum (Al)	$1 + 2.2 \times 10^{-5}$
Sodium (Na)	$1 + 7.2 \times 10^{-6}$
Platinum (Pt)	$1 + 2.8 \times 10^{-4}$
Uranium (U)	$1 + 4.0 \times 10^{-4}$
Diamagnetic Materials	
Copper (Cu)	$1 - 9.8 \times 10^{-6}$
Lead (Pb)	$1 - 1.8 \times 10^{-5}$
Mercury (Hg)	$1 - 3.0 \times 10^{-5}$
Silver (Ag)	$1 - 2.6 \times 10^{-5}$

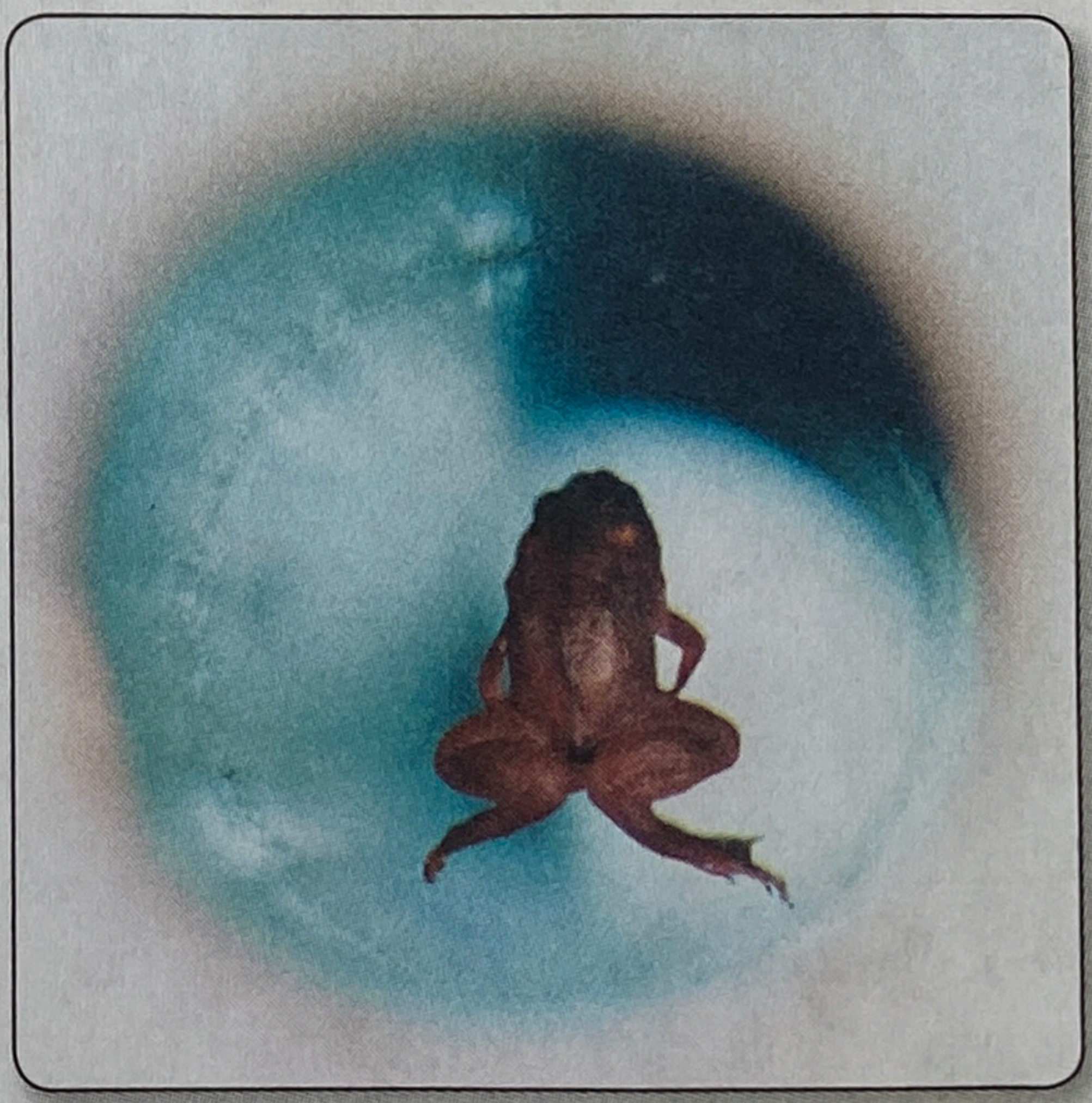
Materials in the third group are those that actually diminish a magnetic field. Their relative permeabilities are slightly less than 1. They are repelled by strong magnets because the external magnetic field causes the atoms of the material to align in a way that forms an opposing magnetic field. This property is called **diamagnetism**. Nearly all elements and compounds are weakly diamagnetic. However, many materials have some stronger magnetic characteristic that masks their diamagnetism. Elements that show dominant diamagnetism include most of the Group 3A–8A elements and most of the Group 1B and 2B metals on the periodic



21-5 Magnetic field line density within (a) a vacuum, (b) a ferromagnetic metal, (c) a paramagnetic material, (d) a diamagnetic material

The magnetic character of materials can be described by their relative permeabilities:

Ferromagnetic	$\mu_r \gg 1$
Paramagnetic	$\mu_r > 1$
Diamagnetic	$\mu_r < 1$



21-6 When diamagnetic materials, such as those in living tissues, are exposed to a strong magnetic field, the diamagnetic force can be strong enough to levitate a small creature. The frog was not injured in this demonstration.

table. Note that there are significant exceptions, such as oxygen, which is strongly paramagnetic.

A fourth category of magnetic materials consists of mixtures of different magnetic compounds that exhibit opposing magnetic orientations. The relative concentrations of the materials determine the strength and orientation of the magnetic field in an object containing the materials. These materials are **ferrimagnetic**. Natural lodestones, the most common ferrimagnetic materials, consist of two oxides of iron in a mineral called *magnetite*.

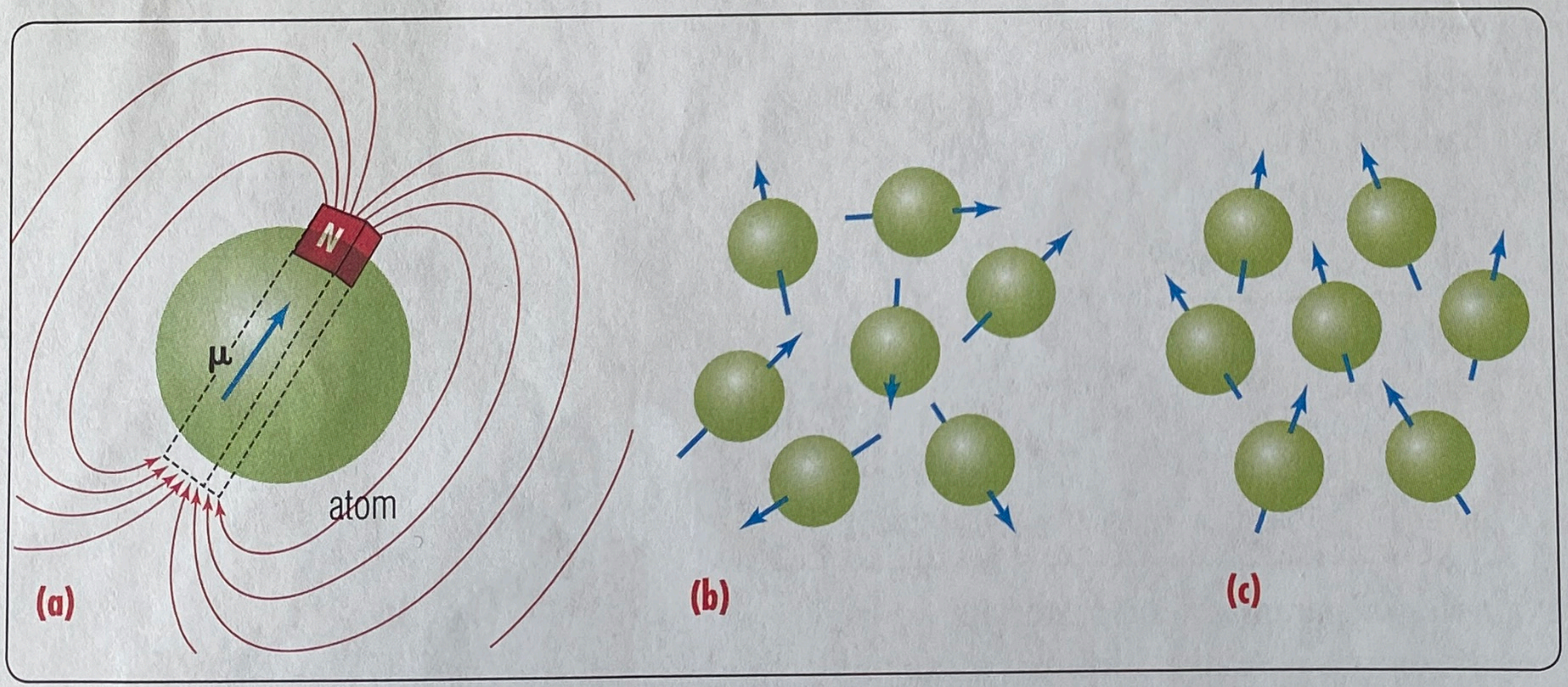
21.4 Causes of Magnetism

What makes a magnet magnetic? In 1820, Hans Christian Oersted discovered that a wire carrying a current influenced a nearby compass needle. From that discovery, André Marie Ampère concluded that all magnetic fields result from currents. Today, most scientists agree with Ampère. Yet permanent magnets need not be connected to a source of potential difference. Where then does the current come from?

Remember, an atom consists of a positively charged nucleus orbited by negatively charged electrons. The electrons are moving charges. Therefore, each atom contains a tiny current. The magnetic effect of an atomic current is represented by its **magnetic dipole moment ($\boldsymbol{\mu}$)** vector. (Do not mistake this vector quantity for the scalar magnetic permeability, μ.) The magnetic dipole moment of an atom is a vector; its direction is the direction of the atom's magnetic field, and its magnitude is related to the strength of the magnetic field. The electrons and protons in an atom also seem to "spin." Each of these subatomic particles therefore has its own magnetic moment.

Pairs of electrons "spin" in opposite directions, so their magnetic moments cancel each other within the atom. Only those substances that have unpaired electrons in certain atomic energy levels may be magnetic. Even then, in most materials the magnetic moments of their atoms point in random directions. On the average, the random magnetic moments sum to cancel each other. That is why most materials have no net magnetic field. In ferromagnetic materials, however, the atomic magnetic dipole moments are strong enough to influence each other. The magnetic moments of all the atoms within tiny crystalline regions of the material are aligned in one direction. These regions are called **domains**.

Usually, the alignment of the domains varies randomly, so there is no overall reinforcement of the individual domain dipole moments. In the presence of a strong external magnetic field, however, the domains tend to align with the field, and the material becomes magnetized. This magnetization becomes permanent if the individual atomic dipole moments are strong enough to overcome the tendency for the moments to become disoriented due to the thermal motion of their atoms (ferromagnetic materials). Otherwise, the magnetism lasts only until the field is removed (paramagnetic materials).



21-7 The atoms of some materials act as tiny bar magnets (a). If they are randomly oriented, the material is completely unmagnetized (b). In ferromagnetic materials, atoms within individual crystals of the material have nearly the same orientation, producing domains of magnetism (c).

Hans Christian Oersted (1777–1851) was a Danish physicist who first demonstrated the relationship between electricity and magnetism—by accident—during a classroom demonstration.

André Marie Ampère (1775–1836) was a French physicist and mathematician. He was largely self-taught and eventually became the Inspector General of the French system of universities.

The quantum-mechanical model of the atom indicates that the electron exists as a three-dimensional wave within the atom. Therefore, the idea that such an entity can have "spin" reveals the inadequacy of our language to describe the properties of such a strange thing as an electron.

Magnetic Fields and God's Wisdom

The discovery of magnetism shows that God created the world with properties that humans can exploit for the benefit of others. In the future, scientists may find other useful properties built into creation.

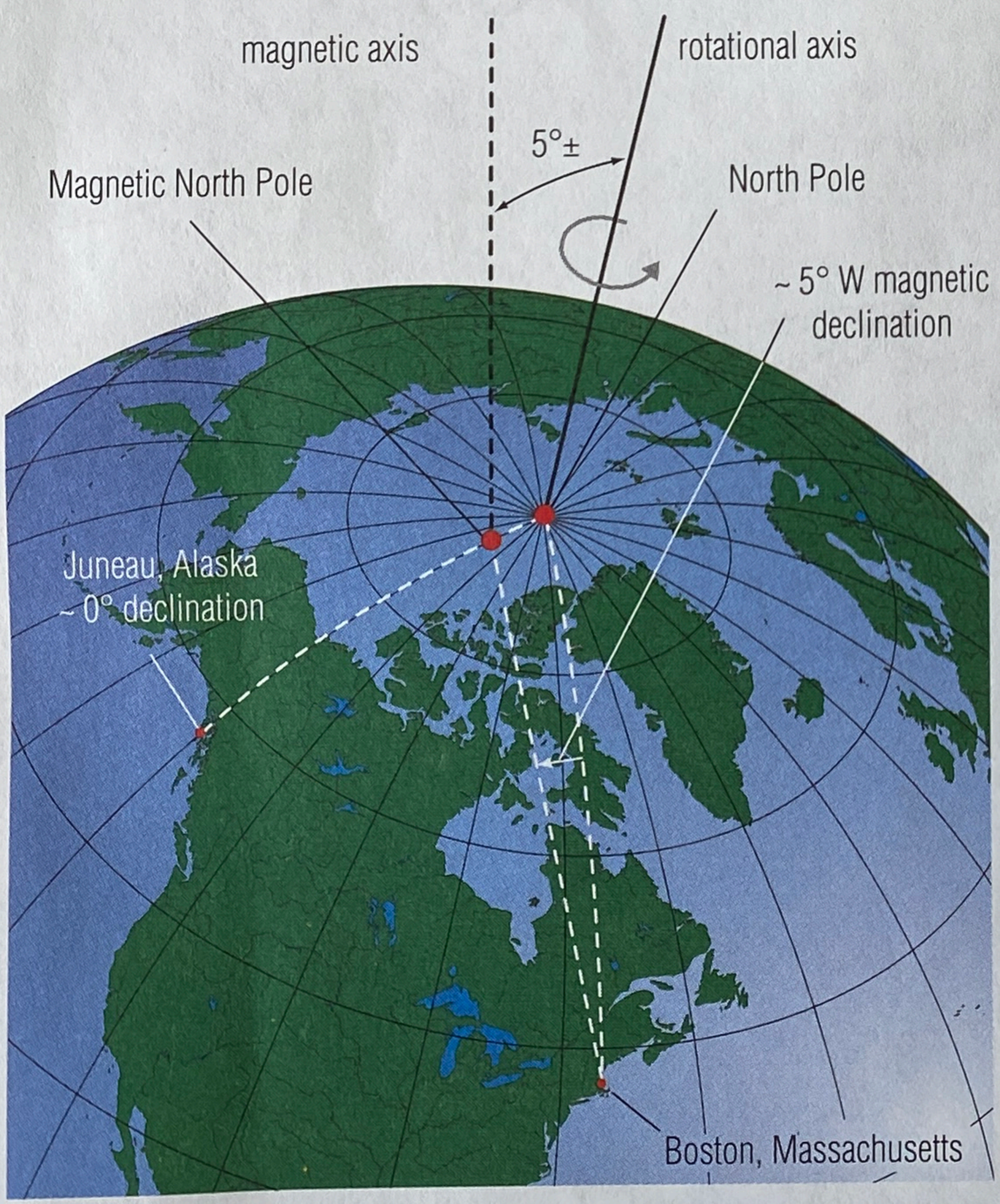
Diamagnetic materials not exposed to an external magnetic field exhibit no net magnetic moment. When an external magnetic field is applied, a magnetic dipole moment is induced in the atoms similar to the way that electrostatic charge is induced in a neutral object. North is attracted to south. The resulting induced field opposes the external field and diminishes its strength within the material. In strong fields, a diamagnetic object can actually be repelled by a magnet or even levitated (see Figure 21-6).

The ordered state of magnetic domains is greatest very close to absolute zero, when there is little thermal motion. At higher temperatures, atomic thermal motion interferes with the alignment of magnetic moments. When it exceeds a characteristic temperature, called its **Curie temperature (T_C)**, a ferromagnetic material loses its ferromagnetic properties and becomes paramagnetic.

21.5 Terrestrial Magnetism

Why does the north pole of a compass point north? A magnetic compass is a small, light magnet mounted on a pivot so that it can rotate freely in a horizontal plane. The poles of a magnet are called the north magnetic pole and the south magnetic pole. A magnet's *north magnetic pole* points toward the earth's magnetic north pole (which is actually a *south* magnetic pole). This confusing state of affairs exists because opposite poles attract, and a north magnetic pole is defined as one that points toward the magnetic north pole.

William Gilbert reasoned that magnets are attracted by magnets. Therefore, the earth must be a magnet. To test his conclusions, Gilbert milled a large piece of lodestone into a sphere. When he placed a compass at various positions on the surface of the lodestone, the compass reacted in the same way as it would when

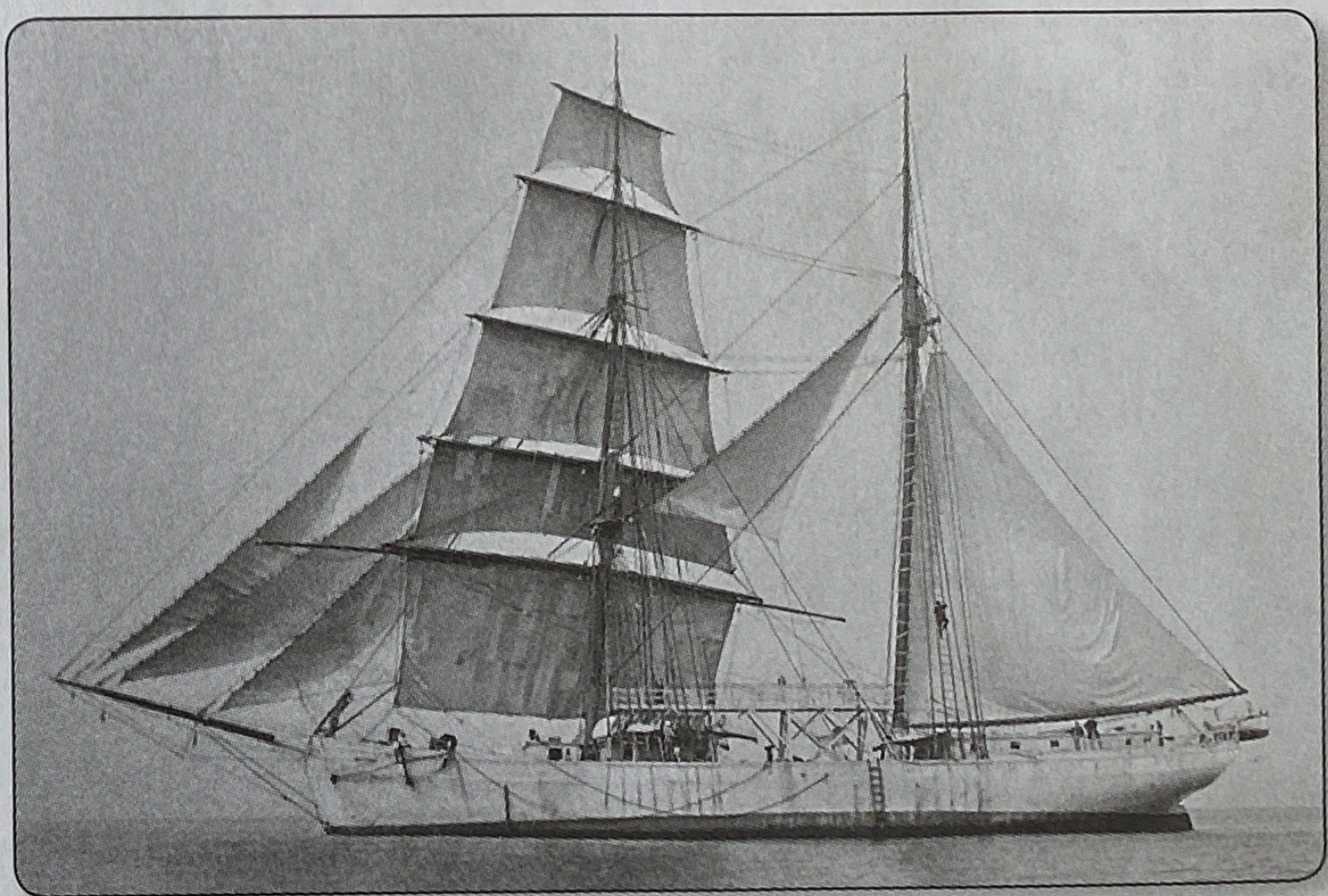


21-9 The poles of the earth's magnetic field are not aligned with its geographic poles. This is the main reason for magnetic declination.

