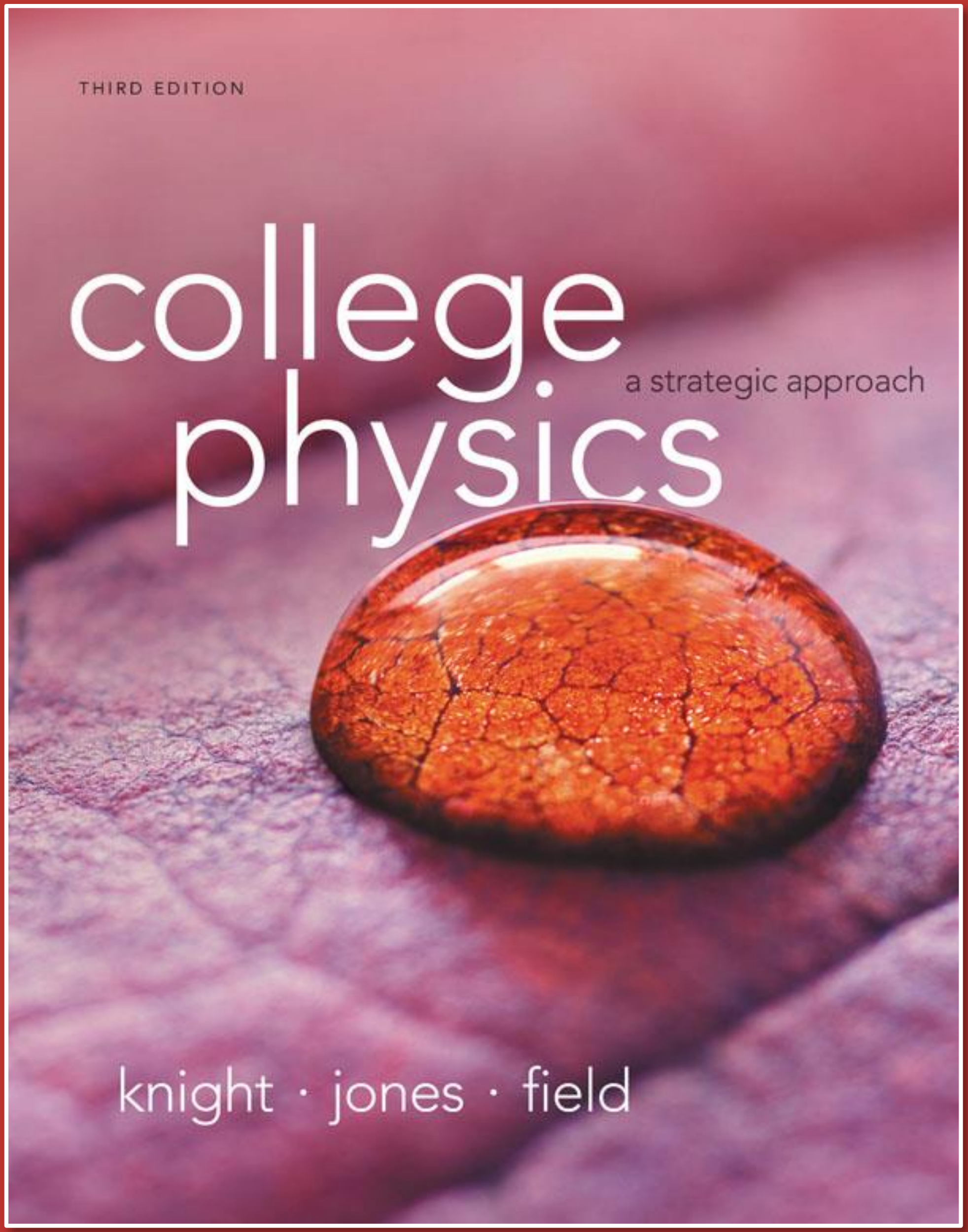


Lecture Presentation

Chapter 24

Magnetic Fields and Forces

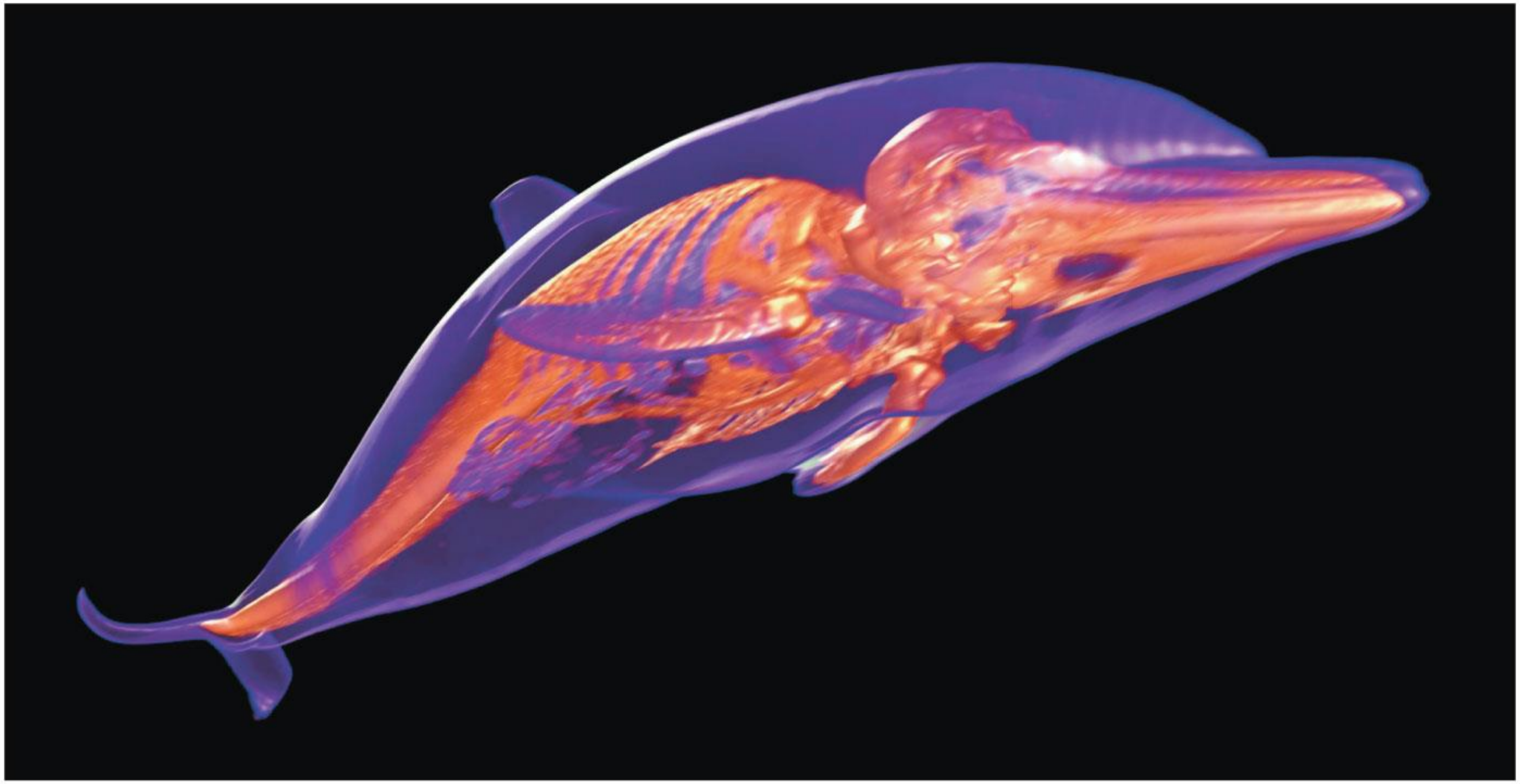
Suggested Videos for Chapter 24

- **Prelecture Videos**
  - *Magnetic Fields*
  - *Magnetic Field Sources*
  - *Magnetic Fields and Forces*
- **Class Videos**
  - *Electromagnetic Flowmeter*
  - *Magnetic Materials*
  - *Magnetic Fields and Current*
- **Video Tutor Solutions**
  - *Magnetic Fields and Forces*
- **Video Tutor Demos**
  - *Magnet and Electron Beam*
  - *Current-Carrying Wire in Magnetic Field*

Suggested Simulations for Chapter 24

- **ActivPhysics**
  - *13.1–13.8*
- **PhETs**
  - *Magnet and Compass*
  - *Magnets and Electromagnets*
  - *Simplified MRI*

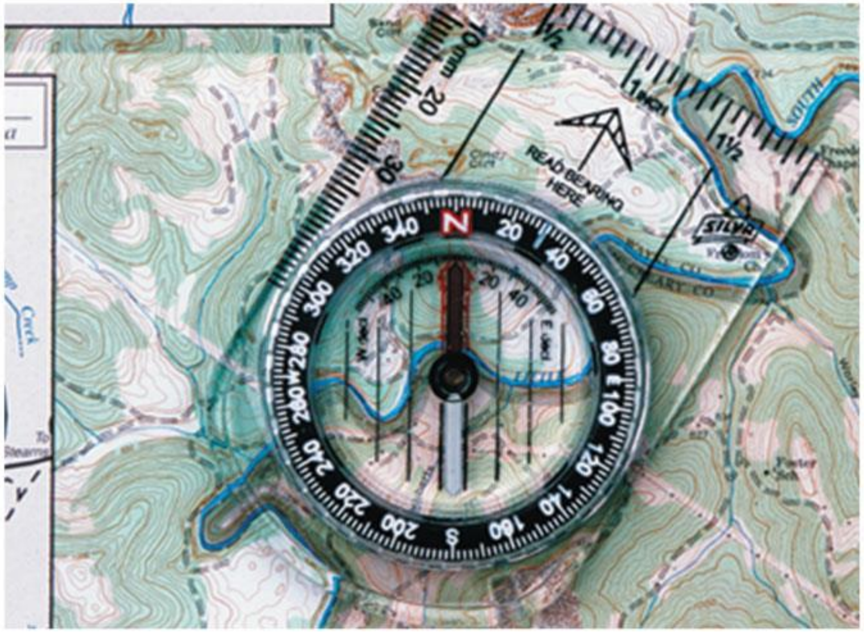
Chapter 24 Magnetic Fields and Forces



Chapter Goal: To learn about magnetic fields and how magnetic fields exert forces on currents and moving charges.

Chapter 24 Preview
Looking Ahead: Magnetic Fields

- A compass is a magnetic dipole. It will rotate to line up with a magnetic field.



- You'll learn how to use compasses and other tools to map magnetic fields.

Chapter 24 Preview
Looking Ahead: Sources of the Field

- Magnets produce a magnetic field; so do current-carrying wires, loops, and coils.

- You'll learn to describe the magnetic fields created by currents. These iron filings show the magnetic field shape for this current-carrying wire.

Chapter 24 Preview
Looking Ahead: Effects of the Field

- Magnetic fields exert forces on moving charged particles and electric currents.

- You'll see how the motion of charged particles in the earth's magnetic field gives rise to the aurora.

Chapter 24 Preview
Looking Ahead

Magnetic Fields

A compass is a magnetic dipole. It will rotate to line up with a magnetic field.