Pierre Curie (1859–1906) was a French physicist who discovered the piezoelectric effect and showed that magnetic properties of a substance change at a given temperature. He and his wife, Marie, discovered the elements radium and polonium and shared the 1903 Nobel Prize in Physics with Henri Becquerel for their studies in radiation.

21-8 A magnetic compass that a hiker might use

The earth's magnetic north pole is continually drifting, and its location is not precisely known from year to year. A computer model places the pole at approximately 85°N, 130°W in 2010. This is well to the northwest of Ellesmere Island in northern Canada in the Arctic Ocean. This location is about 560 km (345 mi) south of the geographic north pole. The pole has drifted more than 1700 km since it was first located in the nineteenth century, and it is currently moving about 50 km per year. The drift speed is variable and is expected to slow in coming years.



21-10 In 1905, the Department of Terrestrial Magnetism of the Carnegie Institute, Washington, D.C., commissioned the first detailed magnetic survey of the Pacific Ocean using a nearly nonmagnetic wooden sailing vessel, the *Galilee*.

Problem-Solving Strategy 21.1

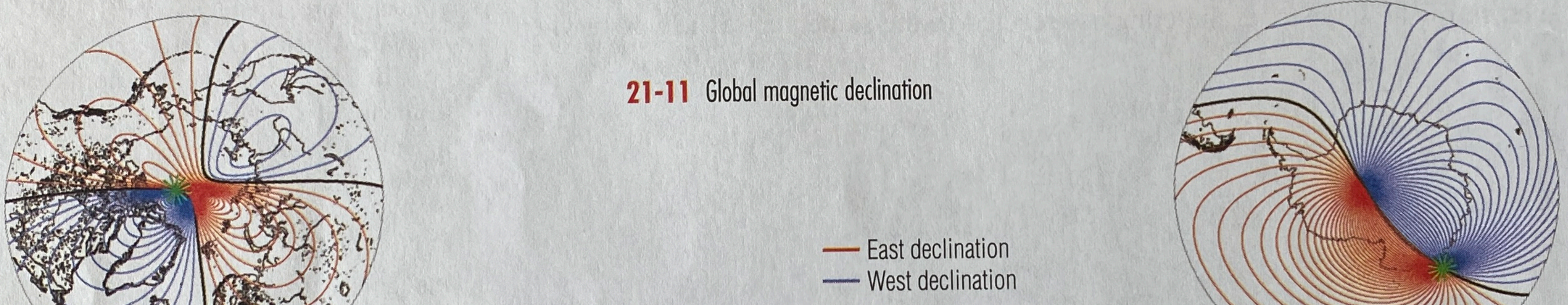
The direction of magnetic declination at your location can be determined by imagining the meridian line connecting your position and the geographic north pole. If the magnetic north pole is to the left (west) of this line, then the declination is west; if it is to the right (east) of the line, then declination is east.

The rate of the annual change of direction of the earth's magnetic field vector at any given point is fairly constant over a span of several years. This rate is called the **annual variation**, and it is usually printed in the legend on better-quality maps. It is given in units of degrees per year east or west, depending on the direction of change of local declination.

responding to the earth's magnetic field. Though some describe the earth as if it had a large bar magnet at its center, this analogy is not completely accurate. The magnetic north and south poles do not lie on a line that passes through the geographic center of the globe, nor do they move at the same rates. These observations indicate that there are highly complex factors deep inside the earth that affect the source of the earth's magnetic field.

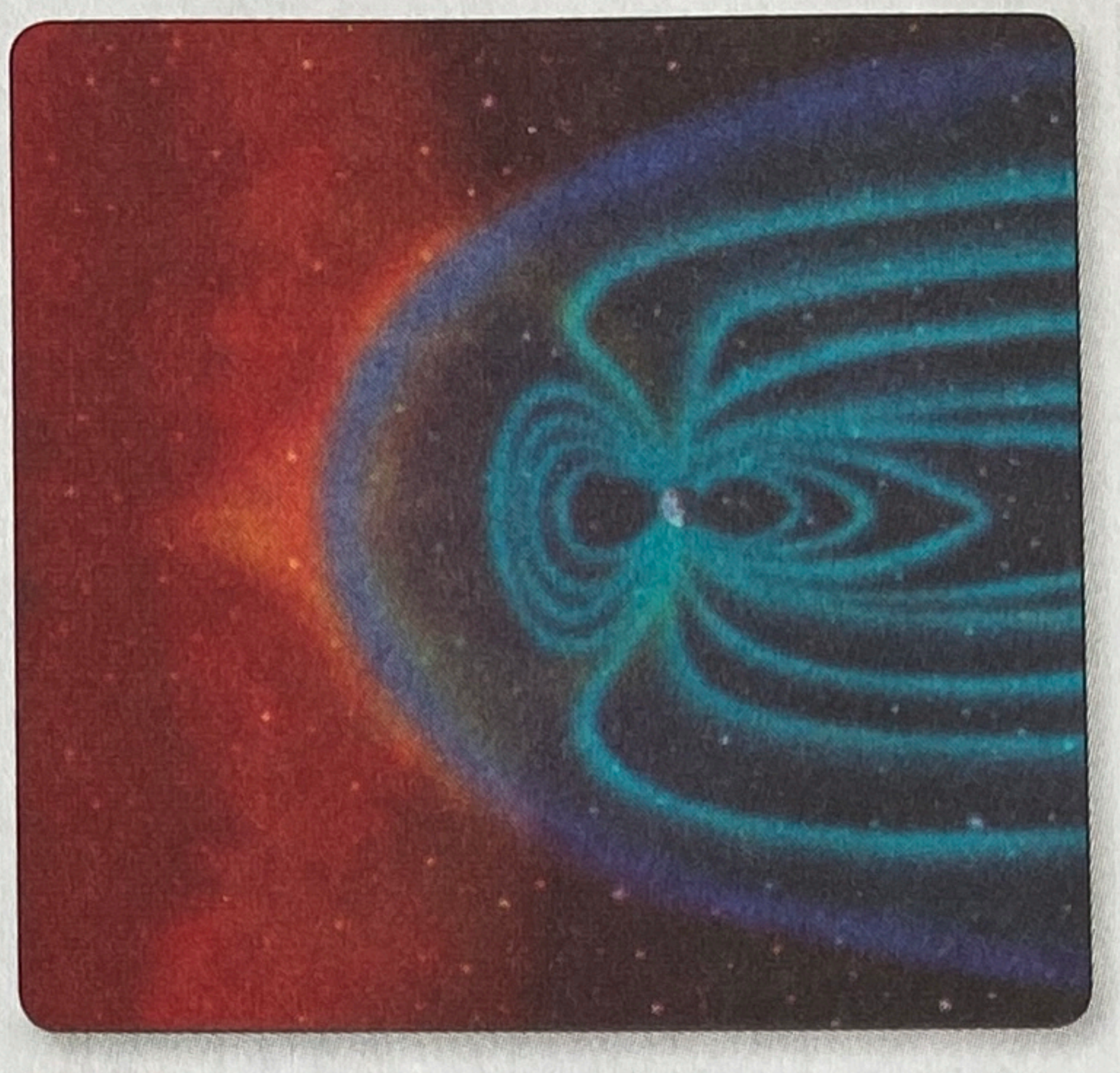
The earth's magnetic axis is not in the same place as its rotational axis. The magnetic north pole is inclined about 5° from the rotational axis. A compass points to the magnetic pole. Assuming that the earth's magnetic field is symmetrically distributed around the line passing through the magnetic north and south poles, a compass would not point to geographic north unless it were aligned with a magnetic field line that coincides with the meridian containing both the geographic north pole and the magnetic north pole. When the magnetic field is not aligned with this meridian, it points a certain angular distance away from the geographic pole. The angular difference between true north and magnetic north is called **magnetic declination**. It is usually given in degrees east (or +) or west (or −).

Determining magnetic declination is far more complicated than a mere exercise in spherical geometry. The distribution and motions of the material in the earth's core that produces the terrestrial magnetic field are not uniform. In addition, the crust's thickness and local conditions also affect the orientation of the earth's field at its surface. As noted above, the locations of the magnetic poles continuously change as well. Therefore, magnetic field data must be periodically taken and plotted on maps such as that shown in Figure 21-11.



21-11 Global magnetic declination

21.6 The Magnetosphere



21-12 The earth's magnetic field, or magnetosphere, distorted by the solar wind

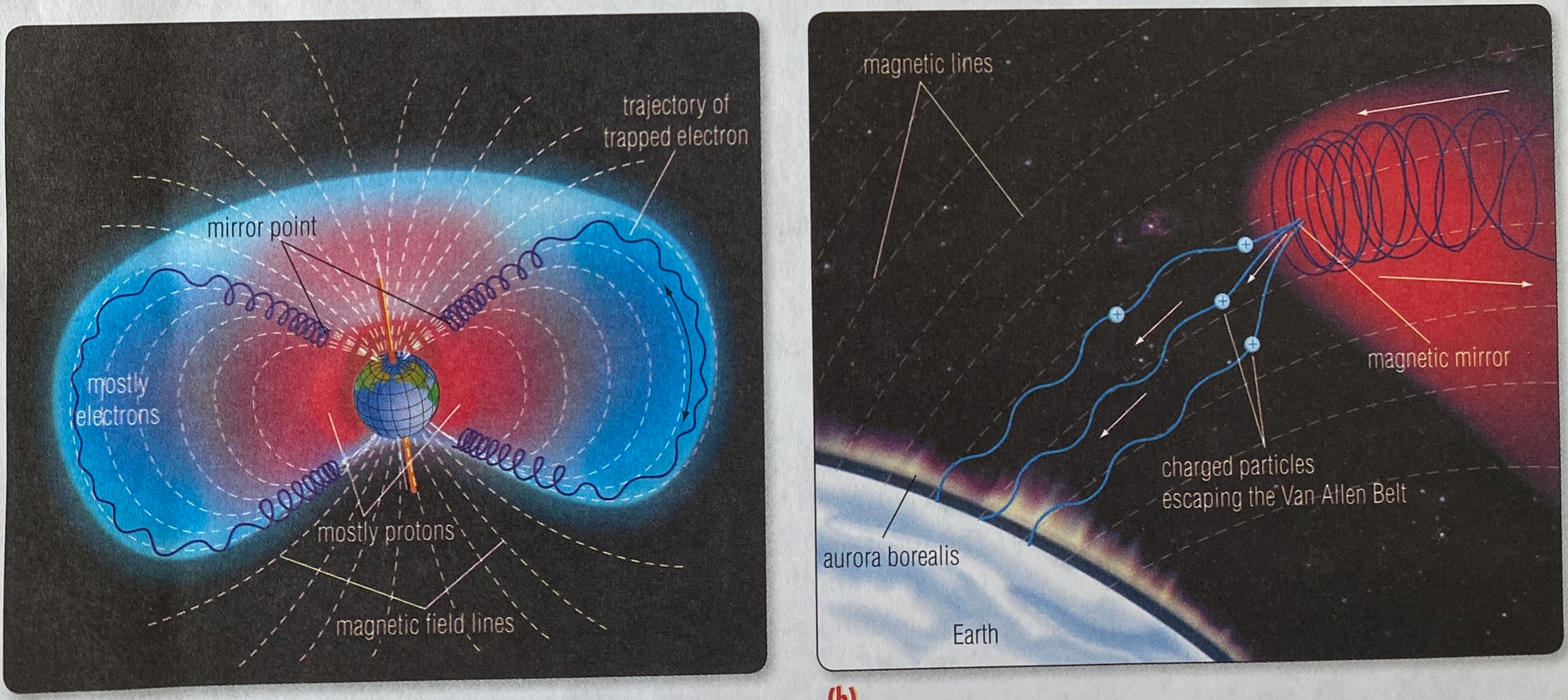
The volume of space containing the earth's effective magnetic field is called the **magnetosphere**. The shape of the magnetosphere is not exactly like the symmetrical field surrounding a laboratory bar magnet. It is distorted by the **solar wind**, the continuous stream of charged particles emitted by the sun. These charged particles form a high-energy fluid (plasma) and are deflected by the magnetic field. The field, in turn, is carried along with the plasma flow. Therefore, the magnetosphere facing the solar wind is not as thick as the side facing away from the sun, which tends to be drawn out like a magnetic tail (Figure 21-12).

Some particles are trapped in two areas of the magnetosphere. These belts of charged particles are called the **Van Allen belts** after James Van Allen, who discovered them in 1958 during the flight of America's first satellite, *Explorer I*. If the earth's magnetic field did not trap or deflect the radiation of the solar wind, it would reach the earth and damage all living things on the earth's surface. The existence of the strong magnetosphere is essential to preserve life on the earth and is evidence of God's protection of His creation.

The particles trapped in the Van Allen belts spiral back and forth from one end of the earth to the other in a few seconds. Sometimes, when the solar wind is especially strong, a high electrical potential ($>10\,000$ V) is established between the lower ends of the belts and the ionosphere. High-energy electrons rain down and collide with the atmosphere's molecules about 100 km above the earth's surface. The energy of the collisions is dissipated by the emission of light. The light as observed from the ground (and space) is known as an **aurora** (from the Latin word for *dawn*). The aurora in northern latitudes is called the *aurora borealis* or the *northern lights*. The southern aurora is called the *aurora australis* or the *southern lights*.

James Alfred Van Allen (1914–2006) was an American physicist who worked in the field of geomagnetism. After the success of the Soviet *Sputnik*, Van Allen began designing a satellite that would transmit data about the earth's magnetosphere. He is most famous for the discovery of the **Van Allen belts**—doughnut-shaped bands of high-intensity radiation surrounding the earth.

"And all the days of Methuselah were nine hundred sixty and nine years: and he died" (Gen. 5:27). Why did people live so much longer before the Flood? Nobody knows for sure, but one theory is that the earth's magnetic field could have been much stronger, giving better protection from the solar wind and cosmic radiation. With the weakening magnetic field, more mutation-inducing radiation has penetrated to the earth's surface, destroying the natural vitality and longevity that God originally created in living things. Other explanations related to the Flood itself are also possible.



(a)

(b)

21-13 (a) The Van Allen belts and (b) the cause of auroras

21A Objectives

After completing this section, I can

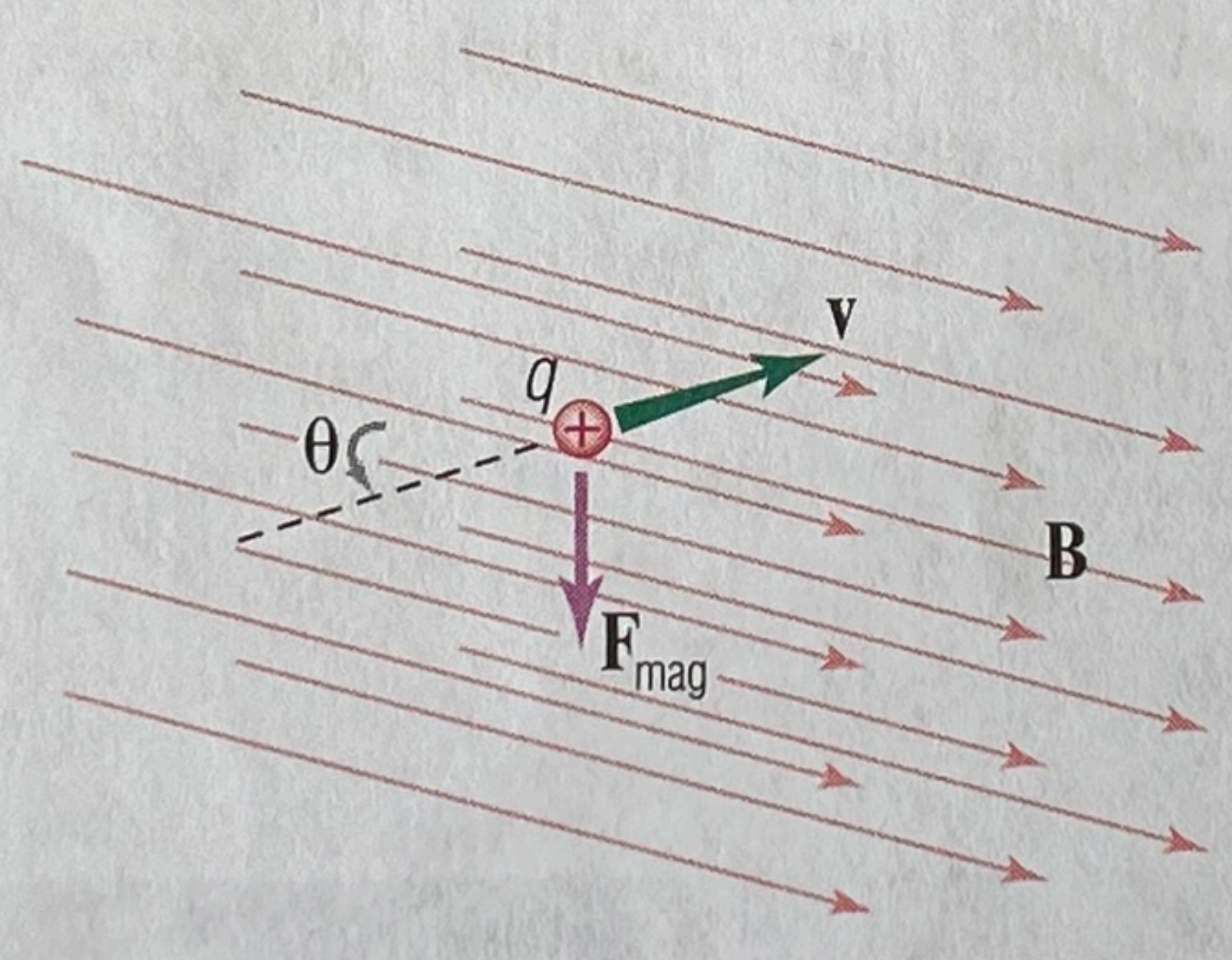
- ✓ summarize the discovery of and early investigations into magnetism.
- ✓ describe the shape, properties, and units associated with a magnetic field.
- ✓ differentiate between the three kinds of magnetic responses a material may exhibit to an external magnetic field.
- ✓ describe how magnetism is produced at the particle level of a material.
- ✓ define the Curie temperature of a ferromagnetic material.
- ✓ differentiate between the earth's geographic and magnetic north poles and explain why magnetic declination and variation exist.
- ✓ describe the magnetosphere and how it is evidence for a good design of the earth.

21A Section Review

1. **a.** What is a magnetic pole?
   b. How many kinds of poles are there?
   c. State the law of magnetic poles.
2. How is the magnitude and direction of the magnetic field represented *at a point* in a diagram?
3. What is the standard unit of magnetism and its SI equivalent?
4. **a.** What is the process that makes magnets out of unmagnetized metals?
   b. What kind of metals retains some magnetism after this process?
5. Ultimately, what two factors result in magnetism in a given material?
6. What condition can negate ferromagnetism in even the strongest magnets?
7. For a point on the surface of the earth, what is the horizontal angle between the directions to magnetic and true north called?
8. Describe the safety mechanism God provided to protect life on the earth from the effects of the solar wind.