You'll learn how to use compasses and other tools to map magnetic fields.

Sources of the Field

Magnets produce a magnetic field; so do current-carrying wires, loops, and coils.

You'll learn to describe the magnetic fields created by currents. These iron filings show the magnetic-field shape for this current-carrying wire.

Effects of the Field

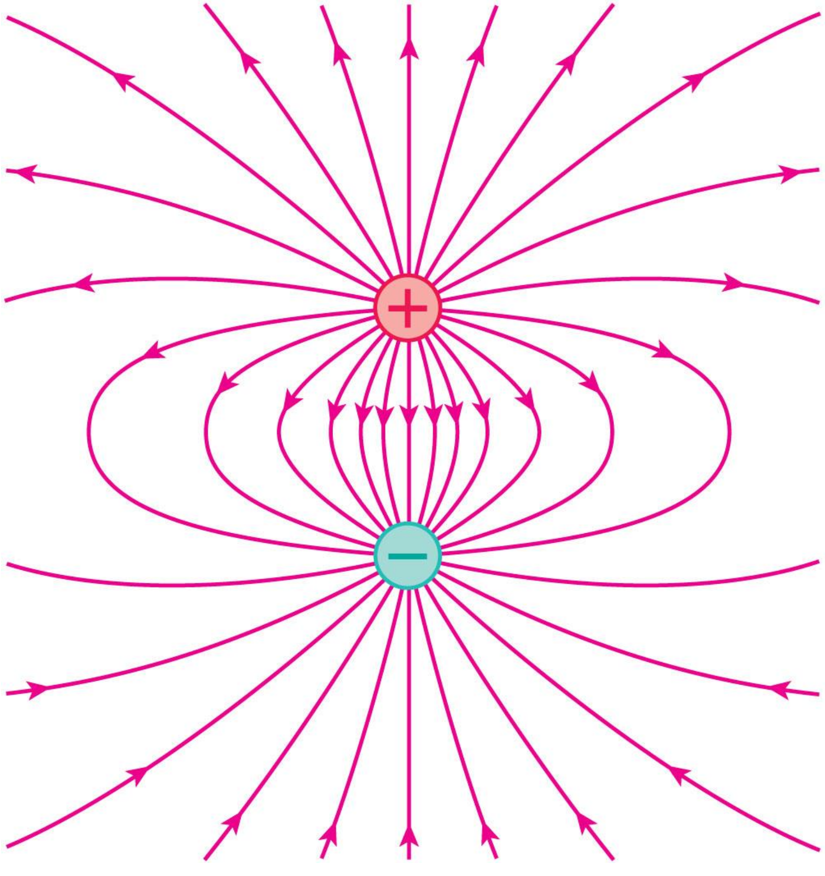
Magnetic fields exert forces on moving charged particles and electric currents.

You'll see how the motion of charged particles in the earth's magnetic field gives rise to the aurora.

Text p. 764

Chapter 24 Preview
Looking Back: Electric Fields

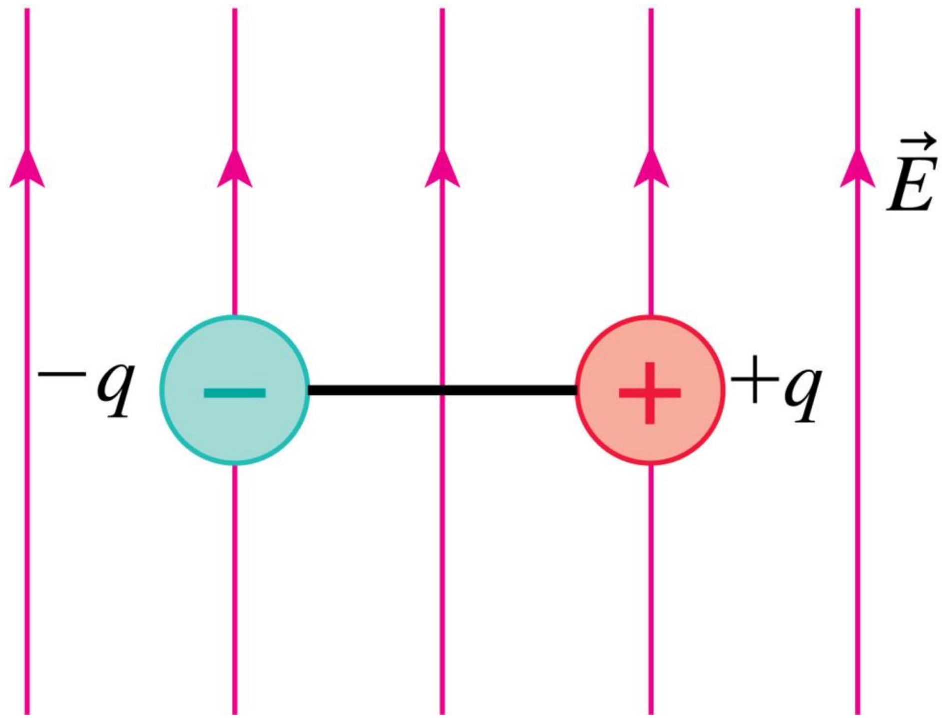
- In Chapter 20, we described electric interactions between charged objects in terms of the field model.
- You learned how to draw and interpret the electric field of a dipole. In this chapter, you'll see how a magnetic dipole creates a magnetic field with a similar structure.



Chapter 24 Preview
Stop to Think

An electric dipole in a uniform electric field experiences no net force, but it does experience a net torque. The rotation of this dipole will be

A. Clockwise.
B. Counterclockwise.



Reading Question 24.1

A compass in a magnetic field will line up

A. With the north pole pointing in the direction of the magnetic field.
B. With the north pole pointing opposite the direction of the magnetic field.
C. With the north pole pointing perpendicular to the magnetic field.

Reading Question 24.1

A compass in a magnetic field will line up

✔ A. With the north pole pointing in the direction of the magnetic field.

B. With the north pole pointing opposite the direction of the magnetic field.

C. With the north pole pointing perpendicular to the magnetic field.

Reading Question 24.2

The magnetic field lines due to a straight, current-carrying wire are

A. Straight lines parallel to the wire.
B. Straight lines perpendicular to the wire.
C. Circles around the wire.

Reading Question 24.2

The magnetic field lines due to a straight, current-carrying wire are

A. Straight lines parallel to the wire.

B. Straight lines perpendicular to the wire.

✔ C. Circles around the wire.

Reading Question 24.3

A loop of wire carries a current. The resulting magnetic field

A. Points away from the loop at all points.
B. Points toward the loop at all points.
C. Is similar to that of a bar magnet in the plane of the loop.
D. Is similar to that of a bar magnet perpendicular to the plane of the loop.

Reading Question 24.3

A loop of wire carries a current. The resulting magnetic field

A. Points away from the loop at all points.
B. Points toward the loop at all points.
C. Is similar to that of a bar magnet in the plane of the loop.
✔ D. Is similar to that of a bar magnet perpendicular to the plane of the loop.

Reading Question 24.4

The direction of the magnetic force on a moving charged particle in a magnetic field is

A. Perpendicular to the velocity.
B. Perpendicular to the magnetic field.
C. Both A and B.

Reading Question 24.4

The direction of the magnetic force on a moving charged particle in a magnetic field is

A. Perpendicular to the velocity.

B. Perpendicular to the magnetic field.

✔ C. Both A and B.

Reading Question 24.5

Two parallel wires carry a current in the same direction. There is ____________ between the wires.

A. An attractive force
B. A repulsive force
C. No force

Reading Question 24.5

Two parallel wires carry a current in the same direction. There is ____________ between the wires.

✔ A. An attractive force

B. A repulsive force

C. No force

Reading Question 24.6

The magnetism of a permanent magnet results from

A. Electric currents inside the magnet.
B. Interactions with the earth's magnetic field.
C. The magnetic moments of nuclei in the material making up the magnet.
D. The magnetic moments of electrons in the material making up the magnet.

Reading Question 24.6

The magnetism of a permanent magnet results from

A. Electric currents inside the magnet.
B. Interactions with the earth's magnetic field.
C. The magnetic moments of nuclei in the material making up the magnet.
✔ D. The magnetic moments of electrons in the material making up the magnet.

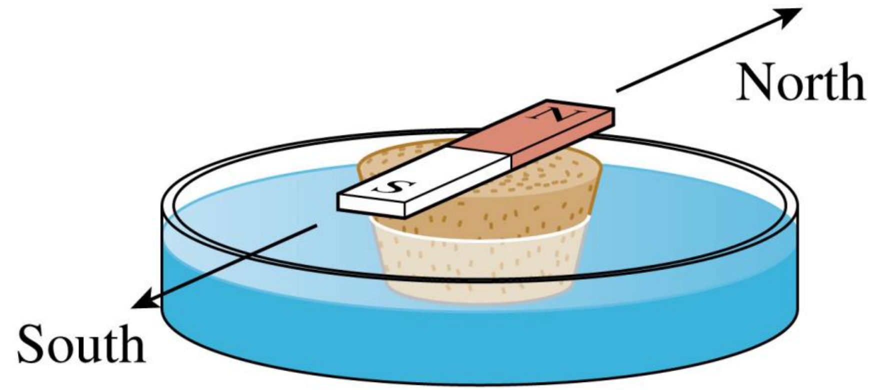
Section 24.1 Magnetism

Magnetism

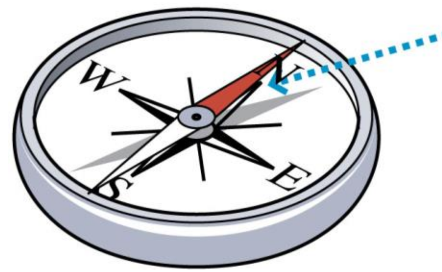
- We begin our investigation of magnetism by looking at the results of some simple experiments.