21B ELECTROMAGNETISM AND CHARGES

21.7 Magnetic Force on a Moving Charge



21-14 A point charge moving through a magnetic field

A current-carrying wire can produce a magnetic force that can attract or repel a magnet. When Oersted discovered this fact, scientists wondered, "Do magnets also affect electrical charges?" The answer is yes—if the charges are moving. A magnet has no effect on a stationary charge, and a stationary charge has no effect on a magnetic field. Scientists have made the following observations regarding the interplay of magnetic fields and electric charges:

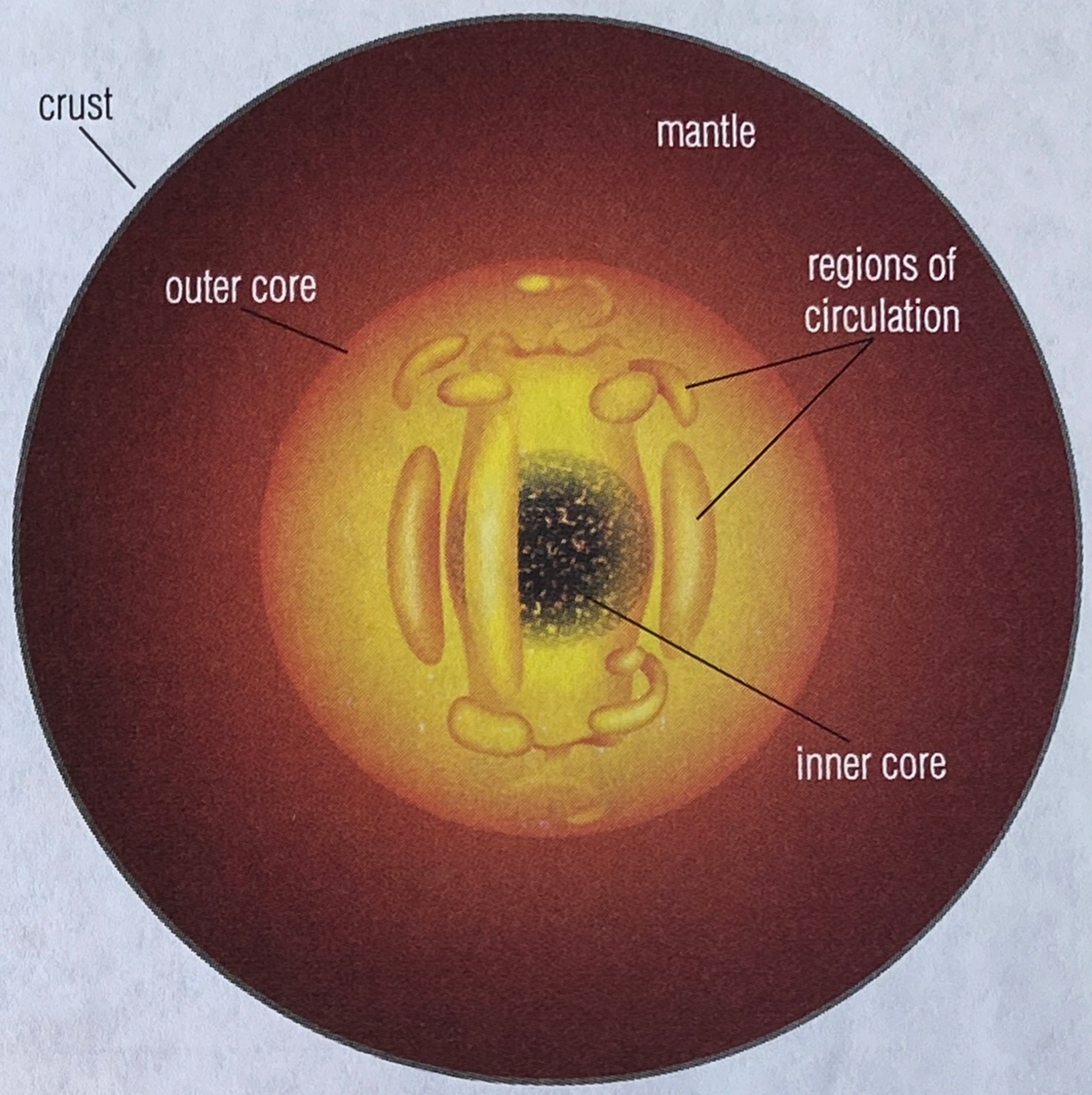
1. A point charge of either polarity at rest in a magnetic field experiences zero force.
2. A charge of either polarity that moves parallel to magnetic field lines in either direction experiences zero force.
3. If any point charge moves so that it crosses magnetic field lines at an angle, *a magnetic force* (F_{mag}) is exerted on the charge. The magnitude of the force is proportional to the speed of the charge and a function of the angle with which it crosses the field lines. For a given relative speed between the charge and the field, the force is maximum when the charge's velocity is perpendicular to the magnetic field lines.
4. The force on a moving charge is proportional to the density of the magnetic field lines, or the magnitude of flux density (B).
5. The direction of the force vector on a charge depends on the polarity of the charge.

Problem-Solving Strategy 21.2

In order to find the angle between the velocity and the magnetic field vectors, place their vectors tail-to-tail. The angle θ is the smallest angle between the vectors.

FACETS of PHYSICS

Paleomagnetism and the Age of the Earth



A model of the magnetically active core of the earth. Geophysicists believe that the earth's magnetic field is produced by complex circulatory flows of liquid metals in the outer core.

Most scientists agree that the earth's magnetic field is the result of some kind of current in the earth's core, but they disagree on the source of the current. The core is far too hot for a permanent magnet to be the cause of the earth's magnetic field. There are many "dynamo" theories that say the earth contains some kind of self-perpetuating electric generator. None of these theories satisfactorily explains the earth's magnetic field. A theory more consistent with observations is that the current was started at some time in the past, and it has not yet been overcome by flow resistance. This theory would predict that the current, and therefore the earth's magnetic field, is decreasing. The earth's magnetic field has decreased by a significant amount since it was first measured in 1839 by Carl Friedrich Gauss.

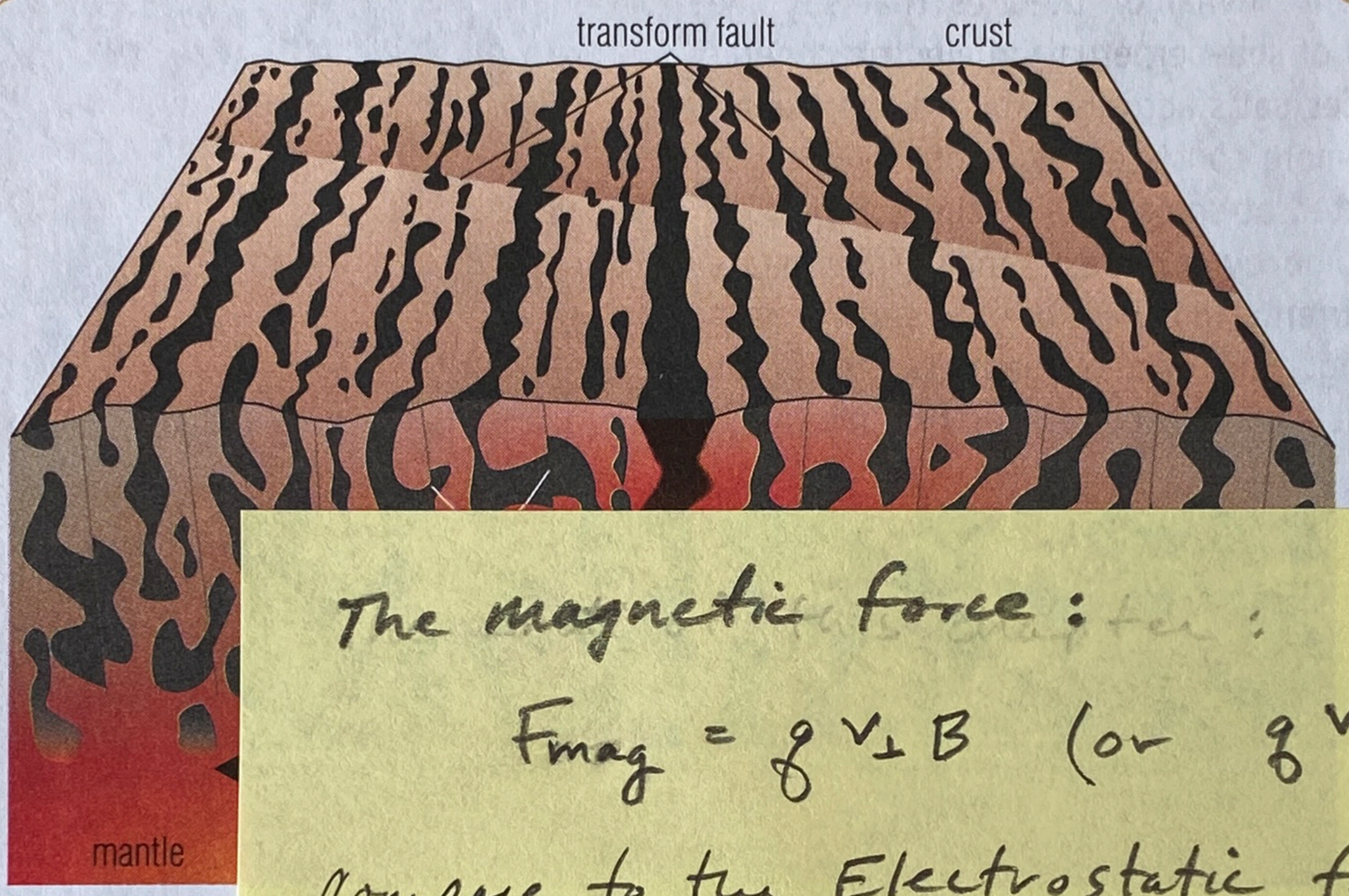
The idea that the earth's magnetic field is consistently decreasing bothers those who believe that the earth is billions of years old. The measurements of the earth's magnetic field show that its strength is decreasing exponentially. The field's half-life—the time in which the magnetic field energy halves—is about 1465 y. Based on these facts, if the earth's magnetic field has been decreasing in the same way since it started, then one million years ago it would have had sufficient energy to melt the crust! Some evolutionists believe that the recorded magnetic field data indicates that the field is decreasing in a linear fashion. If this were the case, then only twenty thousand years ago the magnetic field would have been stronger than most man-made magnetic fields. Such a strong field would require a current so large that it would produce enough heat to damage the earth's core. If the field continues decreasing at the same rate, it will disappear in just a few thousand years, and life on Earth will be seriously endangered.

The rapidly decreasing magnetic field creates a significant problem for evolutionists. Most of those who believe that the earth is billions of years old believe that its magnetic field must be about as old because the solar wind would destroy or damage life on the earth if the magnetic field did not deflect it. Therefore, since a constantly decreasing field would already have disappeared, they have to theorize that the earth's magnetic field oscillates. According to this theory, we are observing only the decrease since the last maximum. For evidence, they cite rocks containing magnetic materials that show magnetism with a polarity opposite to the earth's present magnetism.

When a hot ferromagnetic material cools, it often becomes magnetized by aligning with an external magnetic field. When a volcano erupts, magnetite crystals in the lava usually orient themselves along the earth's magnetic field. Geologists have noticed that igneous rocks bordering the mid-Atlantic ridge contain bands of materials magnetized in opposite directions, as the figure on the next page shows. Assuming that (according to the uniformitarian plate-tectonics model) as the continental plates slowly spread apart and new magma wells up into the crack, the rocks "record" the orientation of the earth's magnetic field at the time of their formation, geologists conclude that the earth's magnetic north and south poles have exchanged places several times in the earth's history.

Scientists working within a Creation-Flood model believe that the magnetic banding detectable near the mid-ocean ridges was caused by the devastating breakup of the earth's crust during and immediately following the Genesis Flood. Except for this short disruption, the earth's overall magnetic field seems to have been decaying continuously in an exponential way since Creation, about 6000 years ago.

Some scientists, especially those who believe that the earth is relatively young, do not find the evidence for changing magnetic fields convincing for several reasons. One reason is that the magnetization in rocks is so small that it is difficult to measure. Some measuring devices can even change the magnetic field they measure. In addition, the evolutionary model assumes that the decay and recovery of the earth's magnetic dipole field is accomplished by storing energy in the weaker 4-pole and 8-pole fields that are components of the much stronger dipole field. However, recent data shows that the slight gain in "poly-pole" field intensity does not account for the loss of energy in the main dipole field during the past 40 years. The theory also assumes that the energy transfer between the fields is 100% efficient. Nowhere else in the universe is energy conversion 100% efficient. In short, the data "proving" that the earth's magnetic field has reversed is not very reliable.



Recent research has c
from the bands reveal
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The magnetic force:

$$F_{mag} = q v_\perp B \quad (\text{or } q v B \sin\theta)$$

Compare to the Electrostatic force:

$F_E = qE$ no velocity term here

F_{mag} requires velocity of the charged particle; F_E does not.

The velocity in Equation 21.2 is the *relative* velocity between the charge and the field. This means that the charge alone, the field alone, or both the charge and field may be moving in an external reference frame.

If Equation 21.2 is solved for B, an analysis of the resulting units gives

$$\frac{\text{N}}{\text{C}\cdot\text{m/s}} = \frac{\text{N}\cdot\text{s}}{\text{C}\cdot\text{m}}.$$

This ratio in SI units is the tesla (T).

The magnitude of the magnetic force on a point charge is calculated by the formula

$$F_{\text{mag}} = |q|vB\sin\theta, \qquad (21.2)$$

or just $F_{mag} = q v_\perp B$

where θ is the smallest angle (≤ 180°) between the velocity vector and the magnetic induction vector (**B**). The absolute value sign is required because the charge q may be either positive or negative.

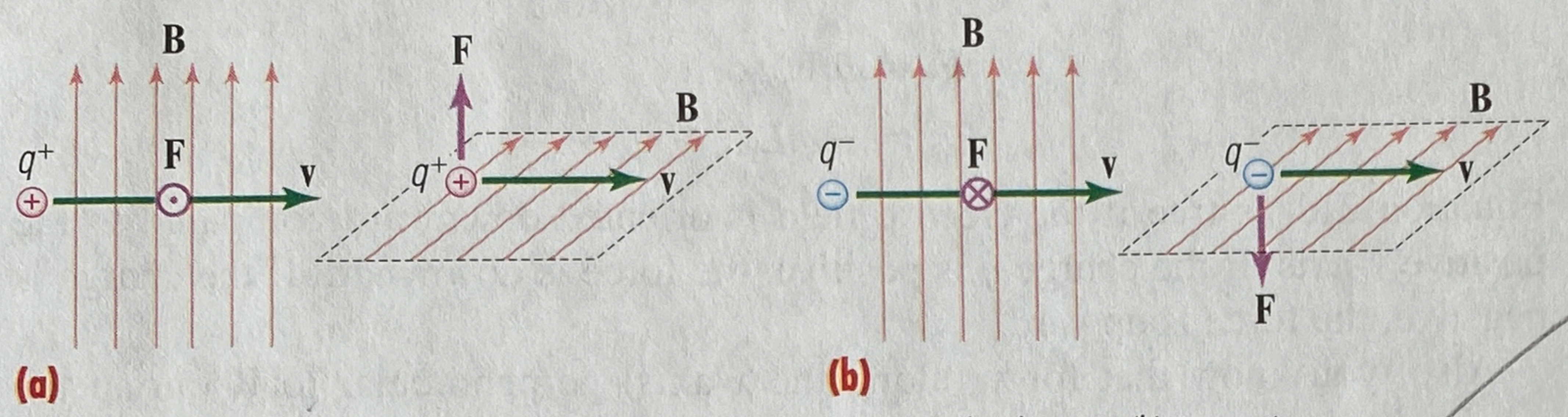
Surprisingly, the force of a magnetic field on a moving charge (or a moving field on a stationary charge) is *not* in the direction of the charge's relative motion, nor is it in the direction of the field; it is perpendicular to both the magnetic induction vector and the velocity vector of the charge. Because the magnetic force on the charge has no component in the direction of the charge's motion, it does no mechanical work on the charge. This interaction is similar to the force of gravity on an orbiting object. Earth's gravity keeps the moon in its orbit. However, the force is perpendicular to the moon's motion, so it does no work on the moon.

Similarly, a magnetic field changes the direction of a charged particle's motion but does no work on the particle. You can see that the magnetic force on a charge is a conservative force just like the electrostatic and gravitational forces.

When the charge's velocity vector is perpendicular to the magnetic field, Equation 21.2 reduces to

$$F_{\text{mag}} = |q|vB,$$

since the sine of 90° is 1. The direction of **F** for such a case is shown in Figure 21-15. The symbol ⊙ stands for a vector pointing up out of the page. Think of it as the view of the tip of an archery arrow pointing toward you. The symbol ⊗ denotes a vector pointing down into the page. It is the view you would have when looking at the feathers on an arrow pointing away from you. These symbols will be used throughout our discussion of magnetic fields to represent vectors in the third dimension.



21-15 Magnetic force on a moving charge. The charge in (a) is positive; the charge in (b) is negative.

To figure out the
orientation of a mag
field in a coil, see
Ch. 22 p. 500 for the
other right hand rule

21.8 Right-Hand Rule for Magnetic Force on a Positive Charge

the main concept

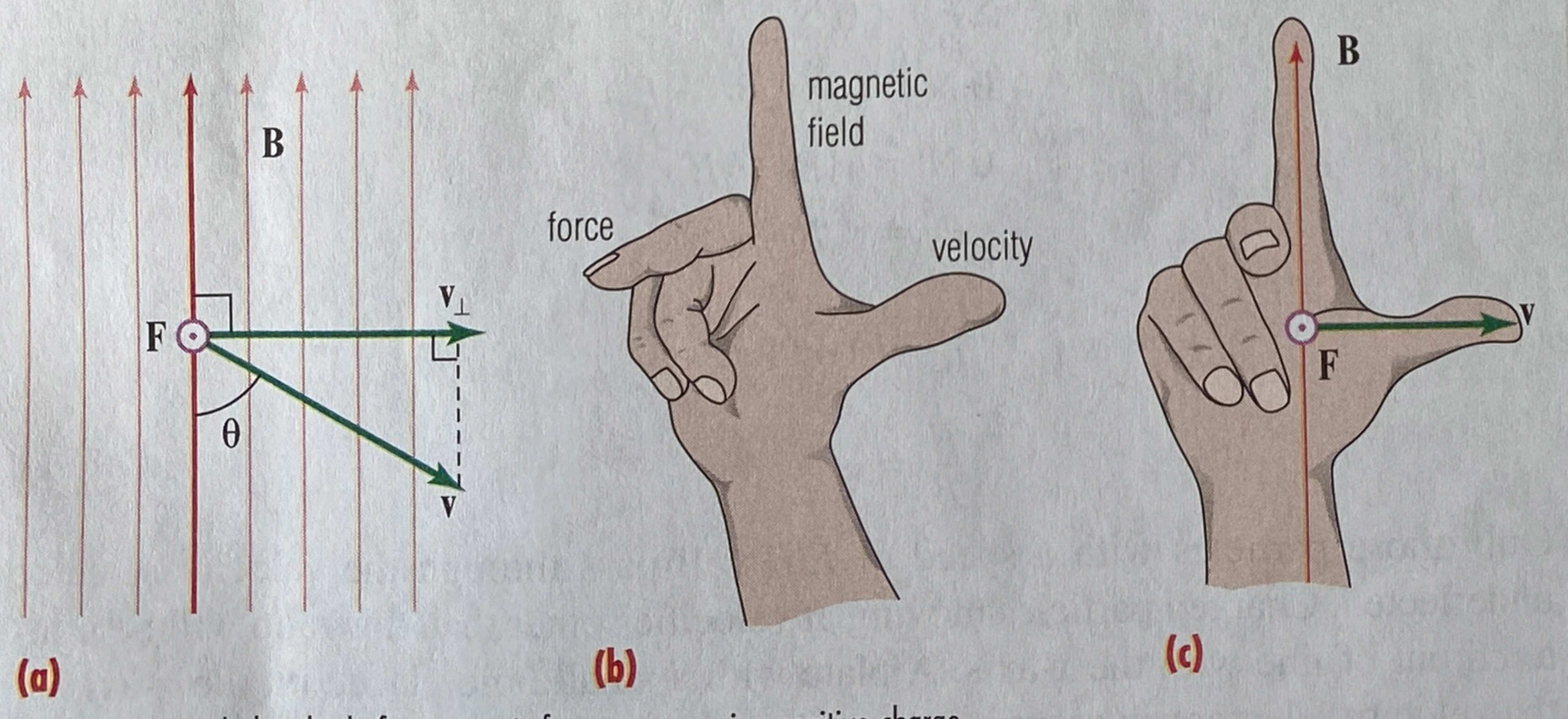
The force vector ($\mathbf{F}_{\text{mag}}$) is always perpendicular to the plane defined by **B** and **v**. You can find the direction of $\mathbf{F}_{\text{mag}}$ on a *positive* charge by another right-hand rule. Refer to Figure 21-16. Find the component of **v** that is perpendicular to **B**, as in figure (a). Extend your right index finger in the direction of the magnetic field. Extend your thumb in the direction of the perpendicular velocity component. Your middle finger extended at a right angle to the index finger and thumb points in the direction of the magnetic force vector ($\mathbf{F}_{\text{mag}}$). You may have to adjust the position of your hand in order to align your fingers in the required directions. Figure (c) shows how to position your hand to show the direction of the magnetic forces in figure (a). The direction of the force on a negative charge is opposite to that on a positive charge.

A magnetic field changes
the direction of a charged
particle motion:

B = the magnetic field
(N to S)

V = velocity of a point
charge (the current).

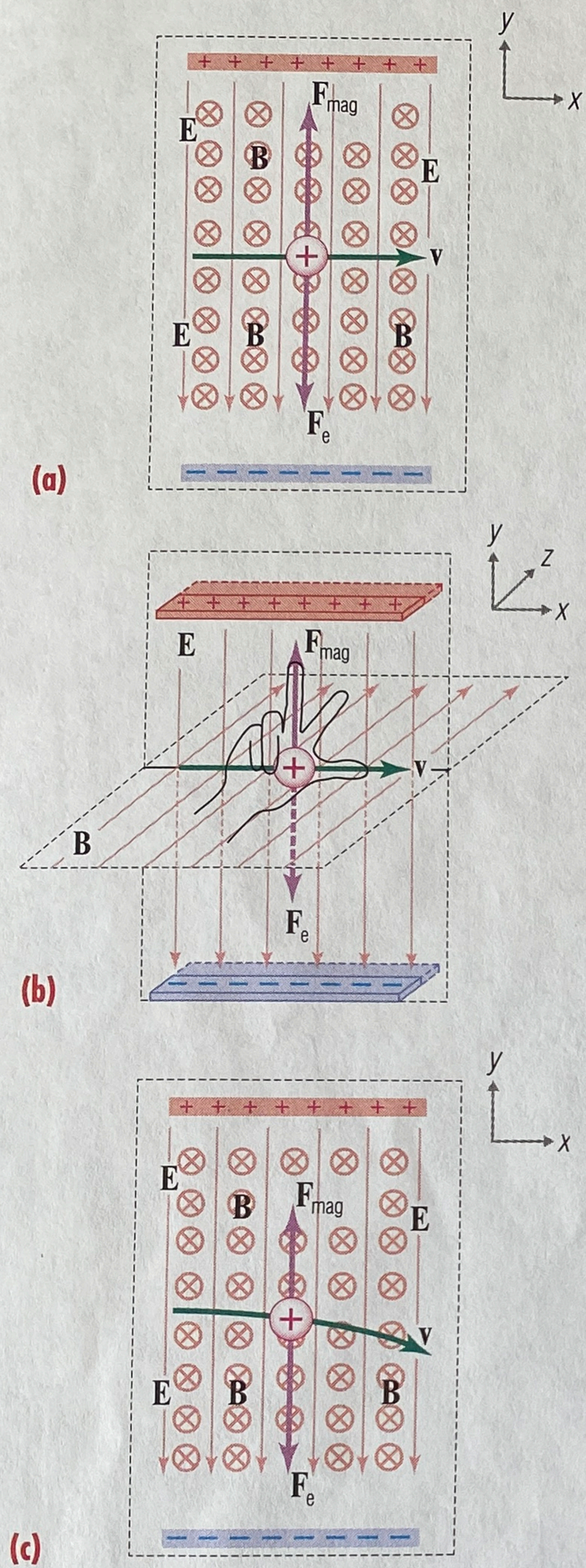
F = the force imposed
on the particle as
it travels with
velocity 'v'



21-16 The right-hand rule for magnetic force on a moving positive charge

21.9 Velocity Selectors and Mass Spectrometers

An electric field displaces a charged particle parallel to an electric field line. A magnetic field deflects a moving charged particle perpendicular to a magnetic



21-17 The motion of an electric charge through mutually perpendicular electric and magnetic fields; (a) magnetic forces are equal but opposite in direction; (b) three-dimensional view of balanced forces; (c) motion of charge when the electric force exceeds the magnetic force

A **mass spectrograph** is an instrument that analyzes and records the composition of mixtures or pure materials by determining the atomic or molecular masses of their constituent substances. Such devices are used in atmosphere quality monitors, for manufacturing quality assurance, and in forensic and archaeological research.

field line. What happens when both an electric field and a magnetic field influence a charged particle? The net force on the particle is the vector sum of the electrical force and the magnetic force:

$$\Sigma \mathbf{F} = \mathbf{F}_e + \mathbf{F}_{mag} \qquad (21.3)$$

If the electric field, the magnetic field, and the velocity vector of the particle are all perpendicular to one another, the magnetic force will be either in the same direction as the electric force or in the opposite direction, depending on the sign of the charge. Figure 21-17a shows a case in which the magnetic and electrical forces are in opposite directions. Using the components of the vectors, Equation 21.3 becomes

$$\Sigma F_y = F_{e\,y} + F_{mag\,y}.$$

In Chapter 19 you learned that

$$\mathbf{F}_e = |q|\mathbf{E}, \text{ so}$$

$$F_{e\,y} = -|q|E_y. \qquad (21.4)$$

Equation 21.4 is true if the electric field is oriented downward compared to the positive y-axis. If the charge q is positive, the force is downward. If the charge is negative, the force is upward.

Also, you know that for **v** (along the x-axis) perpendicular to **B** (along the z-axis),

$$F_{mag\,y} = |q|v_xB_z. \qquad (21.5)$$

Equation 21.5 is true for any possible combination of charge polarity (positive or negative), velocity component (right or left), and magnetic field direction (into or out of the page).

Therefore,

$$\Sigma F_y = -|q|E_y + |q|v_xB_z$$

$$\Sigma F_y = |q|(v_xB_z - E_y).$$

One analytical use of the arrangement of fields and forces in Figure 21-17 is as a **velocity selector**. In a velocity selector, the fields and the velocity are adjusted until the charged particles pass through the fields undeflected. In order for the particles to pass through undeflected (i.e., unaccelerated), the net force on them must be zero according to Newton's first law of motion:

$$\Sigma F_y = 0\text{ N}$$

$$0\text{ N} = |q|(v_xB_z - E_y)$$

$$0\text{ N} = v_xB_z - E_y$$

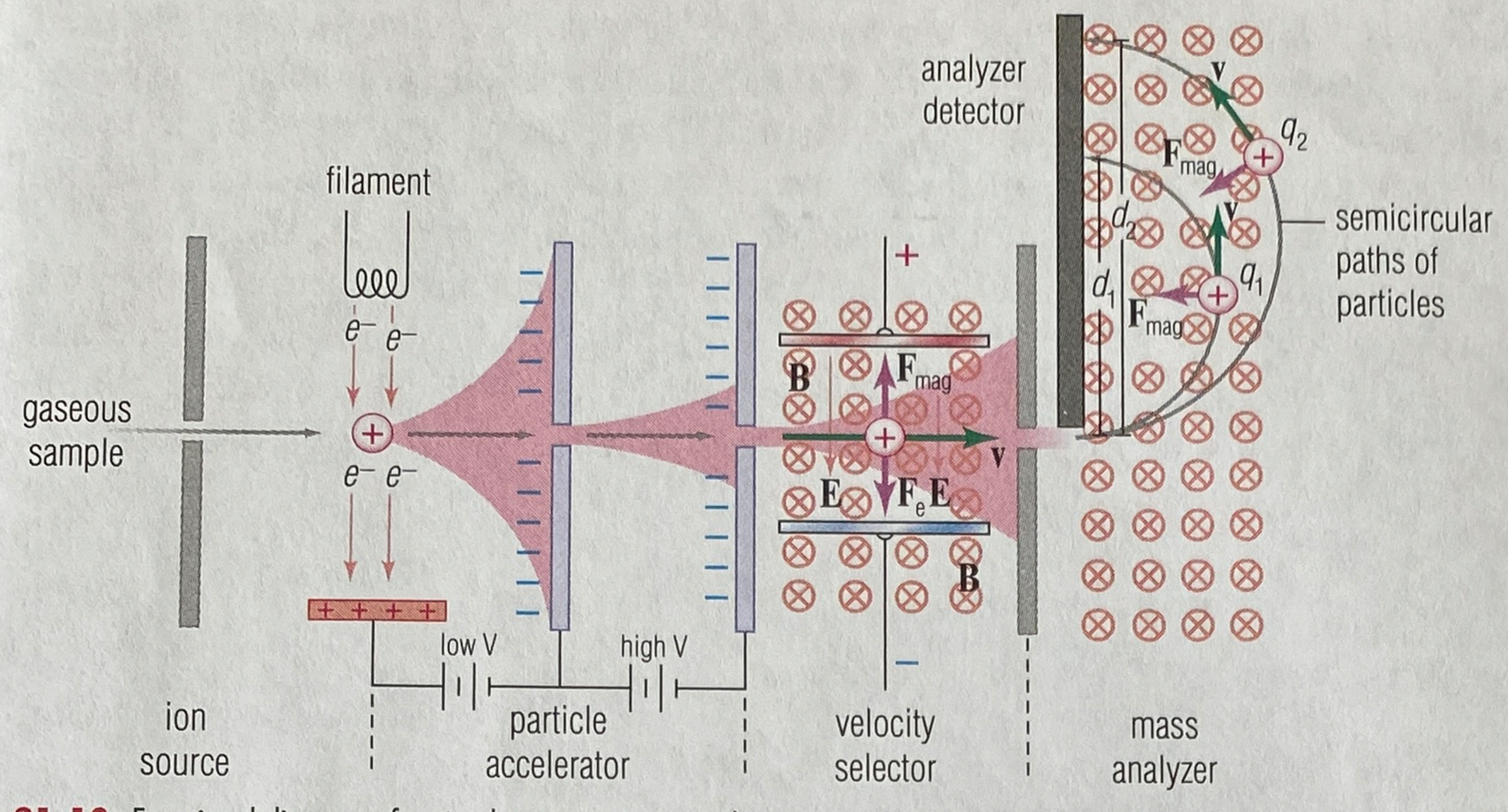
$$E_y = v_xB_z$$

$$\frac{E_y}{B_z} = v_x, \text{ or}$$

$$\frac{E}{B} = v \qquad (21.6)$$

Only those particles with a speed of E/B will pass through the velocity selector undeflected. Charged particles moving at velocities other than this ratio will be scattered out of line with the x-axis. A plate with a small hole placed on the x-axis of the velocity selector can prevent scattered particles from emerging from the selector. Only undeflected particles with a specific speed pass through the hole.

The velocity selector is a component of a mass spectrograph. A charged particle emerges from the velocity selector into a region with a magnetic field of precisely known strength oriented perpendicular to the particle's velocity. The



21-18 Functional diagram of a simple mass spectrograph

← The "velocity selector" led to J.J. Thomson's discovery of "corpuscles" (electrons)

↓

magnetic field influences the particle to follow a semicircular path onto a photographic film or into an electronic detector. The radius of this path is directly proportional to the particle's mass.

To find the exact relationship between path radius and the mass, remember the formula for centripetal acceleration:

$$a_c = \frac{v_t^2}{r}$$

The magnetic force to cause the acceleration must be

$$F_{\text{mag}} = ma_c$$

$$F_{\text{mag}} = m\frac{v_t^2}{r}.$$

However, when the particle exits the velocity selector and enters the spectrometer magnetic field, its velocity vector is perpendicular to the magnetic field. You know that when the particle's velocity and the magnetic field are perpendicular,

$$F_{\text{mag}} = |q|vB.$$

The particle's tangential speed and its velocity selector exit speed are the same. Therefore,

$$m\frac{v_t^2}{r} = m\frac{v^2}{r} = |q|vB$$

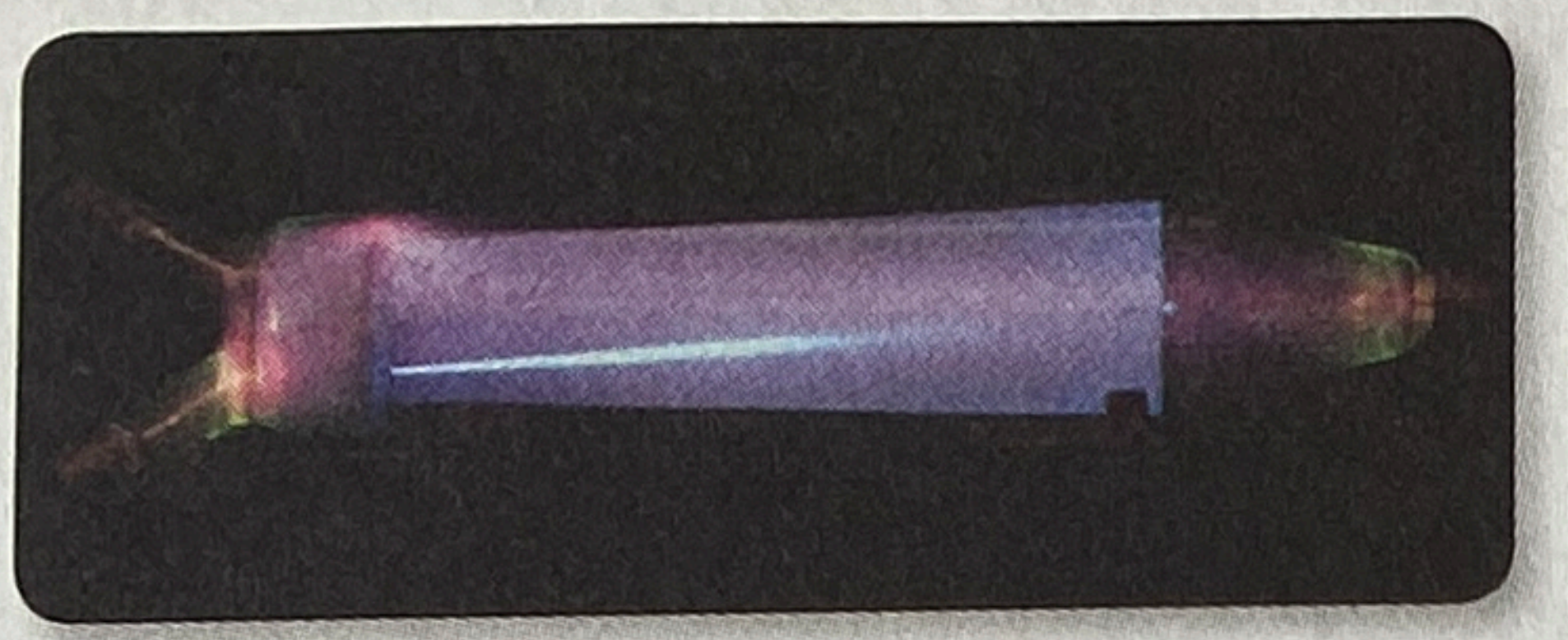
$$mv^2 = |q|vBr$$

$$\boxed{m = \frac{|q|Br}{v}}. \qquad (21.7)$$

The distance from the exit of the velocity selector to where the particle of interest enters the detector or is imaged on film is the diameter of its semicircular path, *d*. The radius (*r*) is half the diameter. If you know the charge on a particle, the magnetic and electric fields in the velocity selector, and the magnetic field in the spectrograph, you can find the mass of the particle as a function of its deflection radius. In order to get a detectable reading with this technique, many particles of the same mass must be present.

21.10 Discovery of the Electron

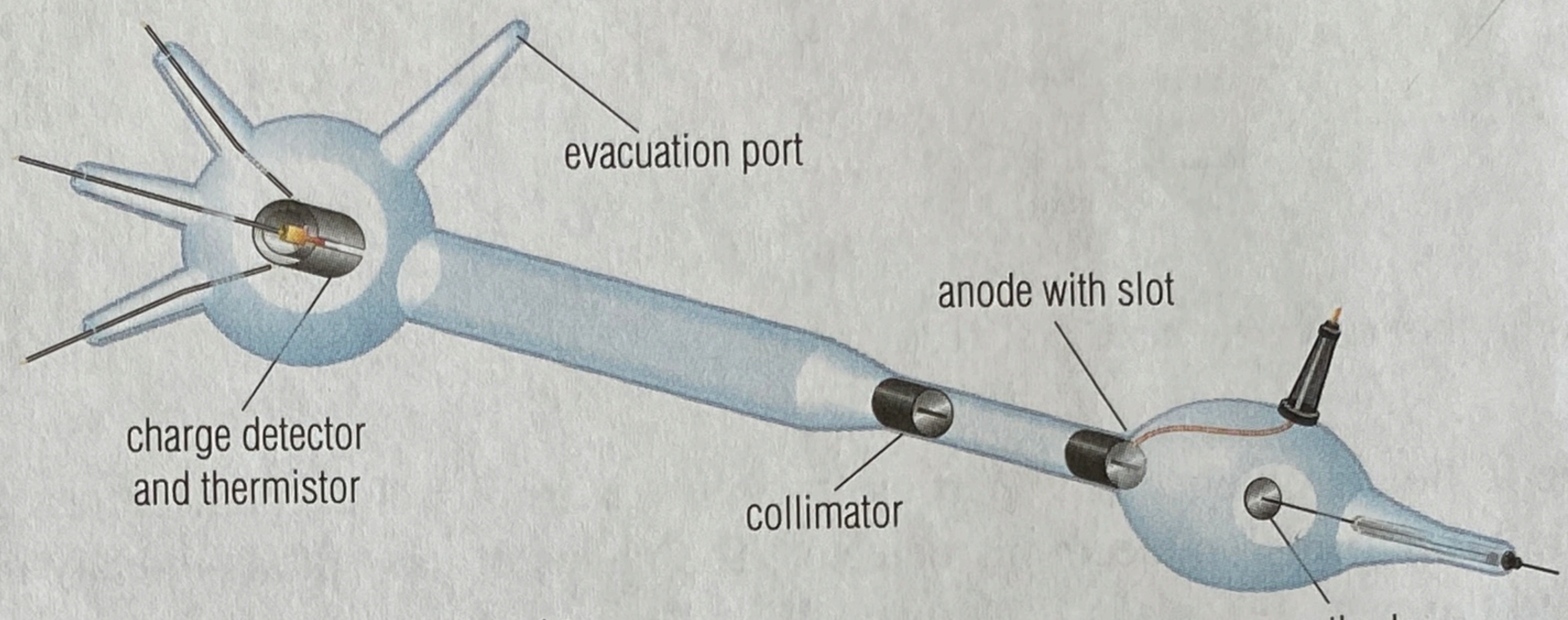
In one of his many experiments with cathode rays, J. J. Thomson used an arrangement of magnetic and electric fields similar to a velocity selector to confirm that



21-19 A cathode-ray tube contains an inert gas to make the beam of electrons visible.

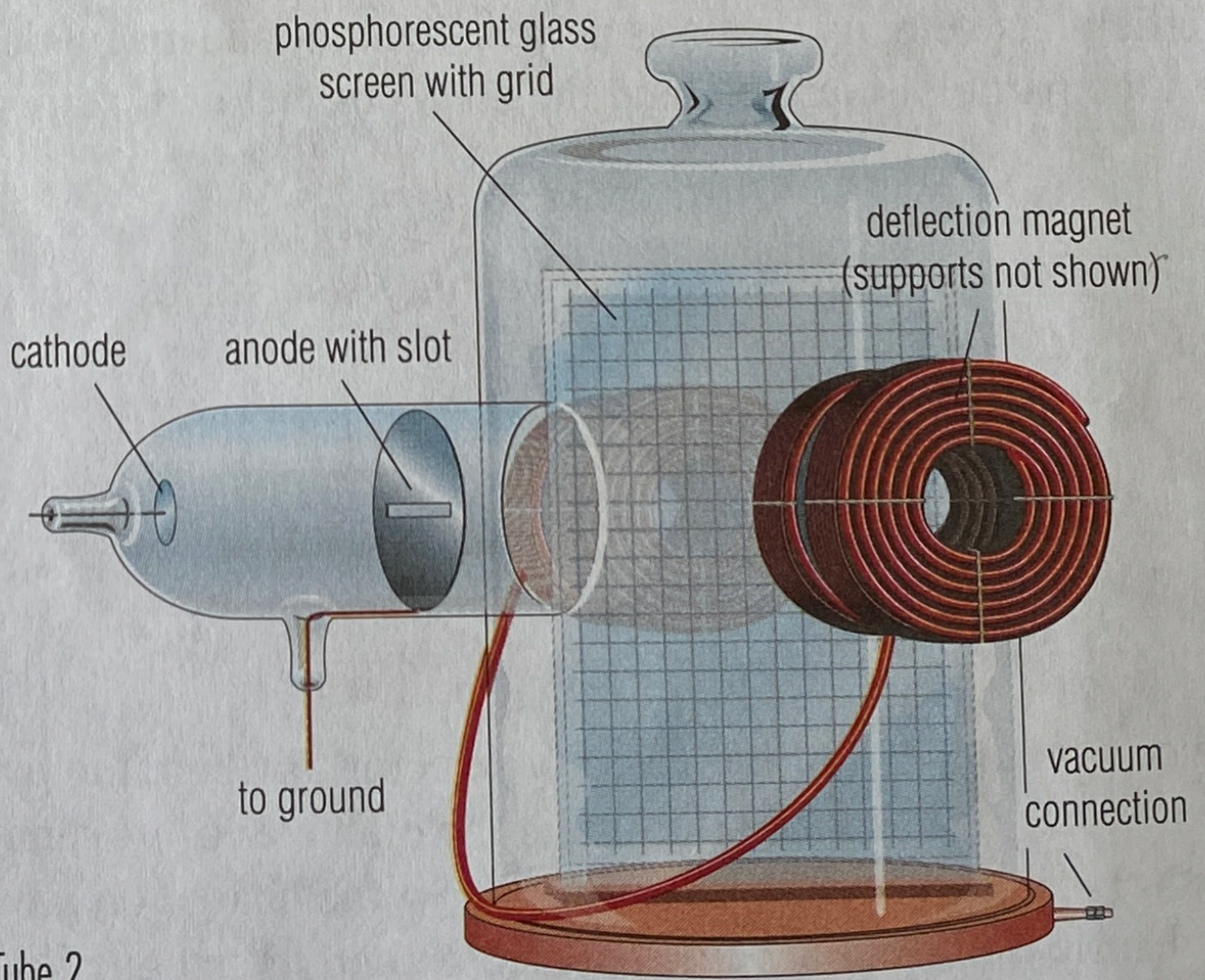
cathode rays were particles and to determine their mass-to-charge ratio. He used several different **cathode-ray tubes (CRT)** to do this. Though Thomson varied the configuration of this important experimental device for his purposes, cathode-ray tubes contain a minimum of three essential parts—a cathode, an anode, and a sealed glass tube to separate and insulate them from each other. The cathode is typically a solid plate of metal attached to a source of negative electrical potential, and the anode is a separate plate, often with a small hole or slot in it, connected to a potential that is positive relative to the cathode. The electrical connections to the external voltage sources pass through airtight penetrations in the glass envelope.