Magnetism

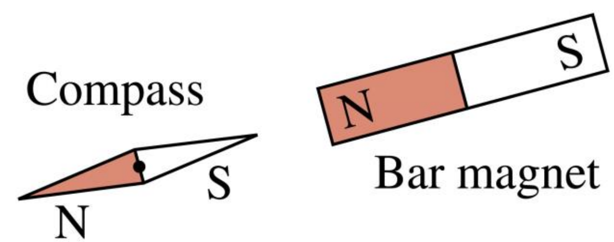
Experiment 1



If a bar magnet is taped to a piece of cork and allowed to float in a dish of water, it turns to align itself in an approximate north-south direction. The end of a magnet that points north is the **north pole.** The other end is the **south pole.**

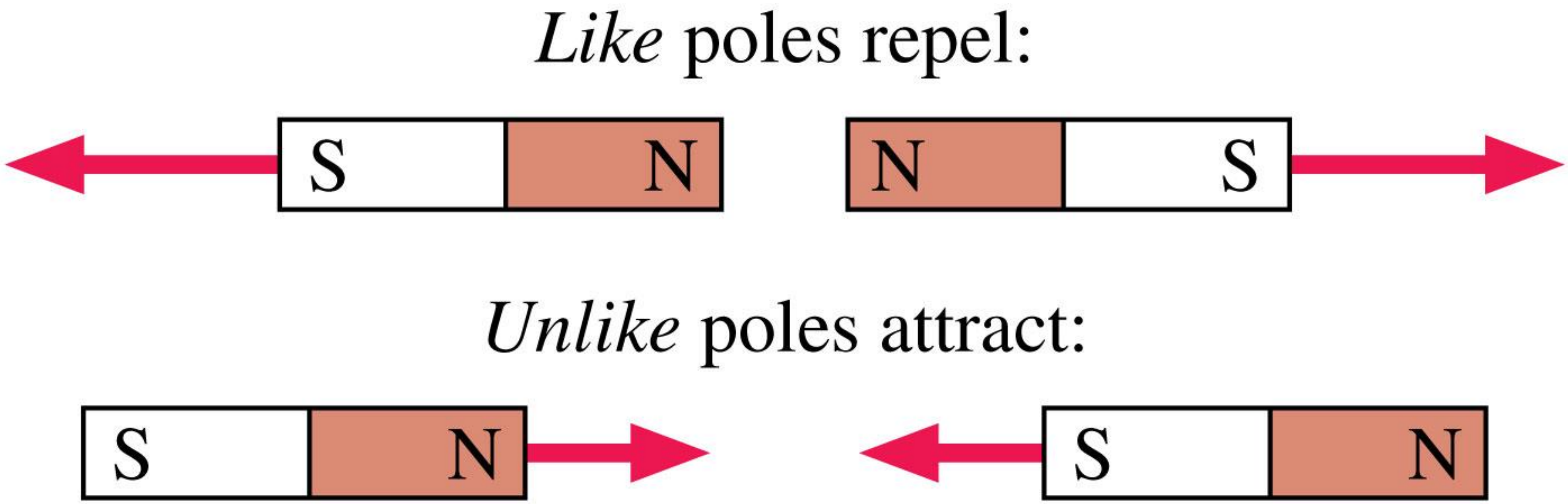


A magnet that is free to pivot like this is called a **compass.** A compass will pivot to line up with a nearby magnet.



Magnetism

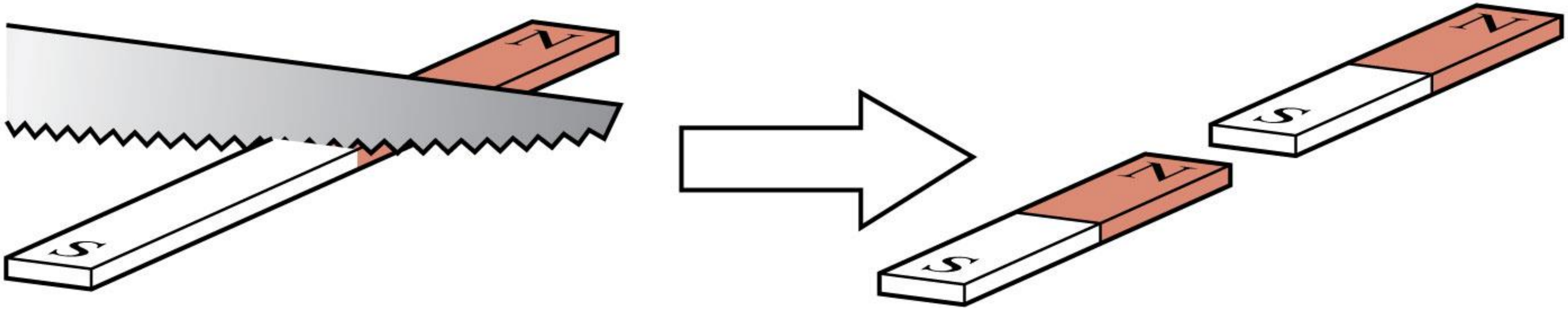
Experiment 2



If the north pole of one magnet is brought near the north pole of another magnet, they repel each other. Two south poles also repel each other, but the north pole of one magnet exerts an attractive force on the south pole of another magnet.

Magnetism

Experiment 3

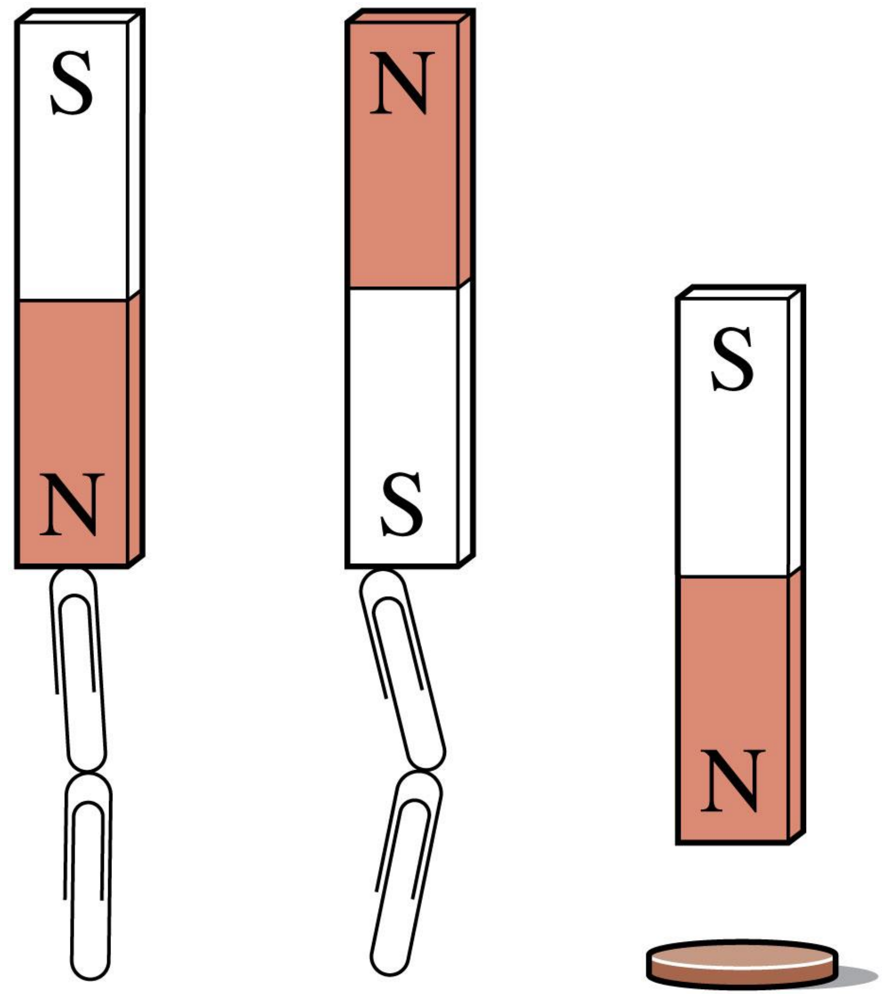


Cutting a bar magnet in half produces two weaker but still complete magnets, each with a north pole and a south pole.

Magnetism

Experiment 4

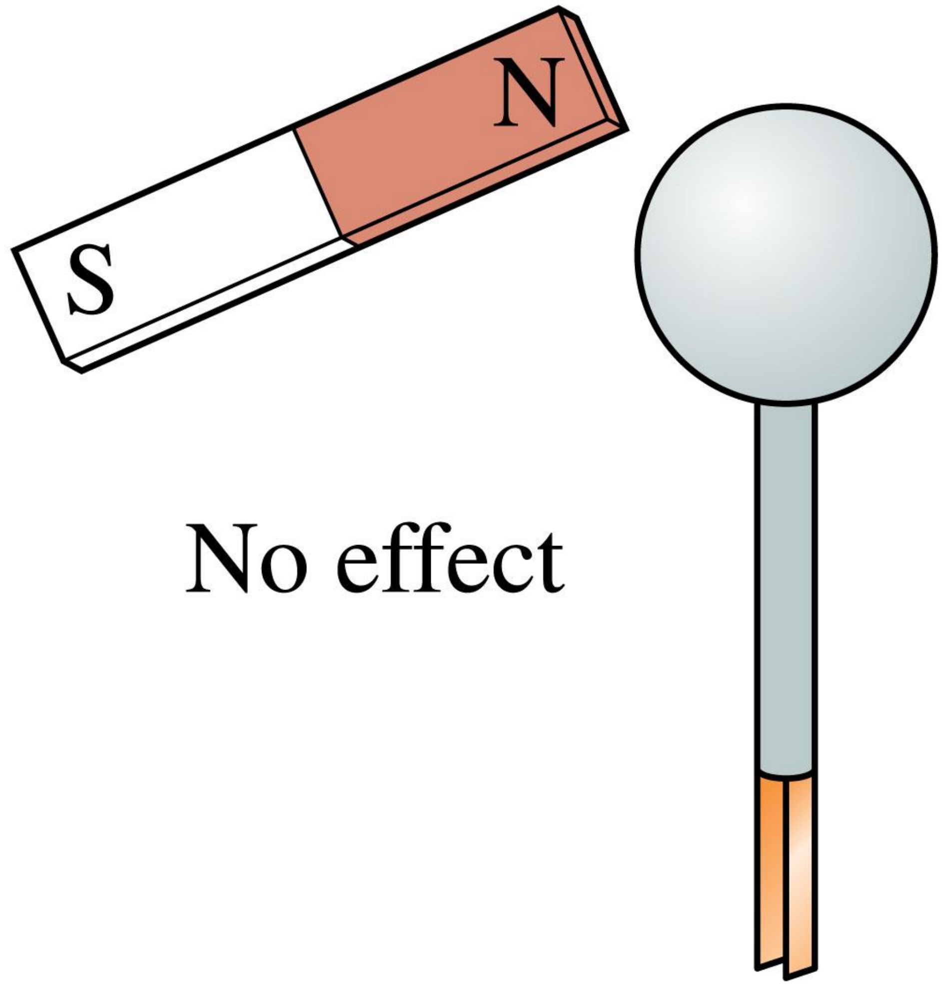
Magnets can pick up some objects, such as paper clips, but not all. If an object is attracted to one pole of a magnet, it is also attracted to the other pole. Most materials, including copper, aluminum, glass, and plastic, experience no force from a magnet.



Magnetism

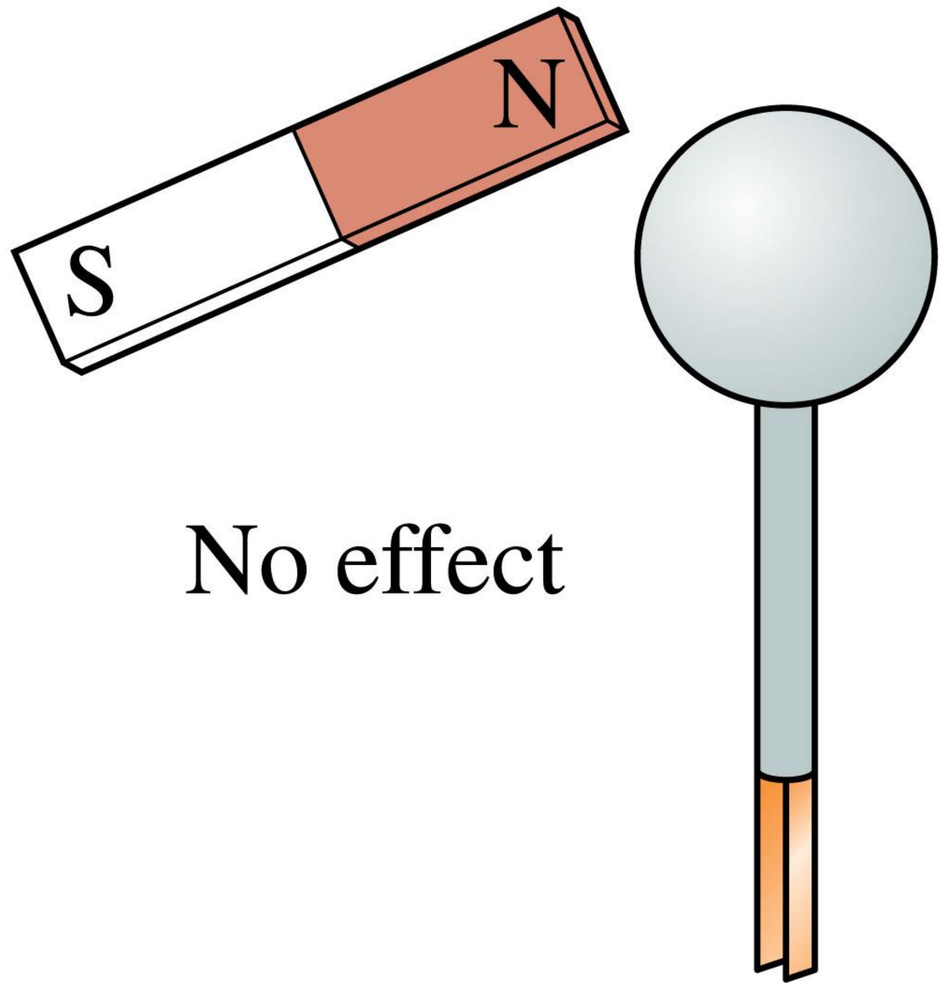
Experiment 5

When a magnet is brought near an electroscope, the leaves of the electroscope remain undeflected. If a charged rod is brought near a magnet, there is a small polarization force like the ones we studied in Chapter 21, as there would be on any metal bar, but there is no other effect.



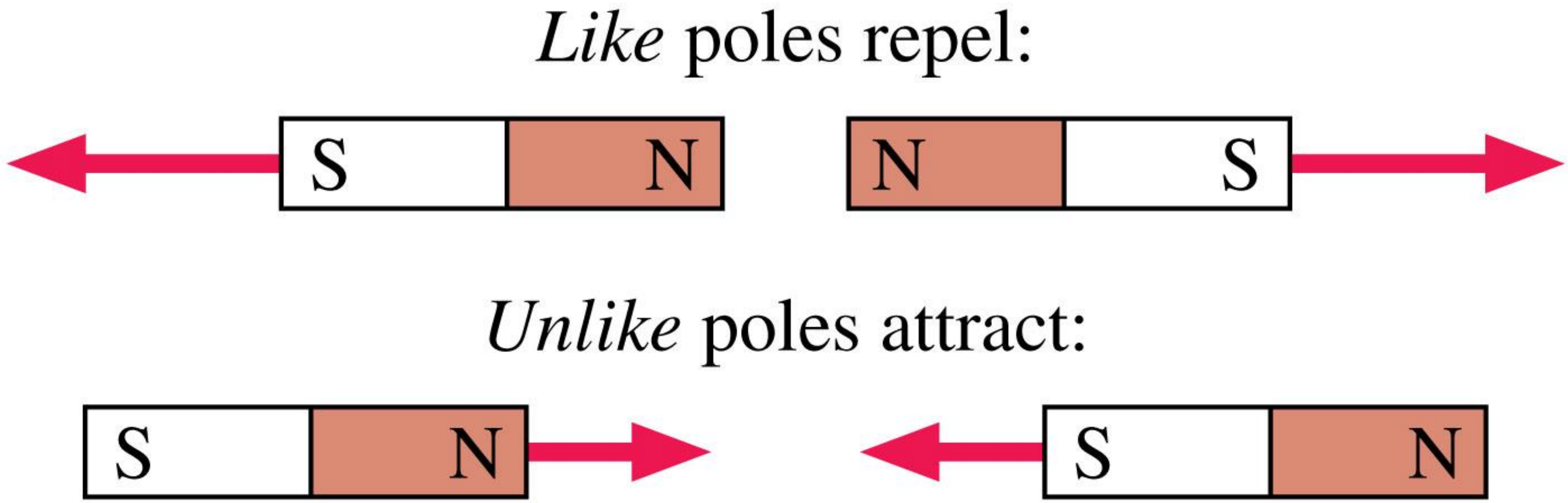
Magnetism

- What do these experiments tell us?
- Magnetism is not the same as electricity.
- **Magnetic poles and electric charges share some similar behavior, but they are not the same.**



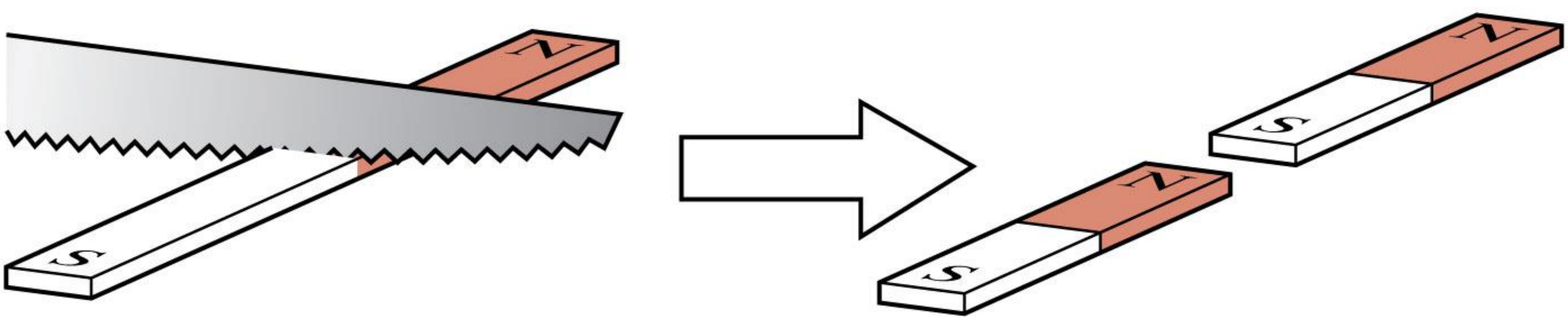
Magnetism

- Magnetism is a long-range force.
- Magnets do not need to touch each other to exert a force on each other.



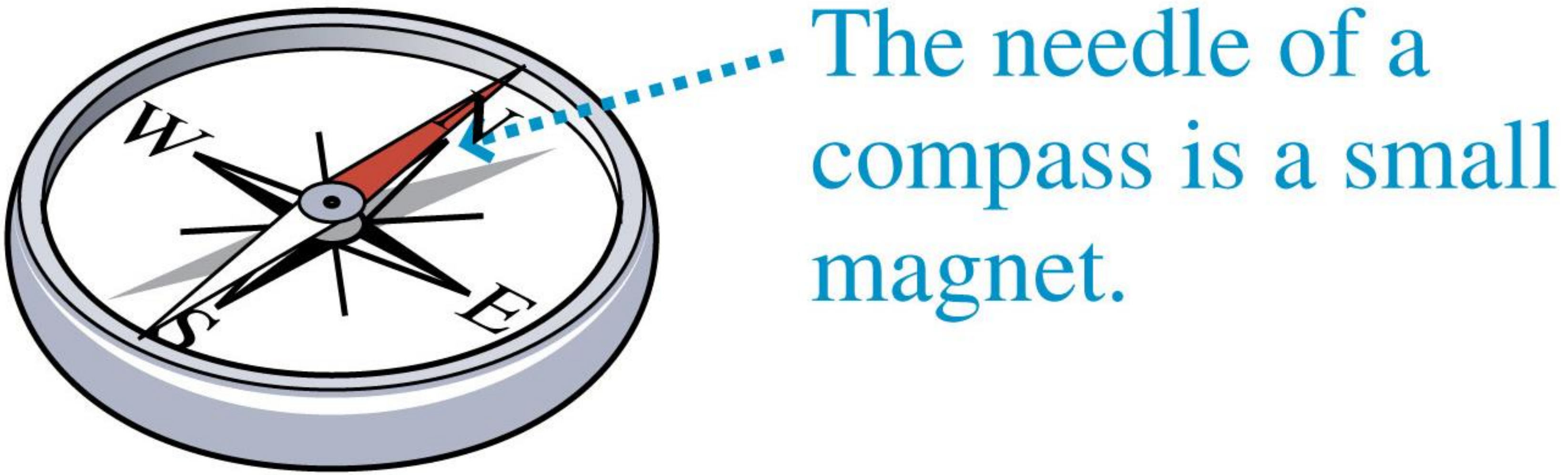
Magnetism

- Magnets have two types of poles, called north and south poles, and thus are **magnetic dipoles.**
- Cutting a magnet in half yields two weaker but still complete magnets, each with a north pole and a south pole.
- The basic unit of magnetism is thus a magnetic dipole.



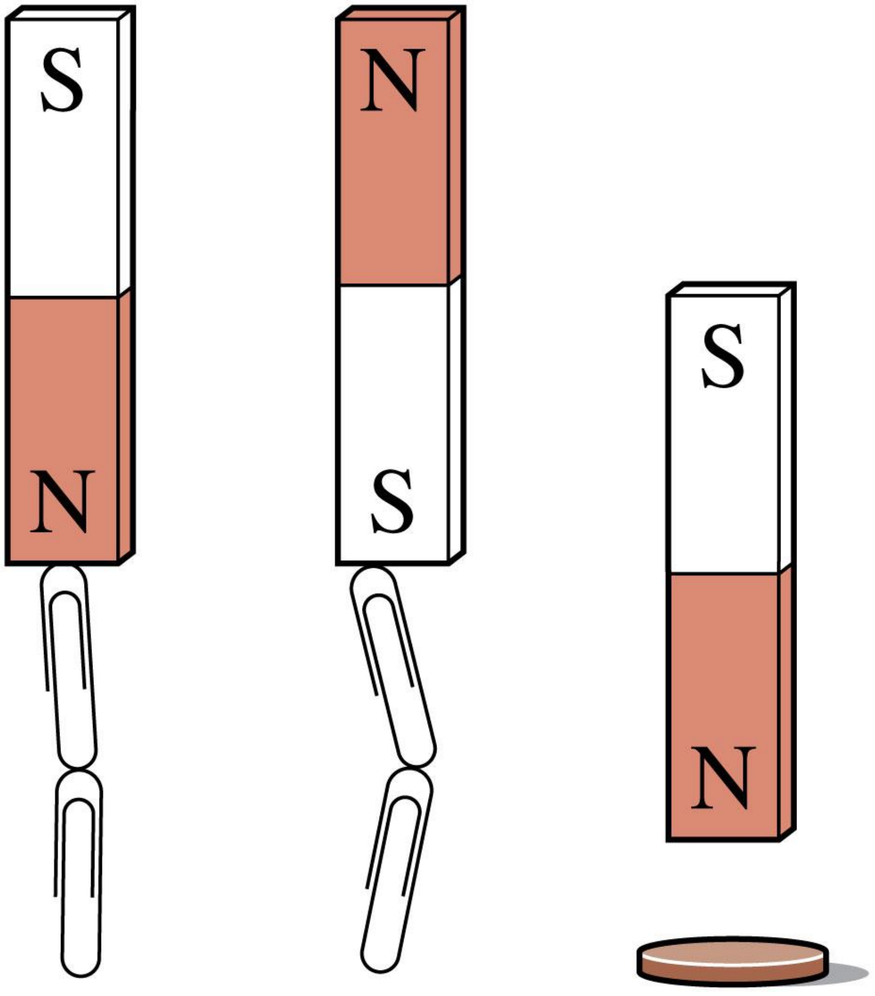
Magnetism

- The poles of a bar magnet can be identified by using it as a compass. Other magnets can be identified by testing them against a bar magnet.
- A pole that repels a known south pole and attracts a known north pole must be a south magnetic pole.