Thomson concluded that cathode rays were actually particles having mass because their deflection in electric and magnetic fields demonstrated that they had inertia and otherwise obeyed Newton's laws of motion.



21-20 Schematic of Thomson's Tubes 1 and 3

When a high potential difference existed between the cathode and the anode, cathode rays streamed from the cathode toward the anode. Because the anode had a hole in it, many of the rays passed through the anode to the end of the tube. Thomson showed that magnetic and electric fields could divert the path of the cathode rays, especially when the tube was almost completely evacuated. Through a series of experiments, Thomson was able to prove that the cathode rays were actually negatively charged bits of matter and that they constituted a more basic particle of matter than atoms or atomic ions. He called the particles *corpuscles.*



21-21 Schematic of Tube 2

21.11 Modeling the Electron's Mass-to-Charge Ratio (*m*/|*q*|)

In his research, Thomson suggested that the kinetic energy (*E*) of the corpuscles in a discrete quantity of cathode rays was given by

$$E = \tfrac{1}{2}Nmv^2, \tag{21.8}$$

where E was given in the CGS unit of energy, the erg, N was the total number of corpuscles, m was the mass of each corpuscle in *eleventh-grammes (gXI)*, and v was their average velocity in cm/s. Their total charge, Q, could be expressed as

$$Q = Nq, \tag{21.9}$$

where q was their individual charge in electrostatic units (esu).

If r is the radius of curvature of the deflected cathode rays under the influence of a stable magnetic field, B, then from Equation 21.7,

$$Br = \frac{mv}{|q|}. \tag{21.10}$$

Thomson labeled the quantity Br with the symbol I in his equations to simplify them. This quantity had the unit of gauss-centimeters (G·cm). Combining and rearranging Equations 21.8–10, he could determine the mass-to-charge ratio of a corpuscle by measuring the total charge deposited by the corpuscles in the tube, the energy deposited, the magnetic field used to deflect the corpuscles, and the radius of deflection:

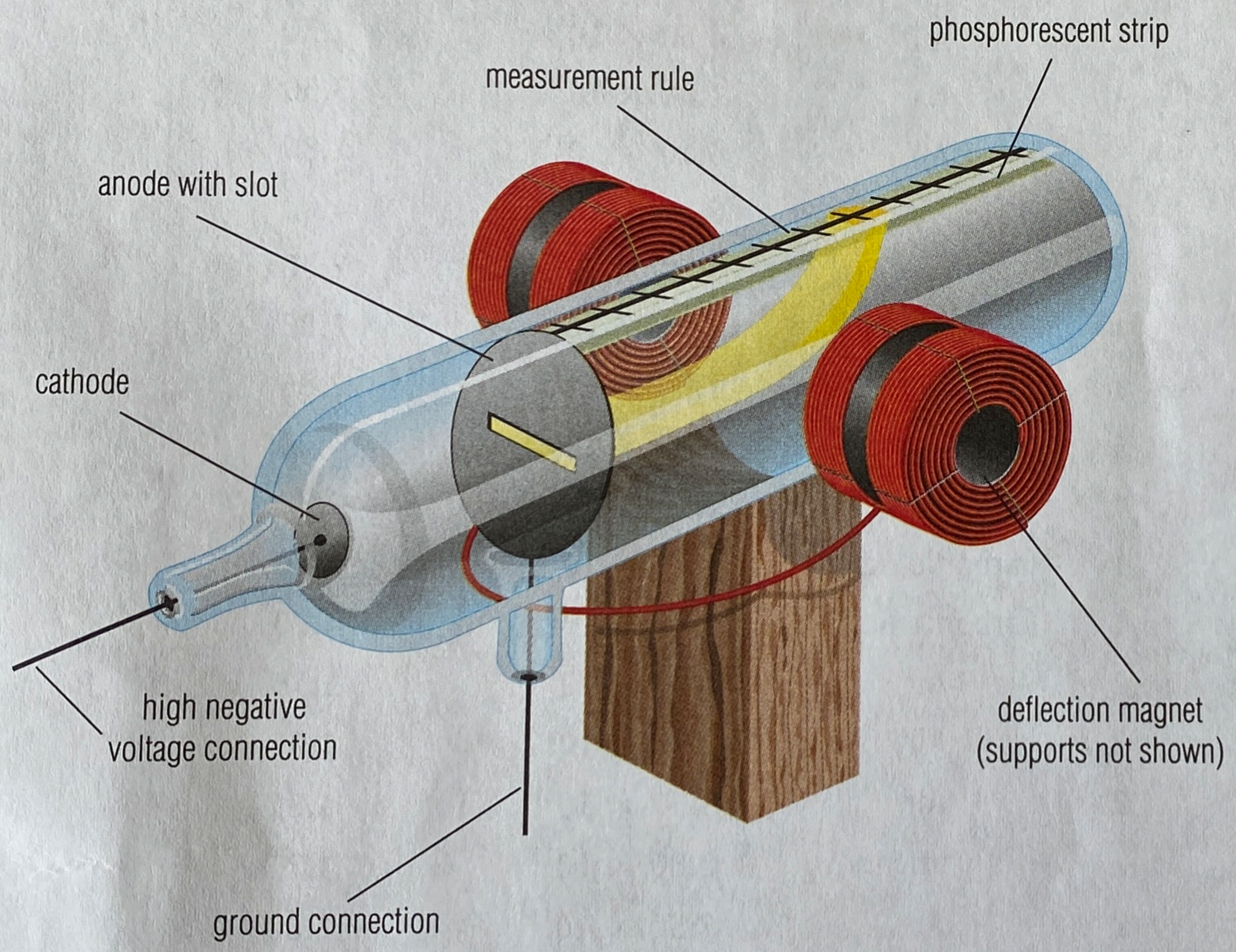
$$\frac{m}{|q|} = \frac{I^2|Q|}{2E} \tag{21.11}$$

In Thomson's 1897 paper, the quantity m/q had the units eleventh-grammes/esu (gXI/esu).

$1 \text{ erg} = 10^{-7}$ J

In England around 1900, the British Association (BA) introduced a complex system of units that supposedly simplified calculations for electromagnetic investigations. The **eleventh-gramme (gXI)** was an extremely small unit of mass equal to 1×10^{-11} g, which seems to be the mass unit used by Thomson.

Thomson's intent in his experiments with cathode rays was twofold: first, to prove that they were matter rather than immaterial rays, and second, that they were substantially less massive than an atom. Scientists had already estimated the mass-to-charge (m/q) ratio of positive hydrogen ions (protons) in a chemical solution. Thomson's task was to show that a cathode ray's m/q ratio was much smaller than a hydrogen ion's.



21-22 CRT used to measure the magnetic deflection radius

Thomson measured the total charge deposited by the cathode rays with an electrometer connected to collector plates inside the CRT. Using a thermistor to measure the increase of temperature at the cathode rays' point of impact, he determined the total kinetic energy deposited by the particles. He calculated the magnetic field according to the known characteristics of electromagnetism between the two current-carrying coils surrounding the CRT. The curvature of the deflected path the corpuscles took could be observed by the glow they imparted to a phosphorescent material applied to the inside of the CRT's glass envelope. He calculated the radius of the path of the rays using simple geometry. This data

A **thermistor** is an electrical device consisting of a conductive material whose resistance varies proportionately with temperature.

was obtained using three different kinds of CRTs with a variety of cathode metals and filling gases. You will use Thomson's data to model his results in order to determine the mass-to-charge ratio of an electron.

Thomson discovered that the $m/|q|$ ratio was essentially constant no matter what material the cathode was made of or the kind of gas filling the tube. He concluded that all materials contain small, negatively charged particles with a mass-to-charge ratio of

$$\frac{m}{|q|} \cong 2.1 \times 10^{-12} \text{ kg/C}$$

in SI units. Considering the relatively crude methods Thomson employed, this result compares well with the modern accepted $m/|q|$ value for the electron of 5.686×10^{-12} kg/C. As a matter of comparison, the m/q ratio of a hydrogen ion (a proton), the smallest possible atomic ion, is 1.044×10^{-8} kg/C, so Thomson thus concluded that corpuscles were distinct particles found within atoms.

TABLE 21-2

Selected Cathode Ray Experiment Data (Thomson, 1897)

Tube	CRT Gas	*E/Q* (erg/esu)	*I* (G·cm)
1	Air	4.60×10^{11}	2.30
1	Air	1.80×10^{12}	3.50
1	Air	6.10×10^{11}	2.30
1	Air	2.50×10^{12}	4.00
1	Air	5.50×10^{11}	2.30
1	Air	1.00×10^{12}	2.85
1	Air	1.00×10^{12}	2.85
1	Hydrogen	2.10×10^{12}	4.60
1	Carbonic Acid*	8.40×10^{11}	2.60
1	Carbonic Acid*	1.47×10^{12}	3.40
1	Carbonic Acid*	3.00×10^{12}	4.80
2	Air	2.80×10^{11}	1.75
2	Air	4.40×10^{11}	1.95
2	Air	3.50×10^{11}	1.81
2	Hydrogen	2.80×10^{11}	1.75
2	Air	2.50×10^{11}	1.60
2	Carbonic Acid*	2.00×10^{11}	1.48
2	Air	1.80×10^{11}	1.51
2	Hydrogen	2.80×10^{11}	1.75
2	Hydrogen	4.40×10^{11}	2.01
2	Air	2.50×10^{11}	1.76
2	Air	4.20×10^{11}	2.00
3	Air	2.50×10^{11}	2.20
3	Air	3.50×10^{11}	2.25
3	Hydrogen	3.00×10^{11}	2.50

* Former name for carbon dioxide

21B Section Review

1. What factors determine the magnitude and direction of the magnetic force on an electrical charge?
2. Why is it necessary to use the absolute value of the charge in Equation 21.2 when finding the magnitude of the magnetic force?
3. How do you determine the direction of the magnetic force on a charge moving through a magnetic field?
4. When a charged particle is propelled along a path that is perpendicular to mutually perpendicular magnetic and electric fields, what condition must exist for the particle to maintain a straight path?
5. Briefly discuss the principle of operation of a mass spectrograph.

DM6. a. What type of device was used by J. J. Thomson to determine the mass-to-charge ratio of an electron?

b. Briefly describe its construction.

DM7. After completing his experiments, what fact led Thomson to conclude that all matter contains the small, negatively charged particles that he called corpuscles?

DM✪8. What atomic theory of matter had to be discarded with the discovery of the electron?

DM✪9. Equation 21.11 can be rearranged in the following way:

$$\frac{|Q|}{E} = \frac{m}{|q|}\frac{2}{I^2}.$$

a. Using Thomson's data in Table 21-2, make a scatter plot of $|Q|/E$ versus $2/I^2$.

b. Apply a best-fit trendline to your data. If the best fit seems to be linear, force the y-intercept to zero, if possible. Report the equation and r^2 value of the fit.

c. What is the relationship of the $m/|q|$ factor in the above equation to your scatter plot trendline?

21B Objectives

After completing this section, I can

- ✓ state the factors that affect the magnetic force exerted on a charge moving through a magnetic field.
- ✓ calculate the magnetic force acting on a moving charge.
- ✓ use the right-hand rule for magnetic force to determine the direction of the force on a charge moving through a magnetic field.
- ✓ describe how a velocity selector works and its use in mass spectrometers.
- ✓ describe J. J. Thomson's experiments with cathode-ray tubes that led to the discovery of the electron.
- ✓ determine the mass-to-charge ratio of an electron using Thomson's original data.
- ✓ explain the significance of the value of the mass-to-charge ratio Thomson obtained from his experiment.

Now on to rotating loops and electric motors...

21C ELECTROMAGNETISM AND CONDUCTORS

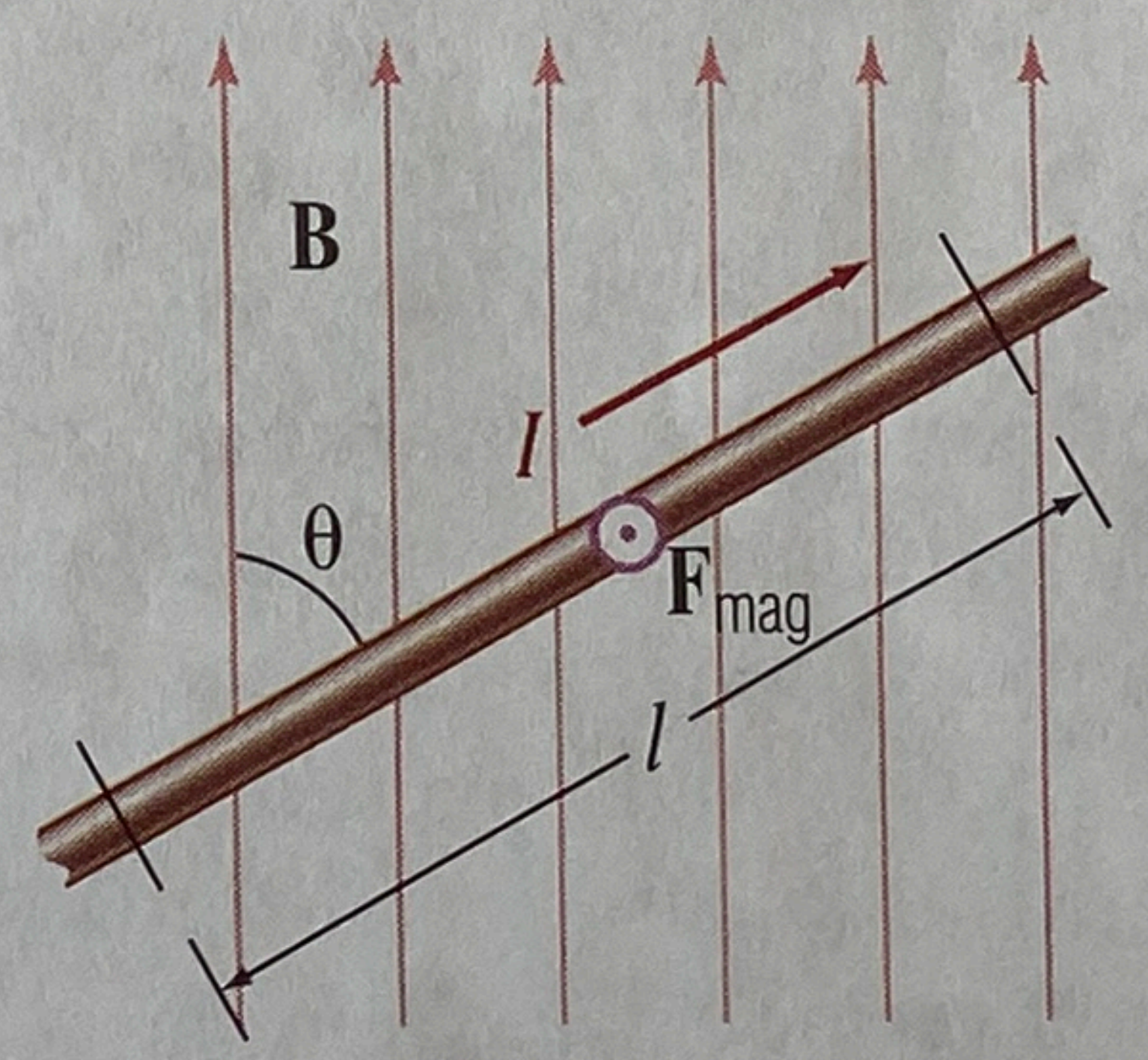
21.12 Magnetic Force on Currents

A current is simply a collection of moving charges. What, then, is the magnitude of the magnetic force on a current-carrying wire segment placed in a magnetic field? In Section 21B you learned that the magnitude of the magnetic force on a moving charge is

$$F_{\text{mag}} = |q|vB \sin\theta. \quad \text{or just } \boxed{F_{mag} = q v_\perp B}$$

The product qv for a single charge has the units C·m/s. This is analogous to the product Il for a current of I in a wire of length l (units: (C/s)·m). The latter product includes the speed and polarity of all the charges in the wire. The units are the same:

$$|q|v \Rightarrow \text{C·m/s} \Rightarrow Il$$



21-23 Magnetic force on a current-carrying conductor

In fact, experiments have shown that the force a magnetic field **B** exerts on a wire segment of length l carrying a current I is

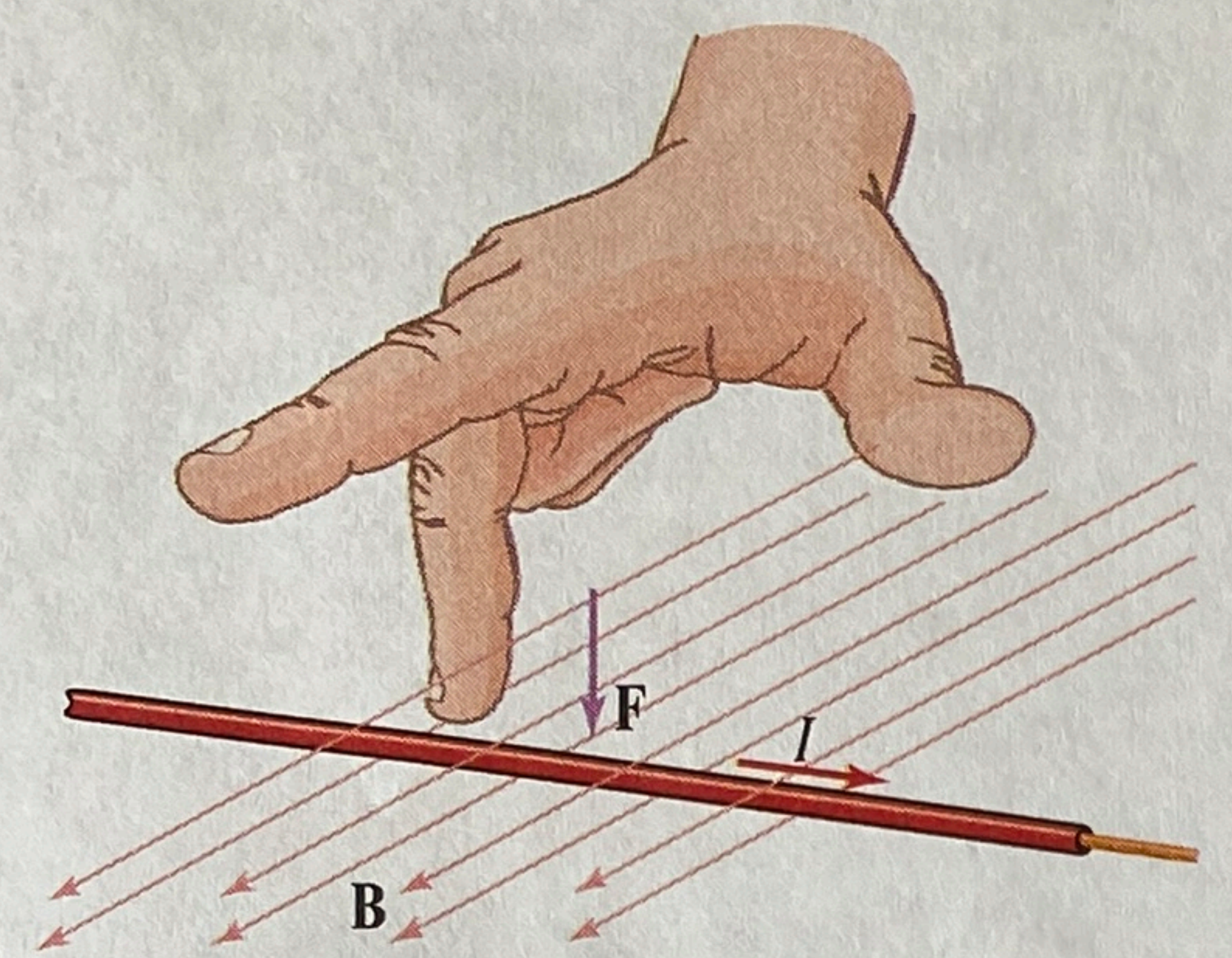
for length of wire $l_\perp$

$$F_{\text{mag}} = IlB \sin\theta, \quad \boxed{F_{mag} = I l_\perp B} \tag{21.12}$$

where θ is the smallest angle (≤ 180°) between the current direction and **B**.