Magnetism

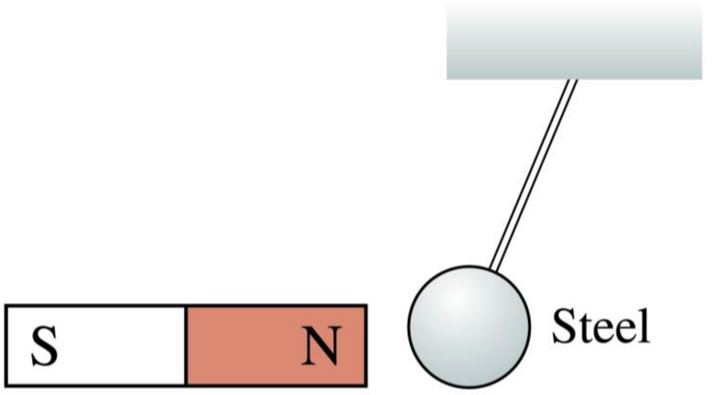
- Only certain materials, called **magnetic materials,** are attracted to a magnet.
- The most common magnetic material is iron.
- Magnetic materials are attracted to both poles of a magnet.



QuickCheck 24.1

If the bar magnet is flipped over and the south pole is brought near the hanging ball, the ball will be

A. Attracted to the magnet.
B. Repelled by the magnet.
C. Unaffected by the magnet.
D. I'm not sure.



QuickCheck 24.1

If the bar magnet is flipped over and the south pole is brought near the hanging ball, the ball will be

✔ A. Attracted to the magnet.
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C. Unaffected by the magnet.
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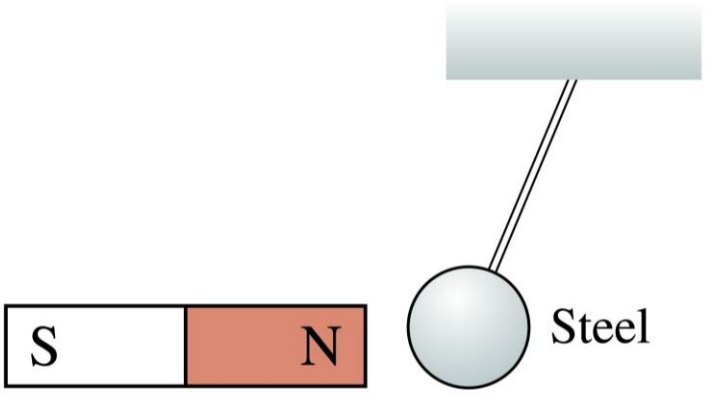
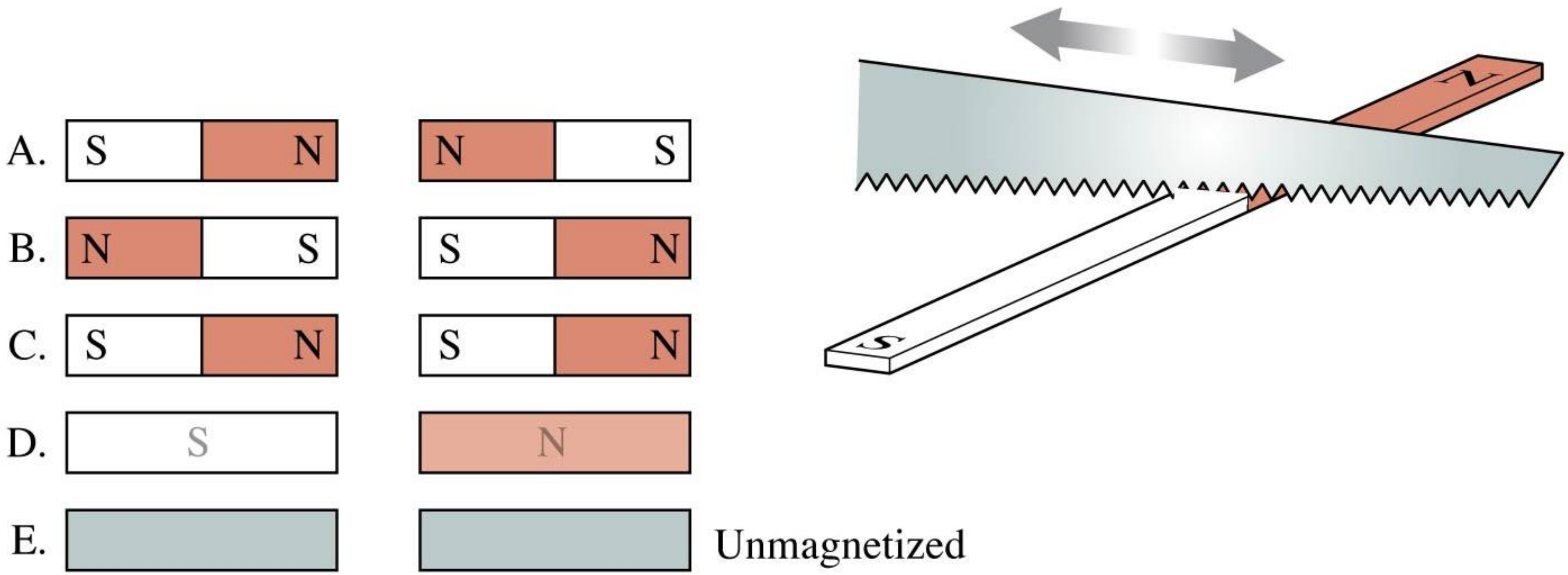


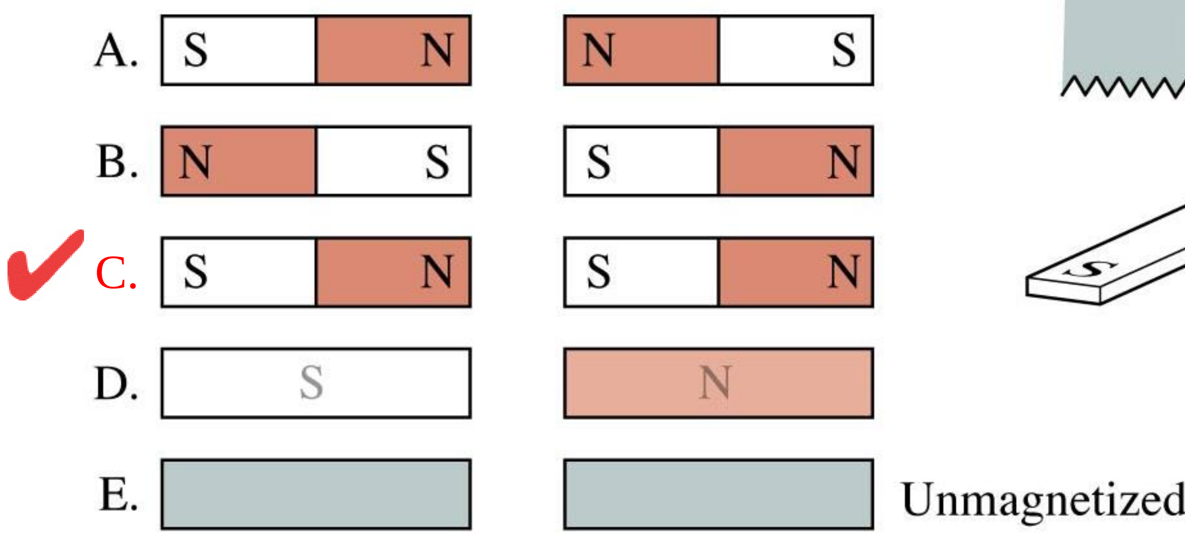
QuickCheck 24.2

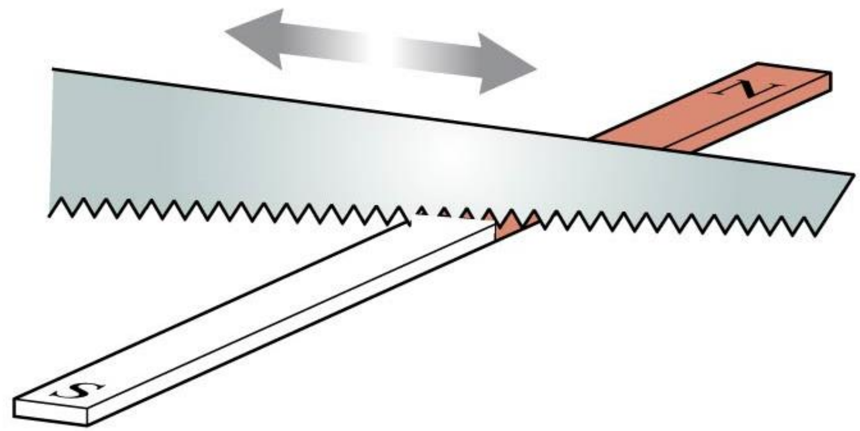
If a bar magnet is cut in half, you end up with



QuickCheck 24.2

If a bar magnet is cut in half, you end up with



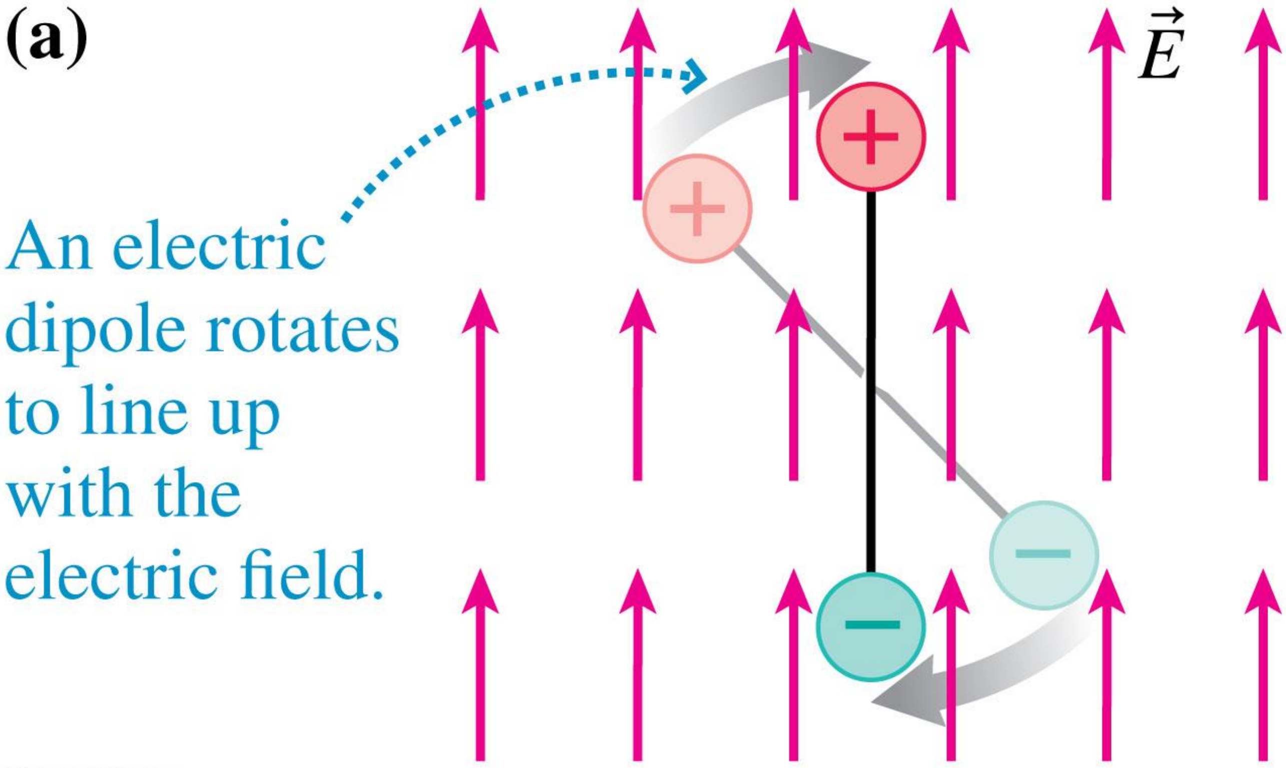


Section 24.2 The Magnetic Field

The Magnetic Field

- **Every magnet sets up a *magnetic* field in the space around it.**
- If another magnet, such as a compass needle, is then brought into this field, the second magnet will feel the effects of the *field* of the first magnet.

Measuring the Magnetic Field

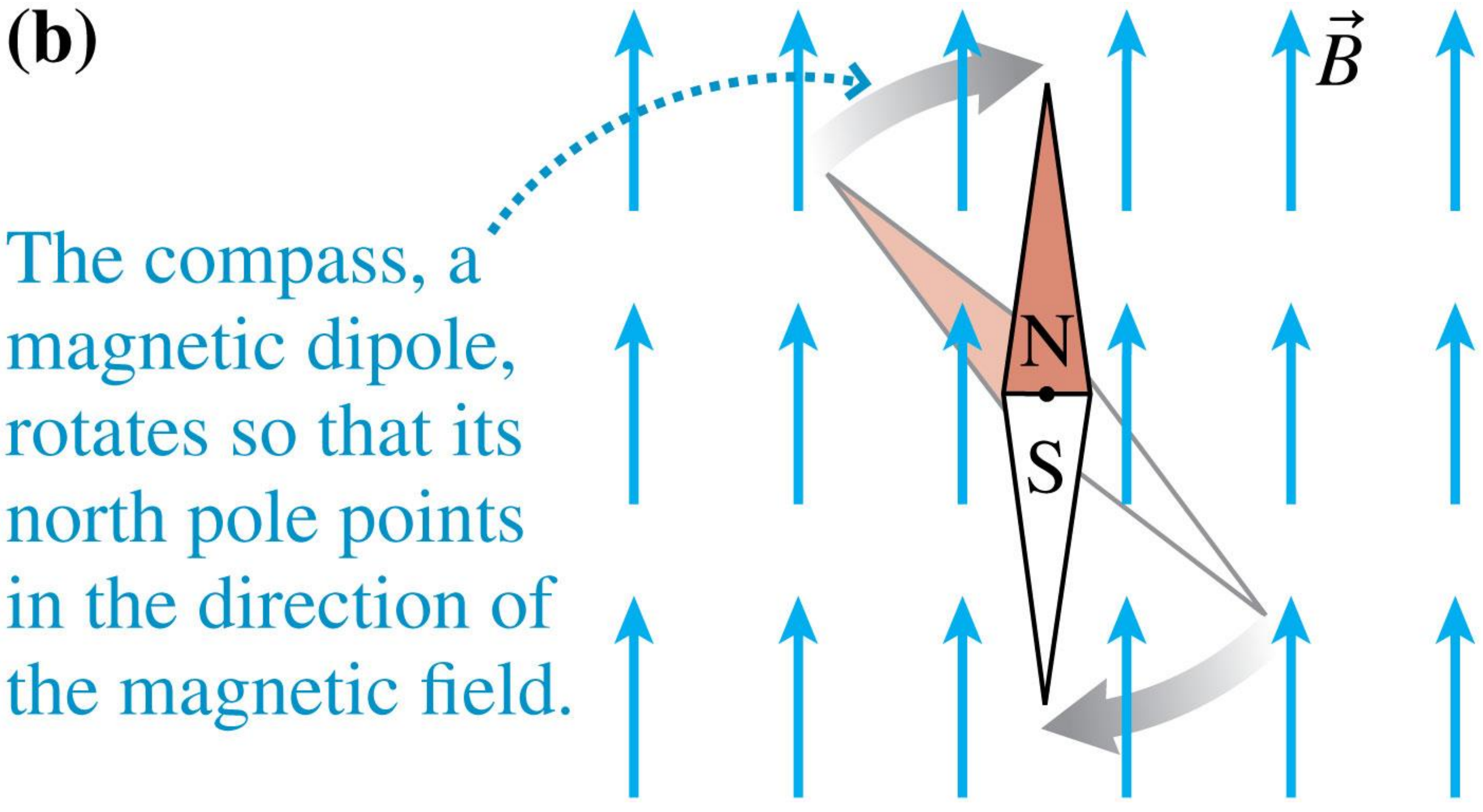


- An electric dipole experiences a *torque* when placed in an electric field.

Measuring the Magnetic Field

- The torque caused by an electric field tends to align the axis of the dipole with the field, so the *direction* of the electric field is the same as the direction of the dipole's axis.
- The torque on the dipole is greater when the electric field is stronger, hence the *magnitude* (or *strength*) of the field is proportional to the torque on the dipole.

Measuring the Magnetic Field



- A magnetic field exerts a torque on the compass needle, causing the needle to point in the field direction.

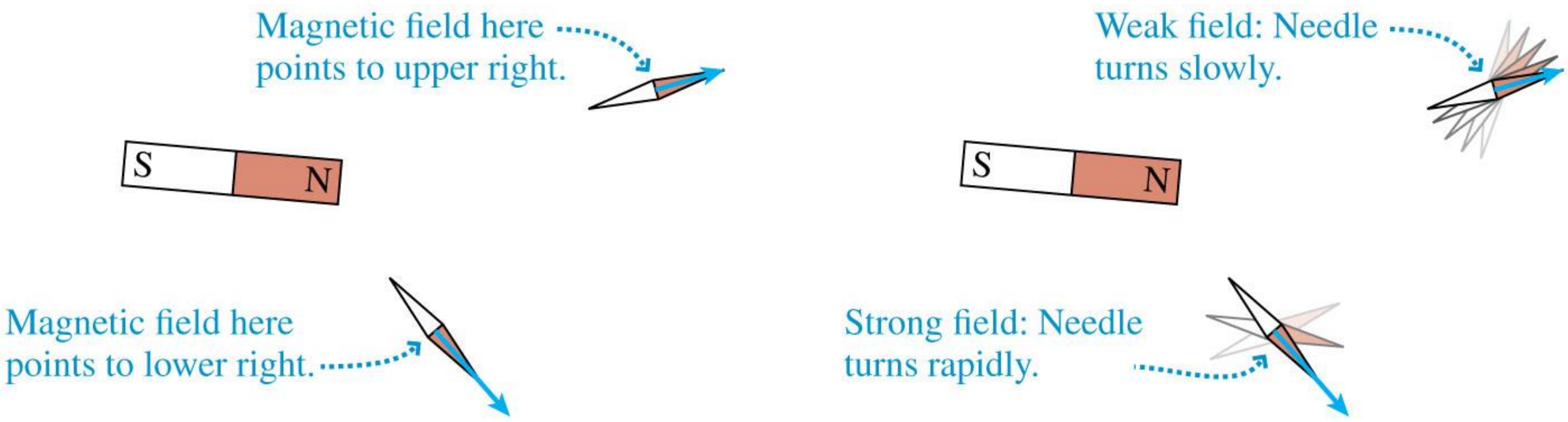
Measuring the Magnetic Field

- Because the magnetic field has both a direction and a magnitude, we represent it using a *vector*, $\vec{B}$.
- *B* represents the magnitude or strength of the field.

Measuring the Magnetic Field

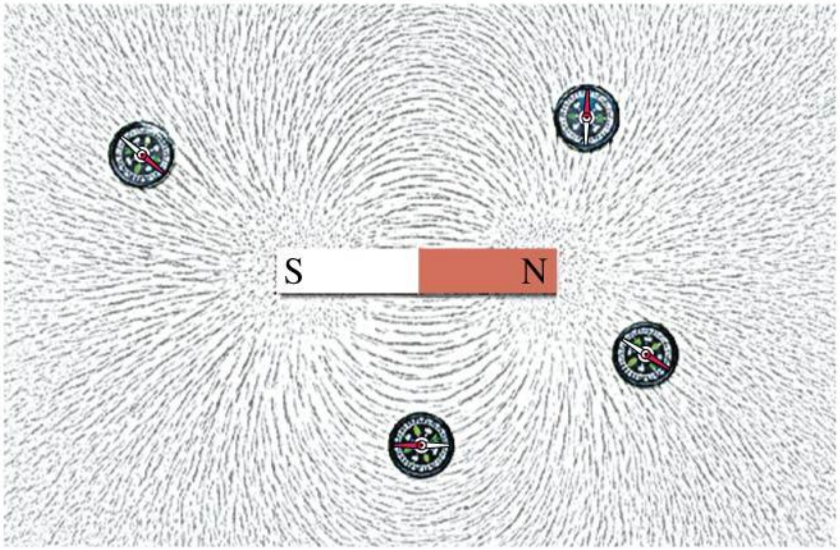
- The direction of a magnetic field is the direction that the north pole of a compass needle points.
- The strength of a magnetic field is proportional to the torque felt by a compass needle as it turns to line up with the field direction.