21.13 Right-Hand Rule for Magnetic Force on a Conductor

The direction of the force on a conductor is found in the same way as the direction of the force on an individual moving positive charge. Point your right thumb in the direction of conventional current flow (or its component) that is perpendicular to the magnetic field. Point your index finger at a right angle to your thumb in the direction of the magnetic field. Hold the middle finger perpendicular to the other two fingers to indicate the direction of the magnetic force on the conductor.

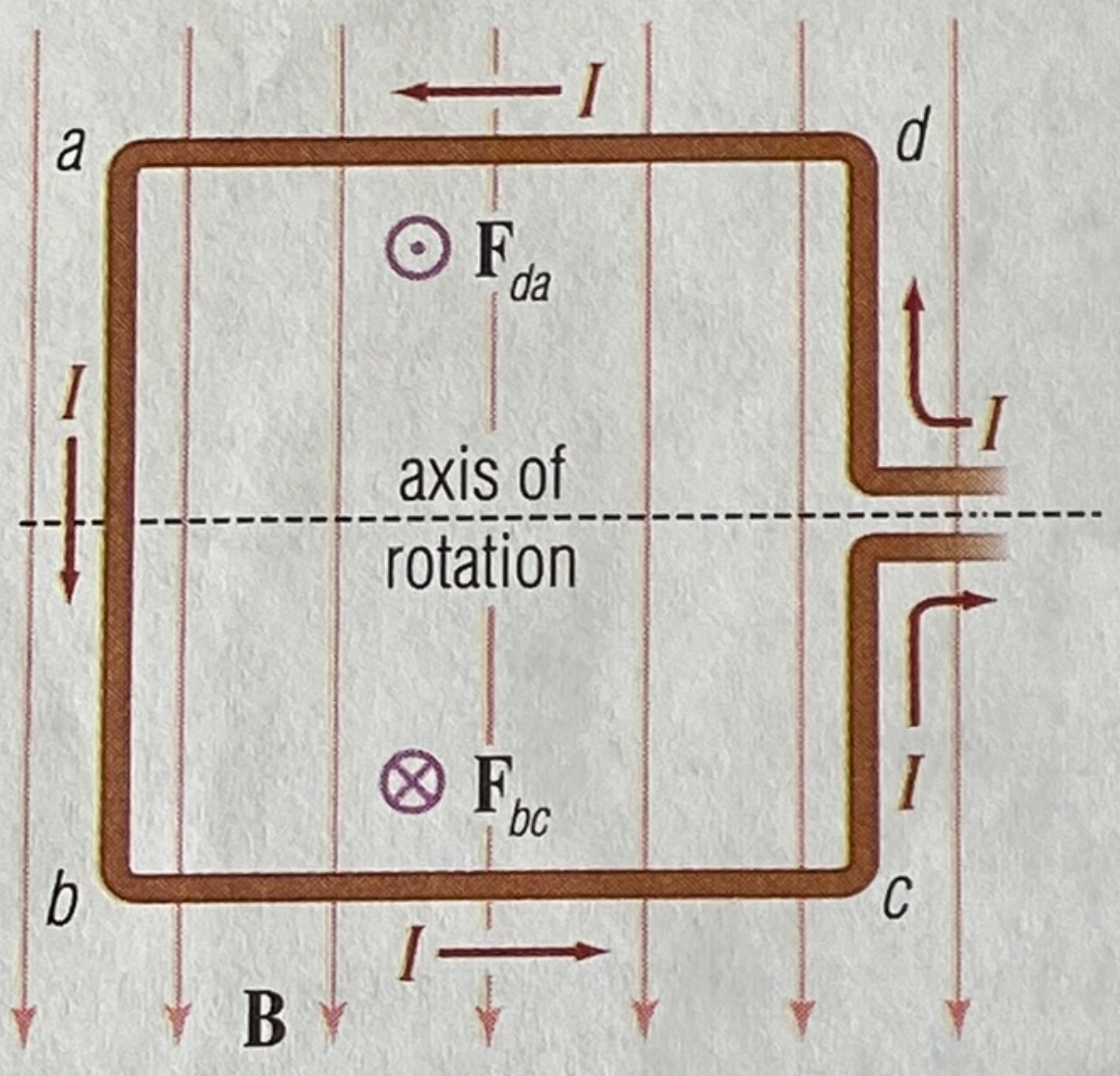


21-24 The right-hand magnetic rule for magnetic force on a conductor

21.14 Rotating Current Loops

One problem with Equation 21.12 is that it applies only to a segment of a conductor. In practice, continuous currents exist only in complete circuits. Therefore, in order to make use of the magnetic force, conductors in the shape of a loop must somehow move within a magnetic field. In order to find the net force exerted on a loop conductor, you must sum the forces acting along its length.

Consider a square conductor loop supplied with a continuous current (I), such as in Figure 21-25. The loop is positioned in a uniform magnetic field (**B**) as shown. The currents in segments ab and cd are in the same direction as **B** and $-$**B**, respectively. Therefore, sides ab and cd experience no magnetic force ($\sin 0^\circ = \sin 180^\circ = 0$).



21-25 Magnetic force on a current loop

The force on side bc is

$$F_{bc} = IlB \sin 90^\circ$$

$$F_{bc} = IlB.$$

The direction of the force is into the page, as shown in the figure.

The force on side da is

$$F_{da} = IlB \sin 90^\circ$$

$$F_{da} = IlB$$

$$F_{da} = F_{bc} = F.$$

However, the direction of $\mathbf{F}_{da}$ is out of the page and opposite to the direction of $\mathbf{F}_{bc}$. The sum of these forces is zero, so the square loop will not be translated from its position.

Although there is no net translational force on the loop, it will rotate if free to do so. Therefore, there must be a net torque on the circuit. Recall from Chapter 7 that the torque (τ) on an object results when a force is applied to a moment arm at a distance r from the axis of rotation. The formula for the magnitude of torque is

$$\tau = rF \sin \theta,$$

where θ is the smallest angle between **F** and **r** when the two vectors are placed tail-to-tail. In Figure 21-26 the torque on side bc is

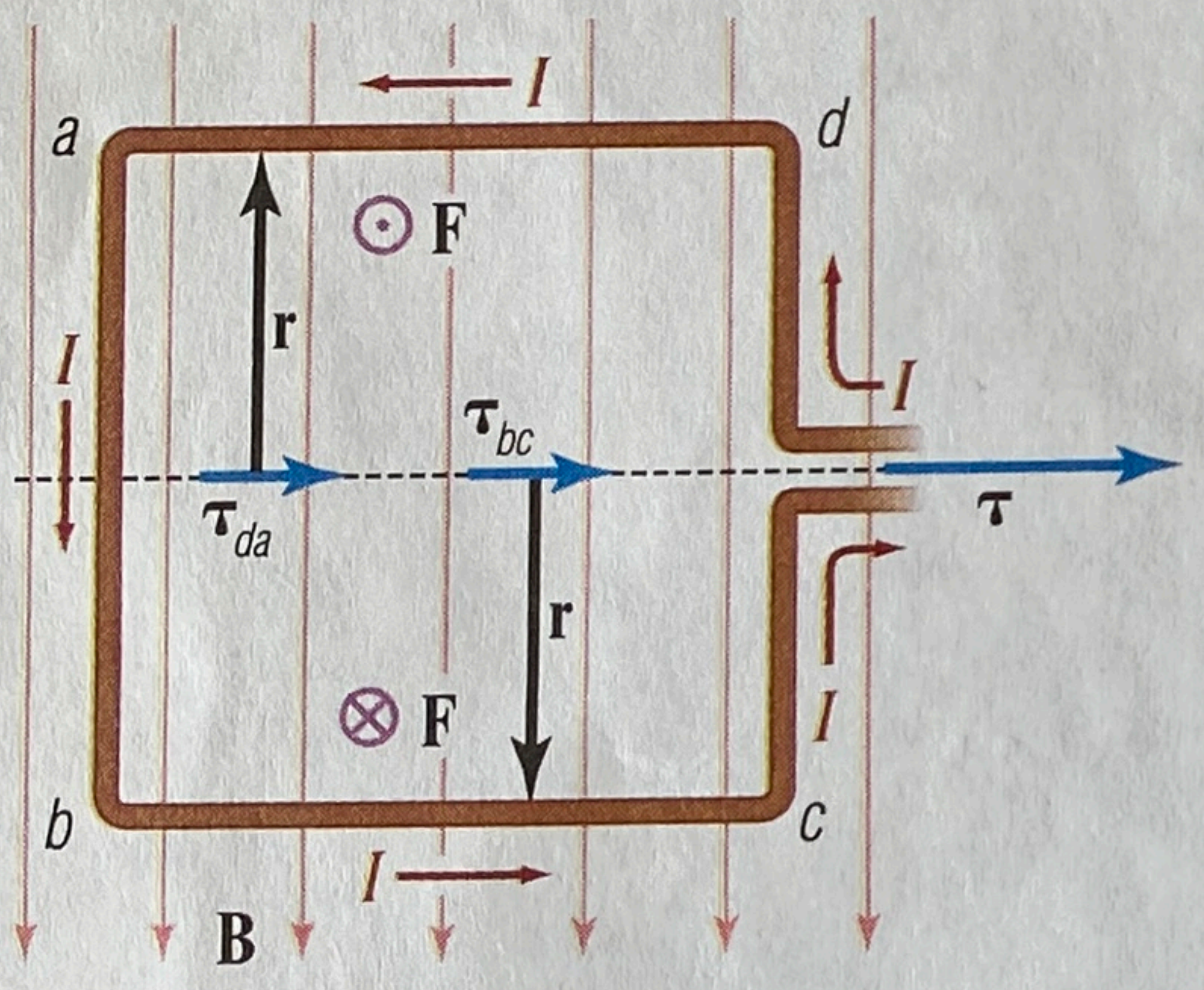
$$\tau_{bc} = rF \sin 90^\circ$$

$$\tau_{bc} = rF.$$

The direction of the torque is found by using the *right-hand rule for torques.* The torque on side da is

$$\tau_{da} = rF \sin 90^\circ$$

$$\tau_{da} = rF.$$



21-26 Torque on a current loop

Problem-Solving Strategy 21.3

The right-hand rule for torques: Hold your right hand flat with the thumb extended at a right angle to the fingers. Point your fingers away from the axis of rotation parallel to the position vector **r**. Curl your fingers toward the direction of the force vector where it is applied to the moment arm. Your thumb points in the direction of the torque vector.

The magnitudes of the torques on segments *bc* and *da* are equal and in the same direction. Therefore, the total torque is

$$\tau = \tau_{bc} + \tau_{da}$$

$$\tau = rF + rF$$

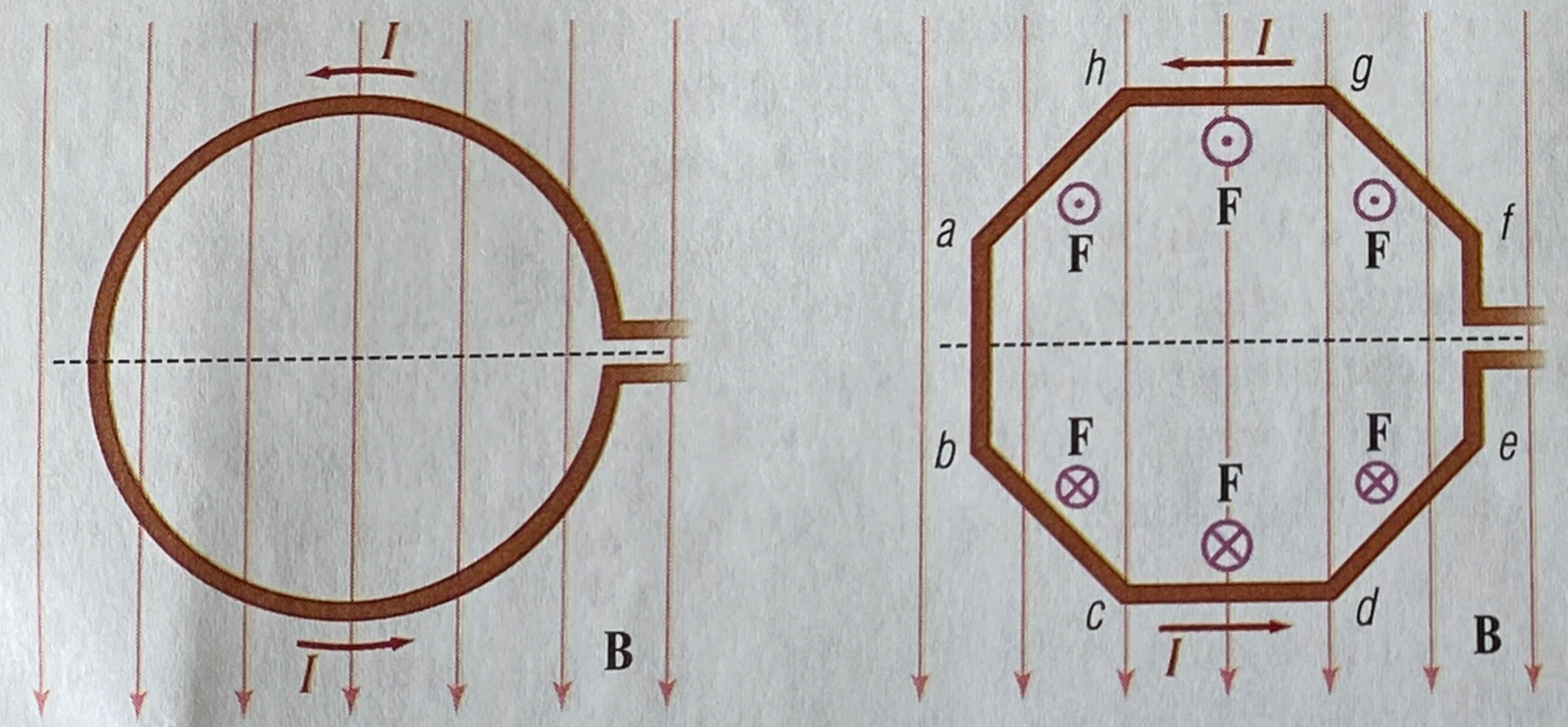
$$\tau = 2rF.$$

In Figure 21-28, each segment of the square current loop is perpendicular to **B**. Therefore, all the sides experience forces of the same magnitude,

$$F = IlB.$$

The net torque is now zero, since all the forces are parallel to their respective moment arms (**r**) and the current loop does not rotate. The current loop in Figure 21-25 will tend to rotate until its plane is perpendicular to **B**. At that point it has no net torque, so it continues to rotate at a constant speed. As the loop moves through the perpendicular position and is no longer perpendicular to **B**, the torque generated by the magnetic forces on the current loop tends to return it to a perpendicular position. Because this is a restoring force, the current loop will oscillate about its equilibrium position, perpendicular to **B**.

Circular current loops have no straight segments. You can get an idea of the direction of the force or torque on a circular circuit by approximating it with a polygon. The currents in segments *ab* and *ef* in Figure 21-29 are parallel to **B**, so there is no force on these segments. The direction of the forces on the other segments can be found from the right-hand rule and Equation 21.12. They are indicated in the figure. As you can see, the circular loop will also tend to rotate.



21-29 Analyzing the magnetic force on a circular current loop

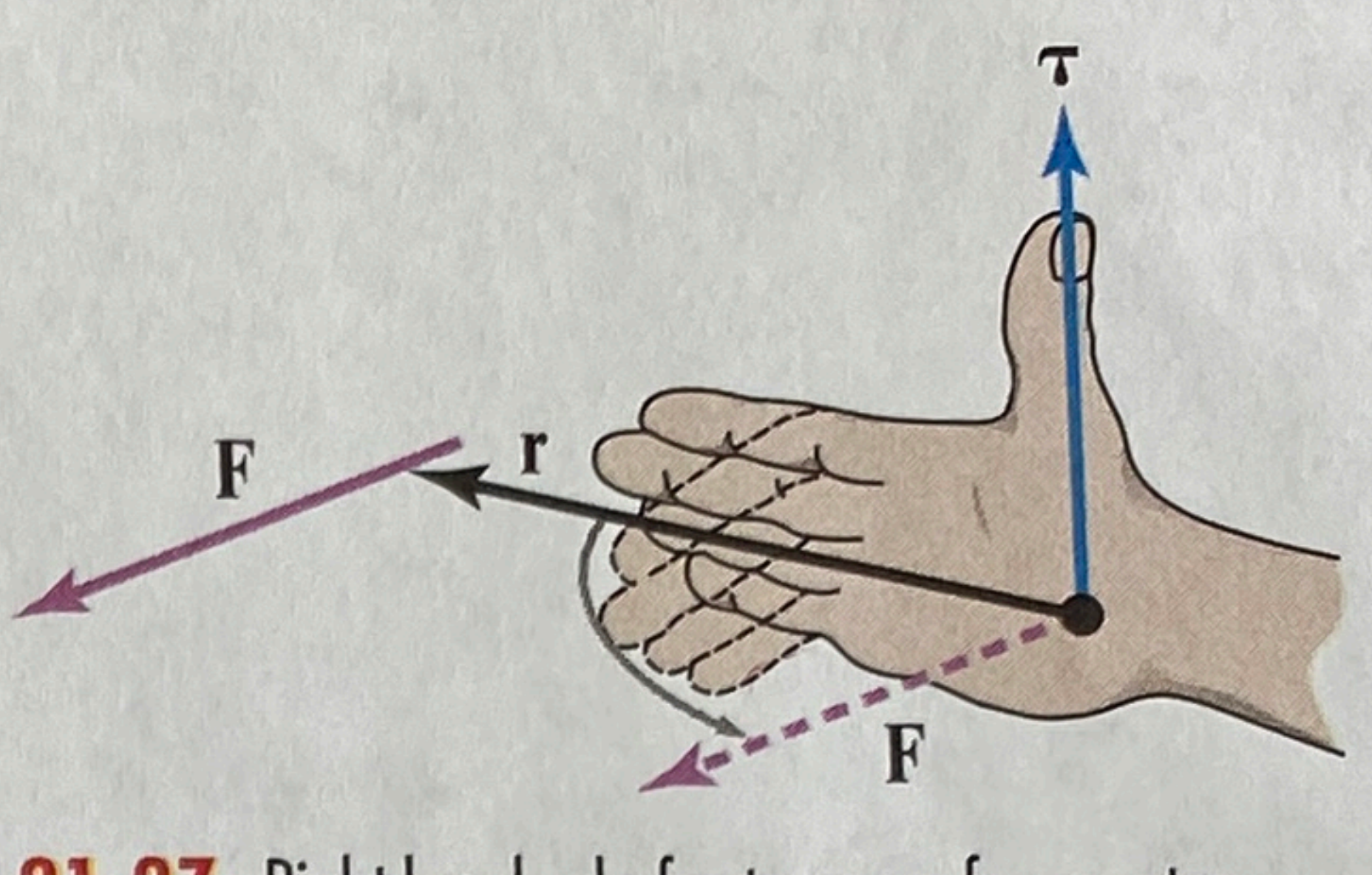
21.15 Rotating Coils

Coils of wire behave like stacks of current loops. The wire may be wound around a solid core, or it may be wound without a core. Consider a coil of *n* wraps or windings. The force of the magnetic field on this coil is the same as the force of the field on *n* current loops with the same width and height. That is, for a coil, the force on a side is

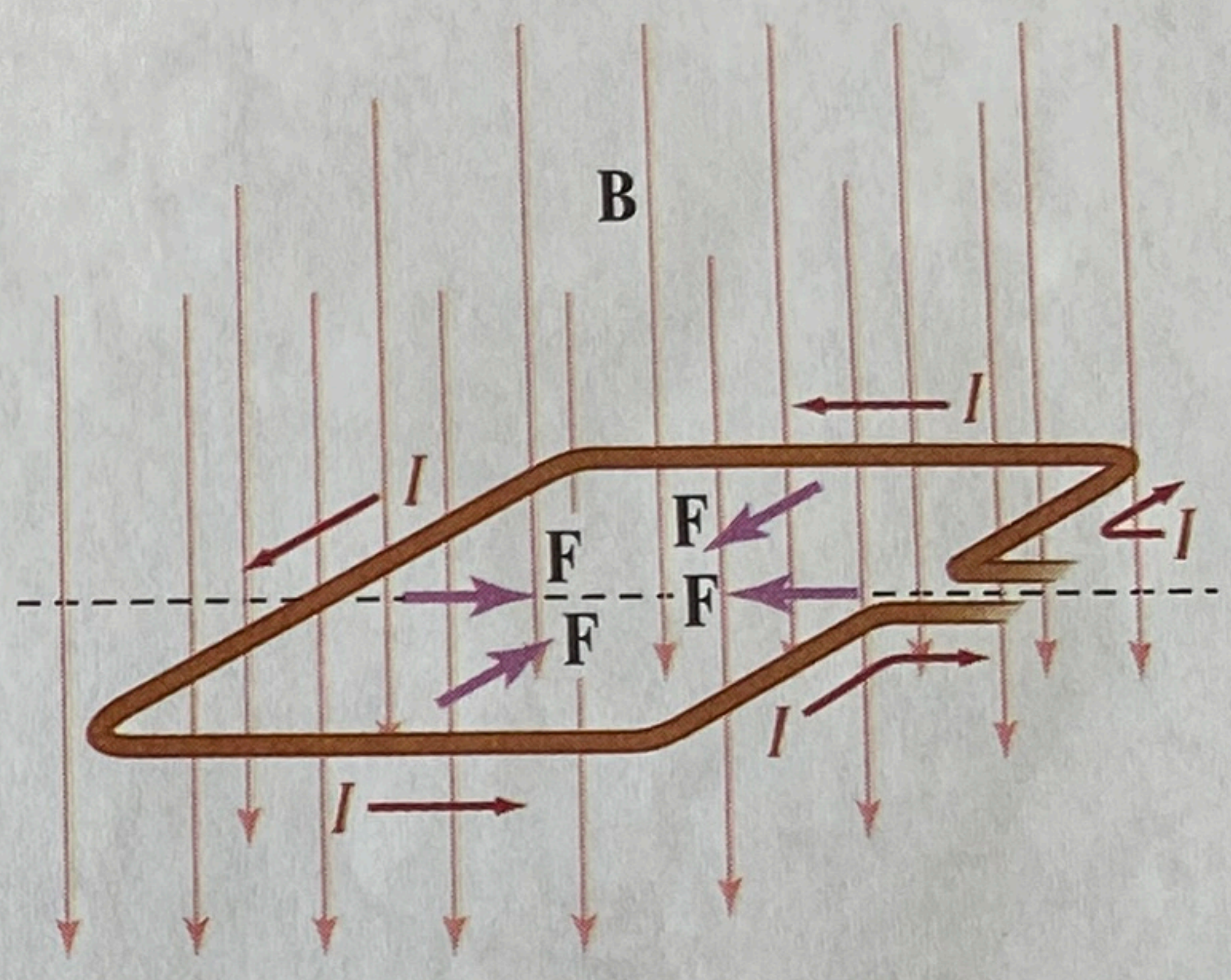
$$F_{\text{mag}} = nIlB \sin \theta \cdot \tag{21.13}$$

A *galvanometer* uses the rotation of a coil in a magnetic field to measure current. Torque is proportional to force, which is proportional to current. Therefore,

The torque vector is parallel to the axis of rotation. For counterclockwise motion in a horizontal plane, the torque vector points up. For clockwise motion, the torque vector points down.