Measuring the Magnetic Field



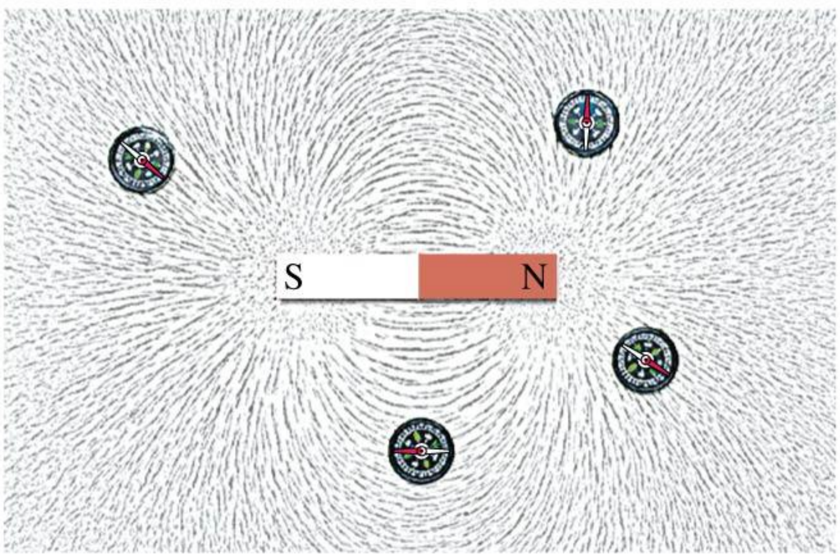
Measuring the Magnetic Field

- We can produce a "picture" of the magnetic field by using *iron filings*—very small elongated grains of iron.
- Each iron filing acts like a tiny compass needle and rotates to point in the direction of the magnetic field.



Measuring the Magnetic Field

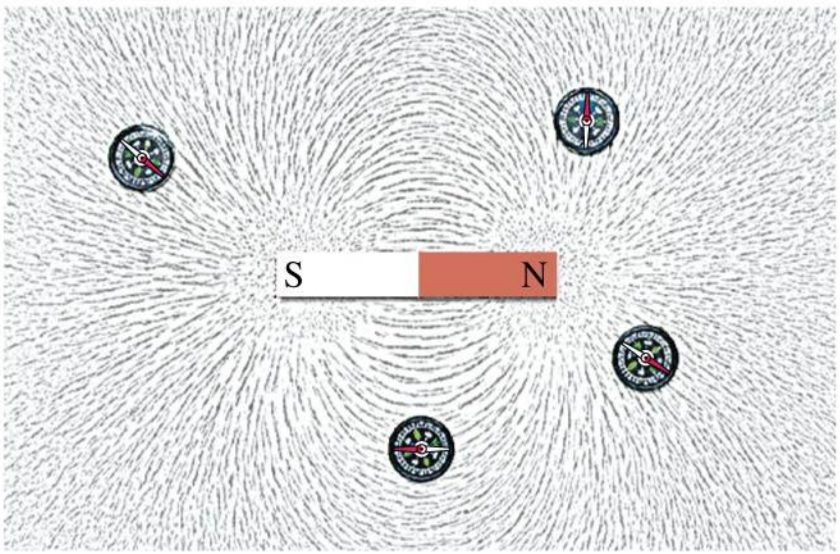
- **The magnetic field of a magnet points away from the north pole and toward the south pole.**



- Since the poles of the iron filings are not labeled, a compass can be used to check the direction of the field.

Measuring the Magnetic Field

- Where the field is strong, the torque easily lines up the filings.
- Where the field is weak, the torque barely lines up the filings.

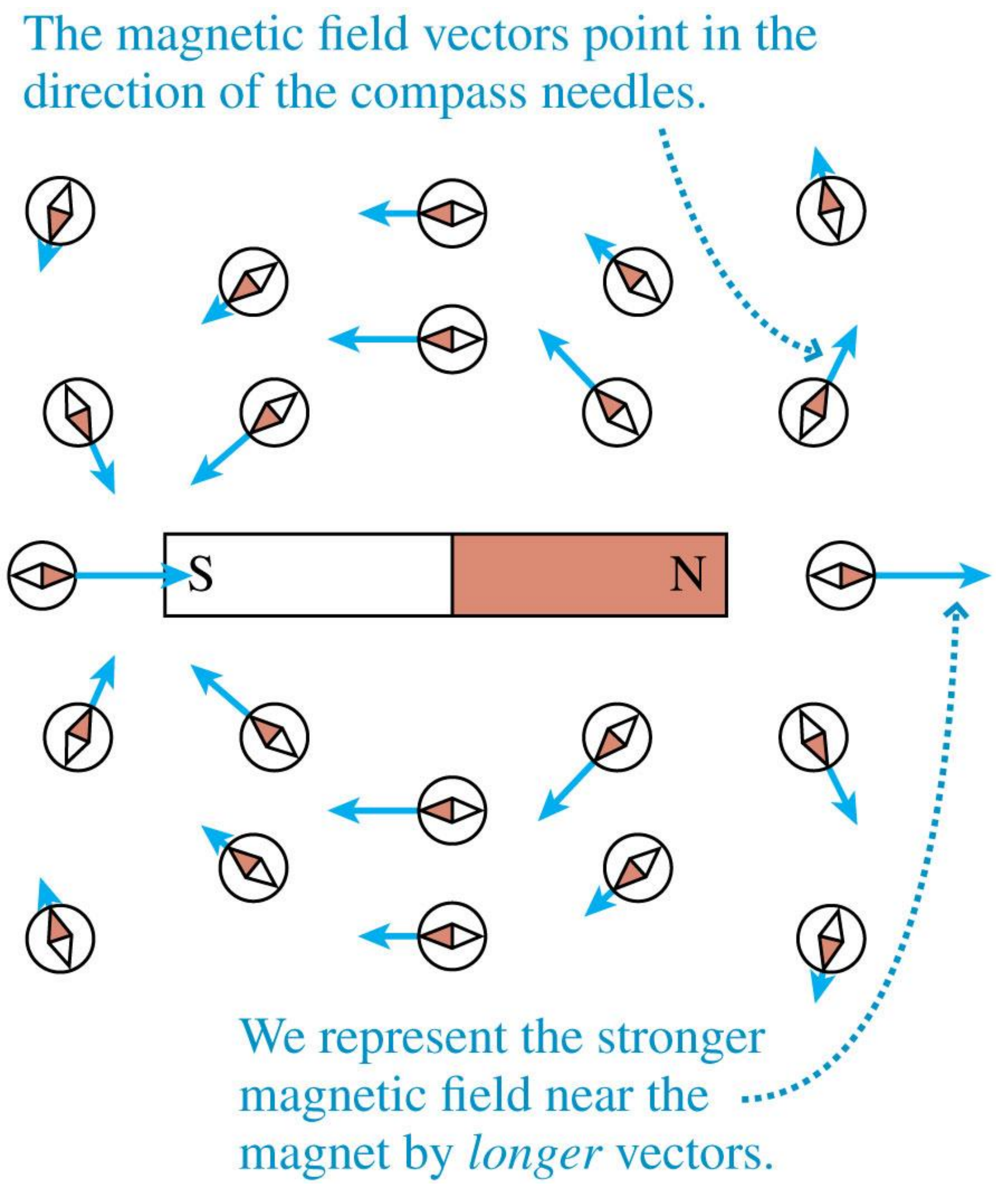


Magnetic Field Vectors and Field Lines

- The **magnetic field vector** representation is useful if we want to represent the magnetic field at one particular point.
- If we want the overall representation of the field, **magnetic field lines** are often simpler to use.

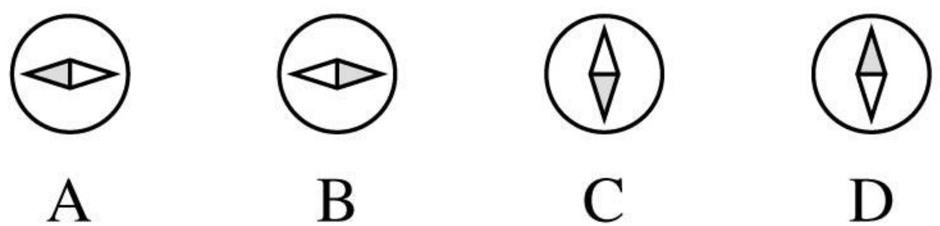
Magnetic Field Vectors and Field Lines

- Mapping out the field of a bar magnet using compasses:



QuickCheck 24.3

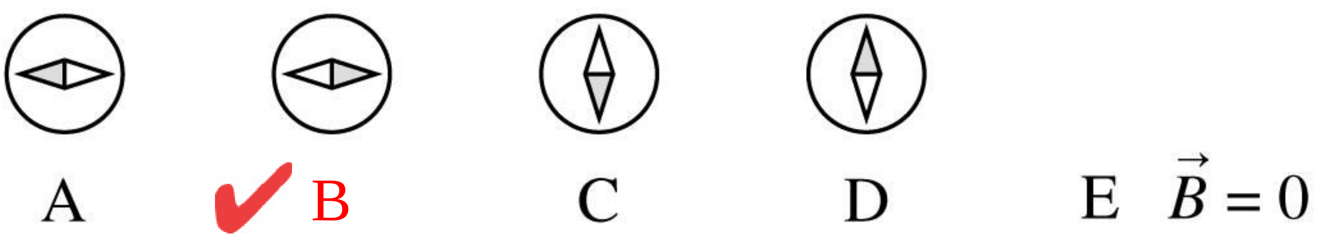
A compass is placed at the black dot. In which direction will the compass point?



E $\vec{B} = 0$

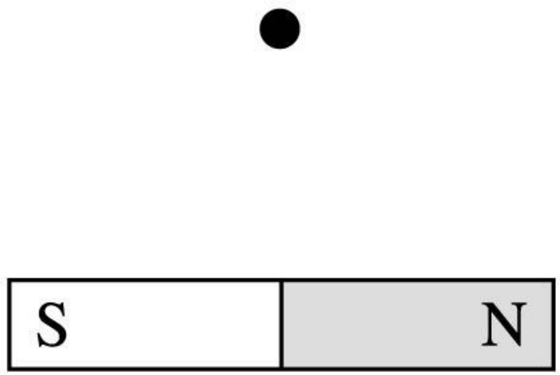
QuickCheck 24.3

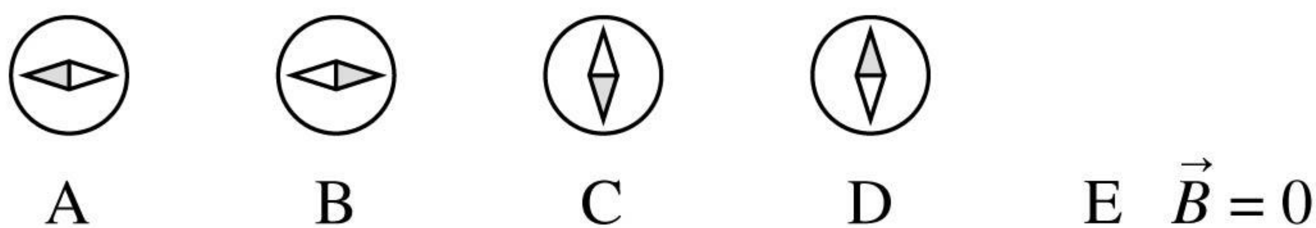
A compass is placed at the black dot. In which direction will the compass point?