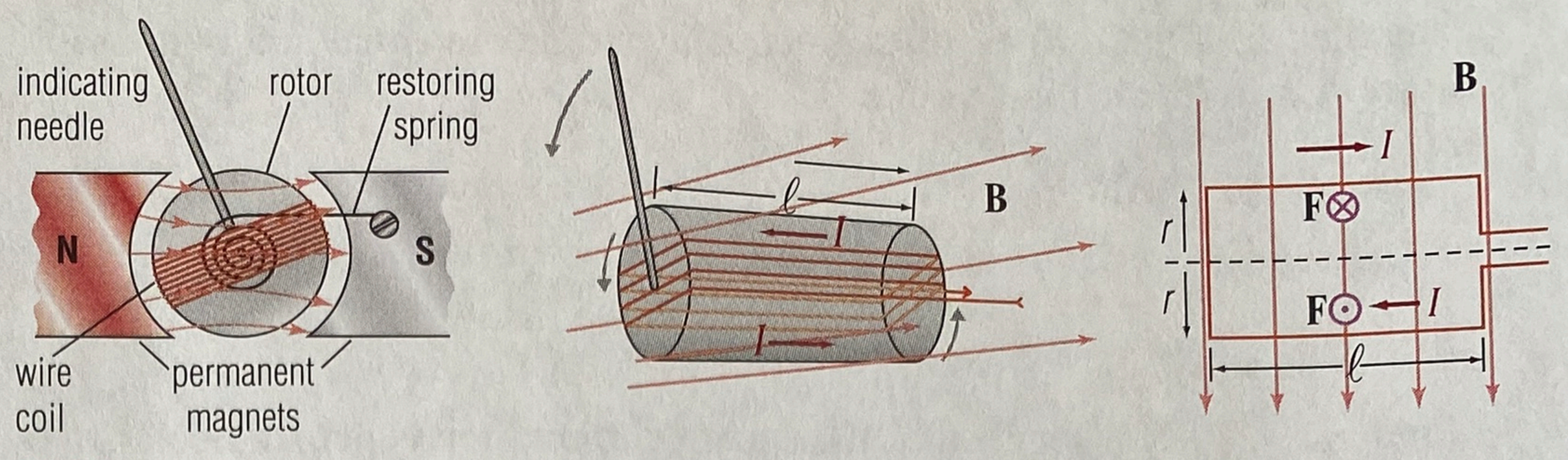
21-27 Right-hand rule for torques: for counterclockwise rotation, the torque vector points up; for clockwise rotation, the torque vector points down.



21-28 Magnetic forces on a current loop oriented perpendicular to the magnetic field

Using the methods of calculus, the circular loop is broken down into innumerable segments. The forces on each segment are summed to find the total torque on the loop.

21-30 A coil of wire acts like a stack of individual current loops.



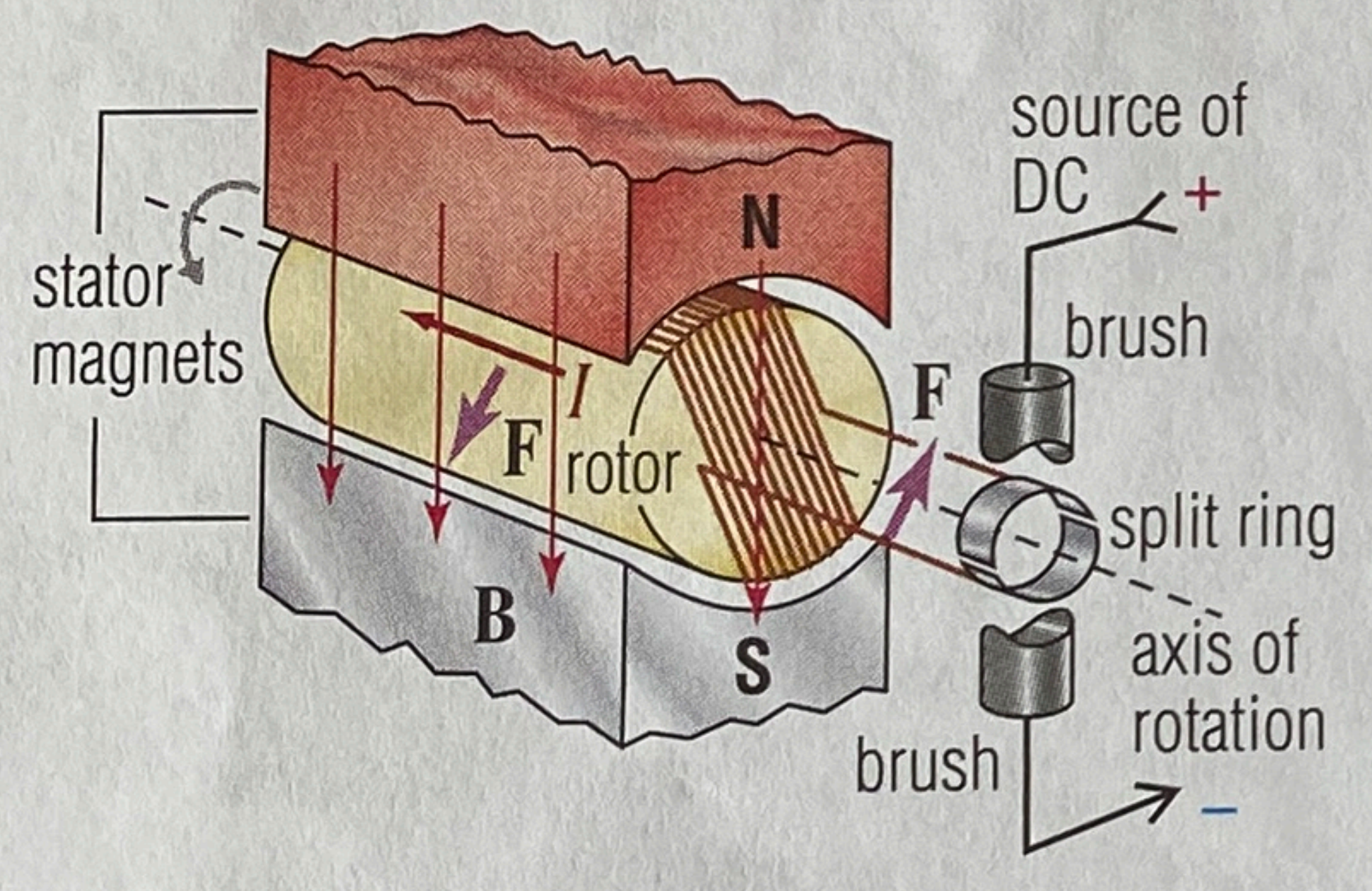
21-31 Functional diagram of a galvanometer

rotational torque can be used to measure current. The galvanometer consists of a coil wound on a cylindrical core, a spring mounted so that it opposes the turning of the coil, a needle to show the amount of turning, a scale, and a magnet with concave poles to produce a uniform magnetic field. When a current flows in the wire, a torque on the coil rotates it in the magnetic field. The rotation of the coil stretches the spring and turns the needle. The needle stops moving when the torque of the magnetic force is balanced by the opposing torque applied by the stretched spring. Greater currents cause greater deflection of the needle. Opposite currents cause deflections in opposite directions. The zero-current position is at the middle of the scale. Sensitive galvanometers contain more turns of wire in their coils in order to increase the magnetic force for a given amount of current.

21.16 DC Motors

The DC motor is, in some ways, similar to the galvanometer. The purpose of the DC motor is to convert electrical energy to mechanical work. A motor, like a galvanometer, has a coil wound on a ferromagnetic core. The core is mounted on an axle supported by bearings to reduce friction. This assembly is called the **rotor**. The coil is surrounded by a magnetic field produced by permanent magnets or electromagnets mounted in the fixed frame of the motor, called the **stator**. The DC current source is connected to the rotating coils through a split ring mounted on the axle of the rotor. (A split ring is two conducting half-rings separated from each other by an insulated gap). Two electrical contacts called **brushes** ride on the split ring and carry the current supplied to the motor. At any given instant, each brush contacts only one side of the split ring. The subassembly of the rotor containing the split ring is called a **split-ring commutator**.

When current flows through the motor circuit, the coil rotates. If the DC current were to remain constantly in one direction, the coiled winding would tend to rotate until it was perpendicular to the magnetic field, then oscillate around that position as discussed above. However, as the rotor turns, the split ring segments move with it. When the rotor has turned far enough, the split ring gap slides under each brush just as the coil becomes perpendicular to the field. Inertia carries the rotor a little farther, and the opposite commutator segments then contact the brushes. This action reverses the current flow through the rotor coils, maintaining the magnetic torque in the same direction as it was initially. The rotor continues another half turn, and the commutator again reverses the current, sustaining the torque in the correct direction. The DC motor continues to rotate, doing useful work.



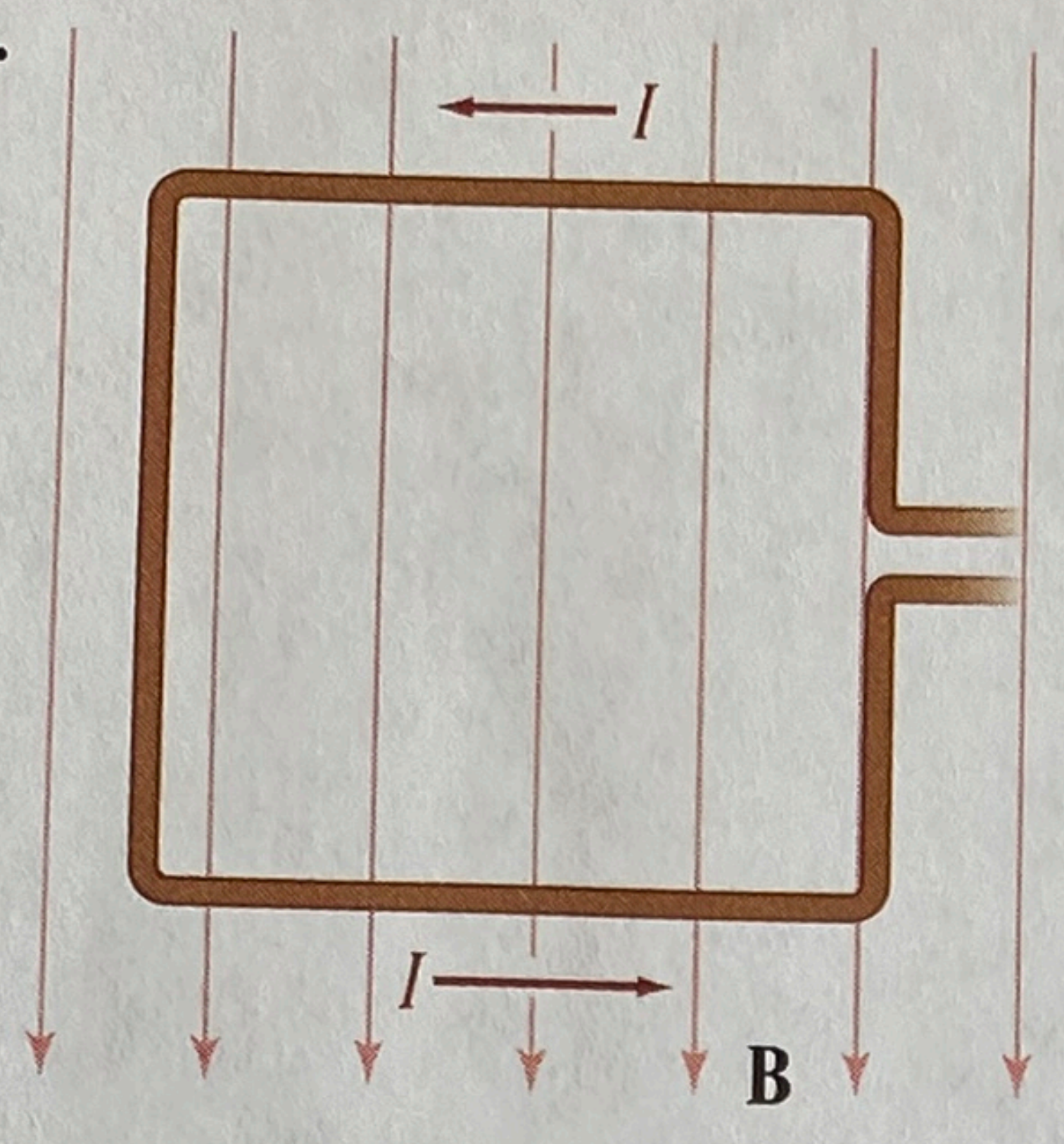
21-32 A DC motor uses a split-ring commutator to reverse the electric current in the rotating coil.

The **commutator** of a DC motor permits continuous rotation of the motor in one direction without having to continually change the polarity of the voltage source connected to the motor.

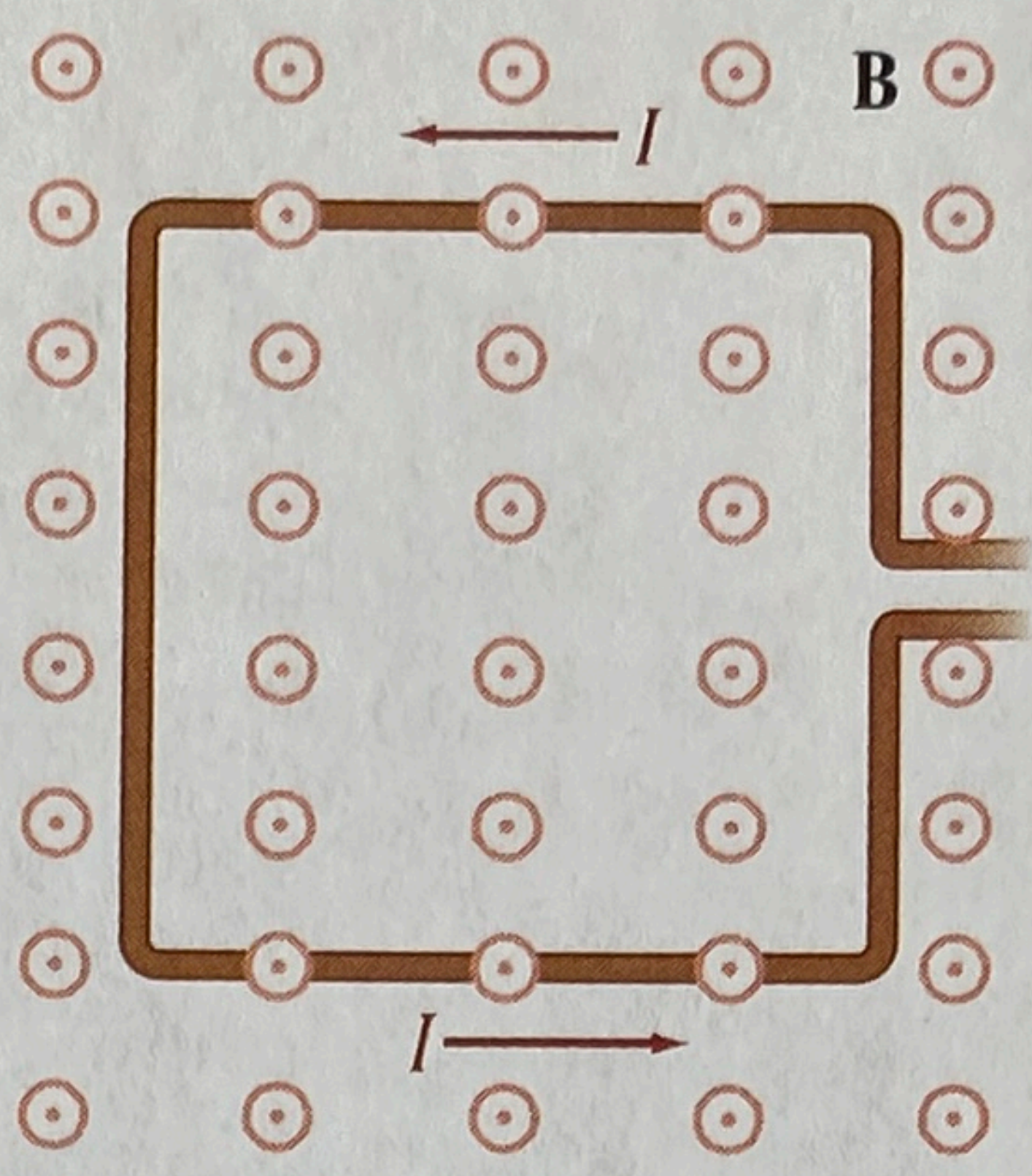
21C Section Review

1. What factors determine the magnitude of the magnetic force on a current moving through a straight conductor in a magnetic field?
2. Copy the following conductor loops onto your paper. Using proper symbols, indicate the direction of the magnetic force on each segment of the loop.

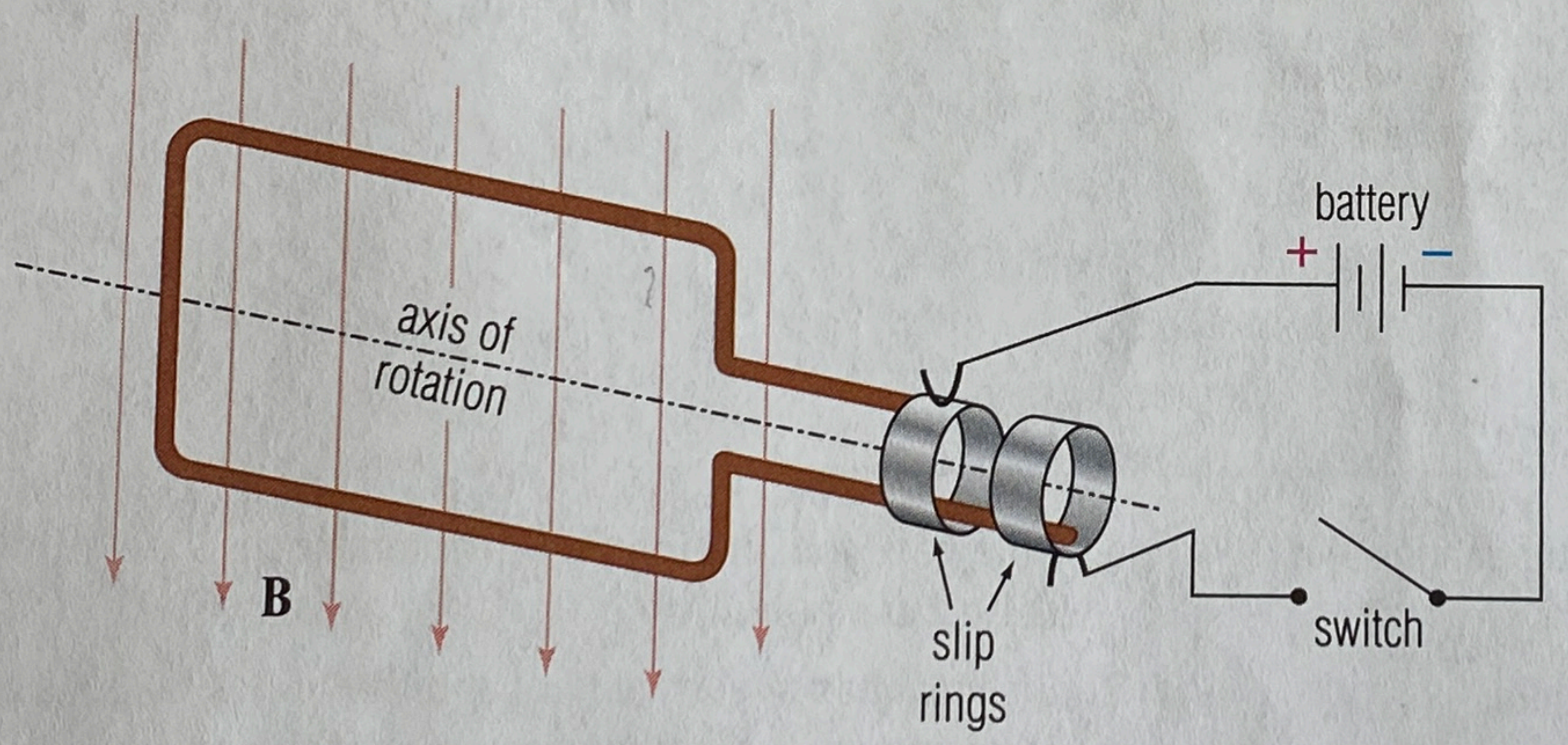
a.



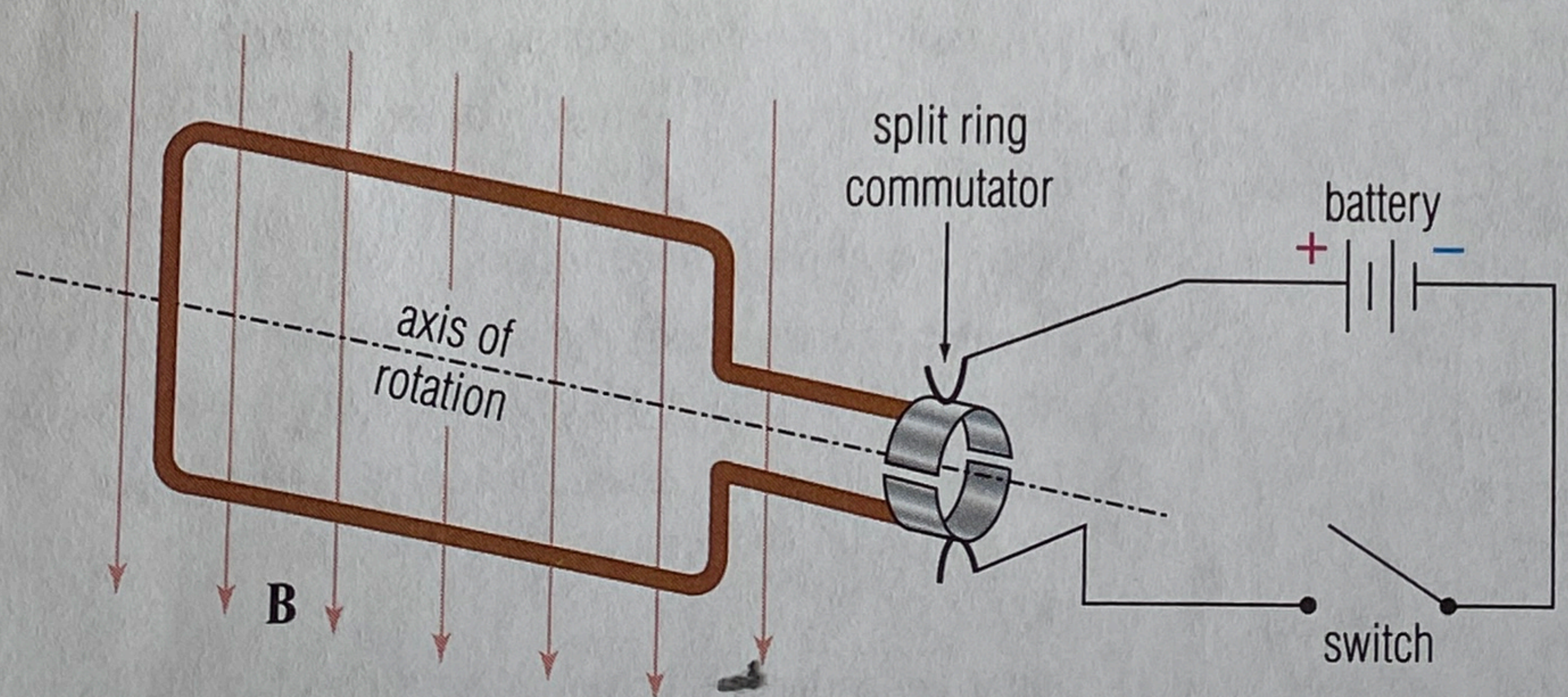
b.



3. Which of the current loops in Question 2 will experience a torque? Explain your answer.
4. What factors determine the magnitude of the magnetic force on a coil of wire containing a current in a magnetic field?
5. The figure below shows a single current loop mounted so that it can rotate. Explain what will happen when the switch is closed.



6. The figure below shows a different current loop mounted so that it can rotate. Explain what will happen when the switch is closed.



21C Objectives

After completing this section, I can

- ✓ apply the theory of magnetic force on moving charges to current-carrying conductors.
- ✓ explain how a current-carrying loop of wire in a magnetic field can generate a torque.
- ✓ use the right-hand rule for torques to predict the direction a current-carrying loop will rotate in a magnetic field.
- ✓ describe how devices containing coils of wire interacting with a magnetic field can be used to measure current.
- ✓ describe the construction and operation of a simple DC motor.

Chapter Review

In Terms of Physics

lodestone	475
pole	475
law of magnetic poles	475
magnetic field vector (**B**)	476
tesla (T)	476
gauss (G)	476
magnetization	476
relative permeability (μ_r)	477
ferromagnetism	477
paramagnetism	477
diamagnetism	477
ferrimagnetism	478
magnetic dipole moment (**μ**)	478
domain	478
Curie temperature (T_C)	479
magnetic declination	480
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magnetosphere	481
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right-hand rule for magnetic force	485
velocity selector	486
mass spectrograph	486
cathode-ray tube (CRT)	488
right-hand rule for torque	492
rotor	494
stator	494
brush	494
split-ring commutator	494

Problem-Solving Strategies

21.1 (page 480) The direction of magnetic declination at your location can be determined by imagining the meridian line connecting your position and the geographic north pole. If the magnetic north pole is to the left (west) of this line, then the declination is west; if it is to the right (east) of the line, then declination is east.

21.2 (page 482) In order to find the angle between the velocity and the magnetic field vectors, place their vectors tail-to-tail. The angle θ is the smallest angle between the vectors.

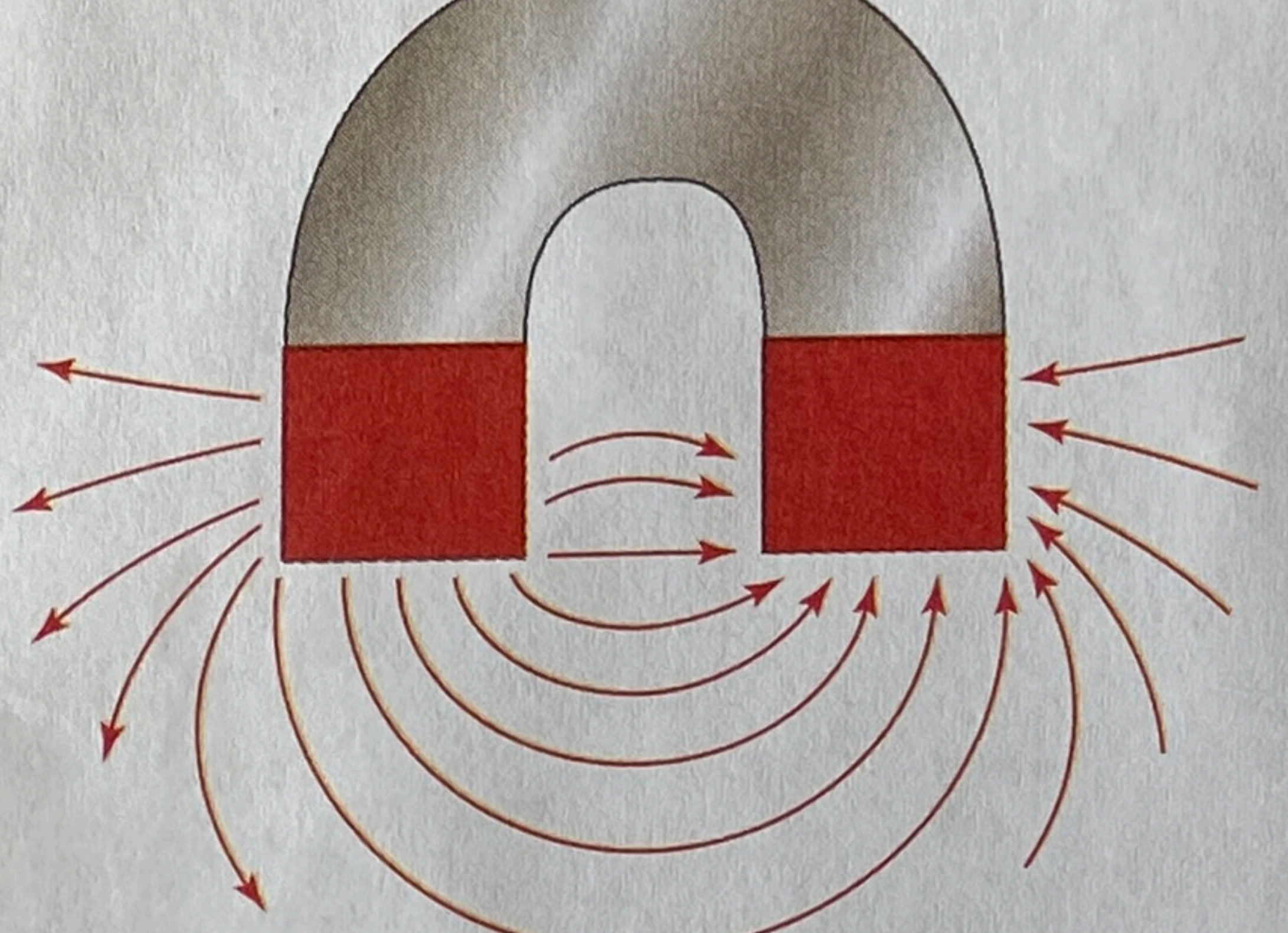
21.3 (page 492) **The right-hand rule for torques:** Hold your right hand flat with the thumb extended at a right angle to the fingers. Point your fingers away from the axis of rotation parallel to the position vector **r**. Curl your fingers toward the direction of the force vector where it is applied to the moment arm. Your thumb points in the direction of the torque vector.

Review Questions

1. Can you obtain isolated poles by breaking a long magnet in half? Explain.

2. Name one way to find the shape of a magnetic field.

3. **a.** Where is this magnet's north pole?
b. Where is its field strongest?



4. What vector represents a magnetic field?

5. How does a magnet attract an unmagnetized piece of ferromagnetic metal?

6. How can you distinguish ferromagnetic steel from paramagnetic aluminum?

7. Bismuth has a relative permeability of 0.99983. Is this element ferromagnetic, diamagnetic, or paramagnetic?

8. If you want a strong magnetic field, in what kind of material should you generate the field?

9. What is the best model for explaining magnetism today?

10. Why does a magnetic compass point north?

11. Are the earth's magnetic poles at its geographic poles? Explain.

12. What is magnetic declination?

13. In what direction does the north-seeking end of a compass point when the compass is placed at the north geographic pole?

14. In what direction does the north-seeking end of a compass point when the compass is placed at the north magnetic pole?

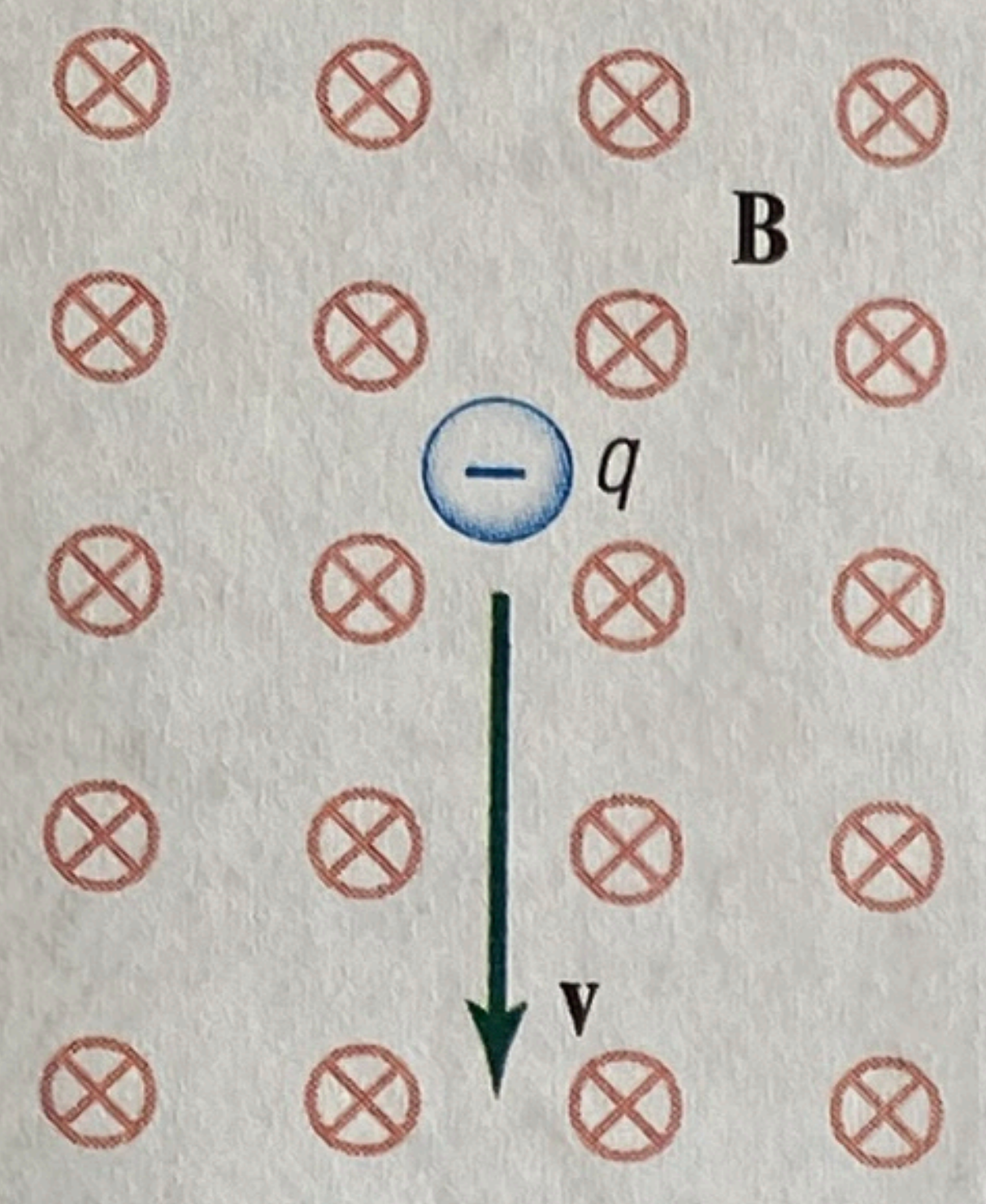
15. What keeps harmful charged particles from the sun from reaching the earth's surface?

16. What causes the auroras?

17. If the earth's magnetic field has always been decreasing as it has been doing since men began observing it, how old might it be?

18. For a charge of a given magnitude moving at a constant velocity through a uniform magnetic field, what is the difference in the magnetic force on the charge when it is positive compared to when it is negative?

19. Study the figure below. In what direction will the charge be deflected?



20. Describe a mass spectrometer.

21. Two kinds of particles are detected in a mass spectrometer sample. One kind of particle is detected at 9.5 cm from the entrance point. The other is detected at 13.8 cm from the entrance. Which kind of particle has greater mass?

22. A current-carrying conductor is aligned parallel to a magnetic field. In which direction is the magnetic force on the conductor?

23. A current loop lies in a magnetic field so that all of its sides are perpendicular to the field lines. Will the loop rotate? Explain.

24. A circular current loop lies in a magnetic field so that it is in a plane parallel to the magnetic field lines. Will the loop rotate? Explain.

25. Why does a DC electric motor rotate continuously rather than oscillate?

True or False (26–40)

26. All magnets have both a north and south pole.

27. One tesla is approximately the strength of the terrestrial magnetic field at the earth's surface.

28. A magnetic field is not affected in any way by the material in which it is located.

29. The strength of a magnet depends not only on the dipole moments of its atoms but also on their orientation.

30. Magnetic declination over the surface of the earth is relatively constant from one decade to the next.

31. A charge at rest in a magnetic field will be accelerated perpendicularly to the field lines.

32. A moving electric charge is deflected in the direction of a magnetic field line.

33. The closer the crossing angle between a charge's velocity and a magnetic field line is to 90°, the greater the magnetic force on the charge.

34. Magnetic force is a conservative force.

35. The right-hand rule for magnetic force is valid only for positive charges.

36. The torque vector on a current loop in a magnetic field points in the direction of rotation.

37. The formula for magnetic force in a coil of wire (Equation 21.13) assumes that all the coils have the same dimensions.

38. A galvanometer works by balancing an electromagnetic torque against a spring torque.

39. In a simple DC motor, the stator contains the electric current that drives the motor, and the rotor contains the magnetic field.

40. The purpose of a commutator is to reverse the current in the motor coil so that it can continue to turn in one direction.

DM✪**41.** Using the accepted mass-to-charge ratio for an electron given on page 490, determine the mass if the electron's charge is -1.602×10^{-19} C.

✪**42.** A $+1.00 \times 10^{-6}$ C charge moves through a magnetic field, $B = 3.00 \times 10^{-5}$ T, initially perpendicular to the field, with a constant speed of 1.33×10^{-3} m/s. What is the magnitude of the magnetic force initially exerted on the charge?

✪**43.** A magnetic field exerts a force of 5.50×10^{-10} N on a -1.10 mC charge initially moving perpendicularly to the field at a constant speed of 2.50×10^{-2} m/s. What is B?

✪**44.** A point charge moving at a constant speed of 1.50×10^{-2} m/s perpendicular to a magnetic field of $B = 3.00 \times 10^{-4}$ T experiences a force of 9.00×10^{-12} N. What is the magnitude of the point charge?

✪**45.** A velocity selector has a magnetic field of 3.00×10^{-4} T and an electric field of 4.50 N/C. What velocity does it select?

✪**46.** You want a velocity selector to allow charged particles with a speed of 2.25×10^{3} m/s to pass undeflected. The magnet is capable of producing a field with $B = 3.333 \times 10^{-4}$ T. What must the electric field strength be?

DM✪**47.** In the history of science, at the time when J. J. Thomson discovered that his corpuscles were less than one-thousandth the mass of the smallest atom, what impact did his discovery have on the model of the atom? What were some new scientific questions that came out of his discovery?

✪**48.** Prove that the unit ratio $\frac{\mathrm{N \cdot s}}{\mathrm{C \cdot m}}$ equals the tesla $(\mathrm{V \cdot s/m^2})$. This combination of units occurs when solving for the magnetic field (B) by rearranging the magnetic force equation (21.12).

✪**49.** If there are two kinds of particles detected in a mass spectrometer, such that one kind is twice as far from the beam entrance as the other, how do their masses compare? (Assume that both kinds of particles have the same velocity and the same charge when they enter the spectrograph.)