QuickCheck 24.4

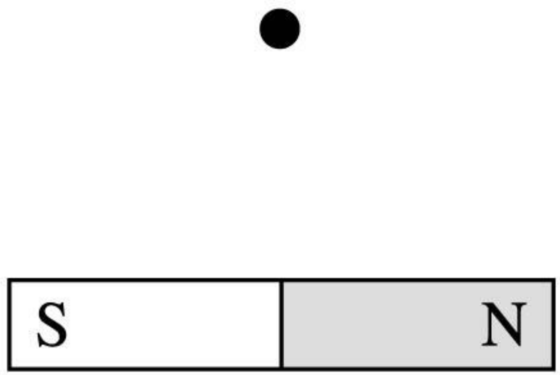
A compass is placed at the black dot. In which direction will the compass point?

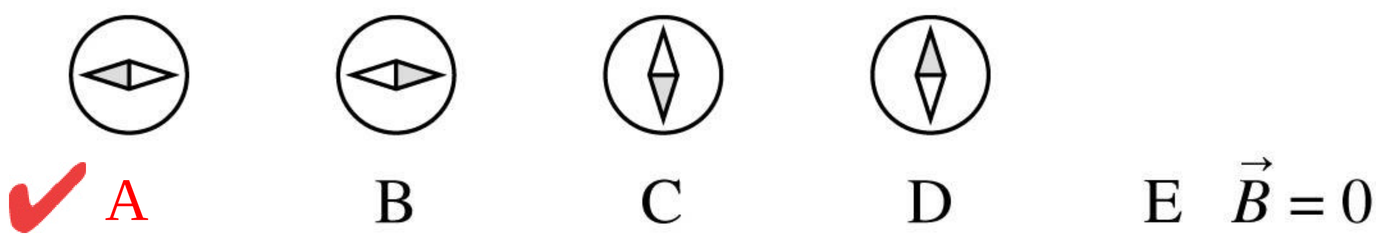




QuickCheck 24.4

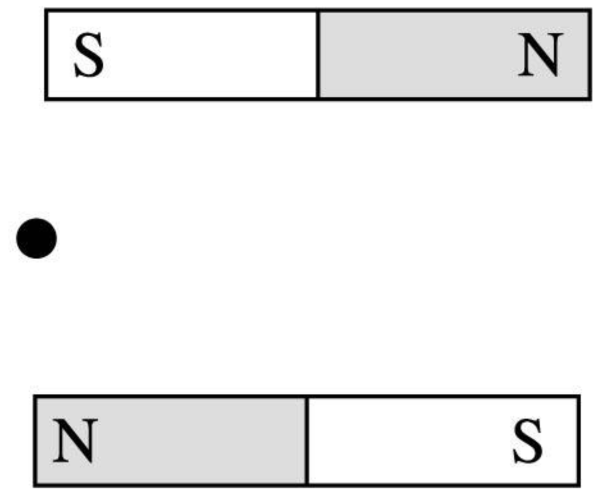
A compass is placed at the black dot. In which direction will the compass point?

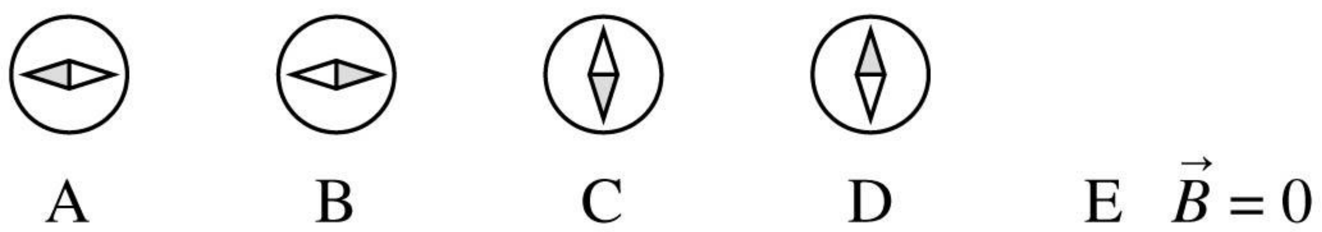




QuickCheck 24.5

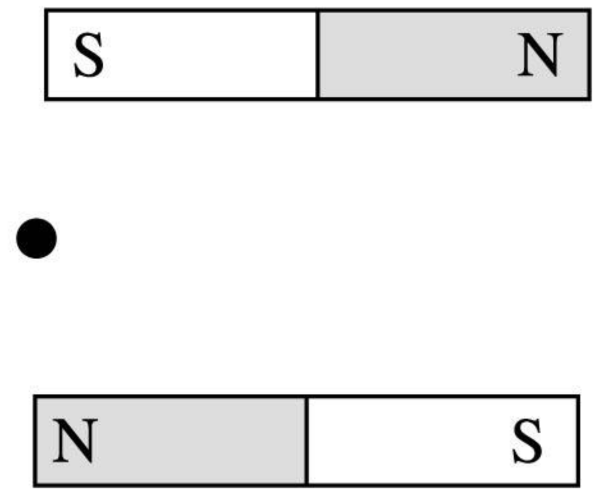
A compass is placed at the black dot. In which direction will the compass point?





QuickCheck 24.5

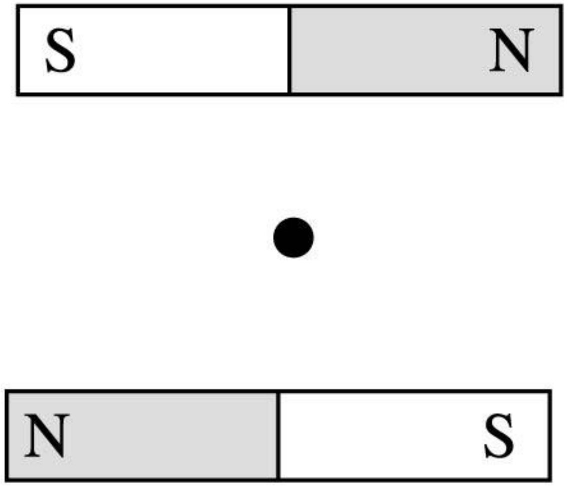
A compass is placed at the black dot. In which direction will the compass point?

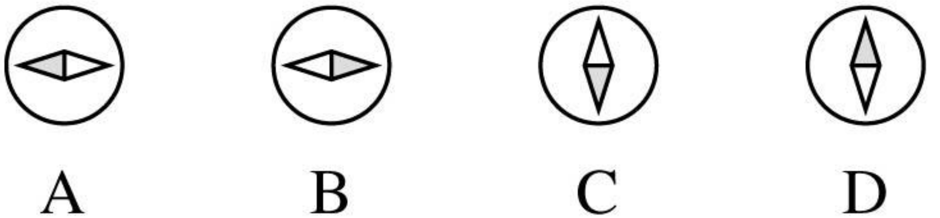


A B C ✔ D E $\vec{B} = 0$

QuickCheck 24.6

A compass is placed at the black dot. In which direction will the compass point?

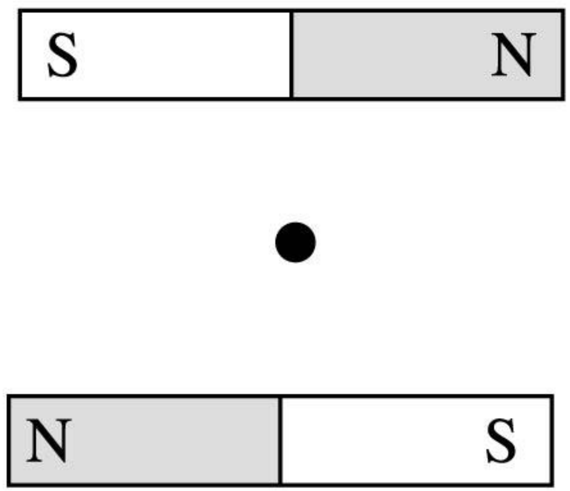




E $\vec{B} = 0$

QuickCheck 24.6

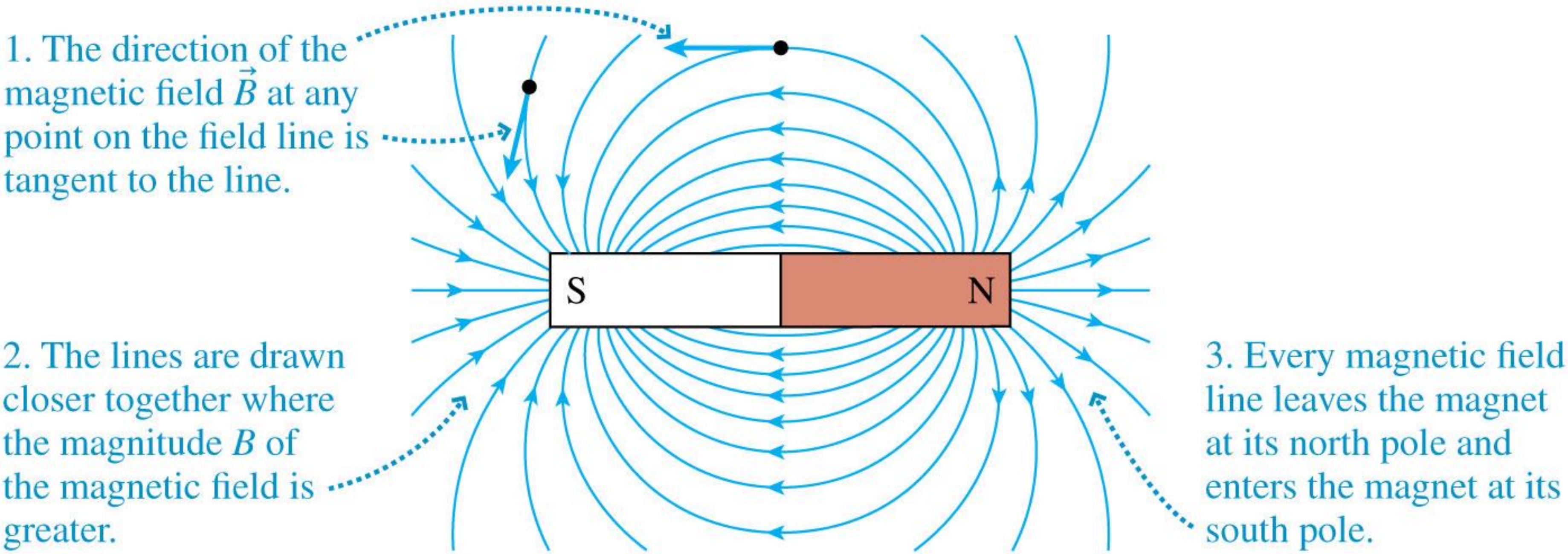
A compass is placed at the black dot. In which direction will the compass point?



A B C D ✔ E $\vec{B} = 0$

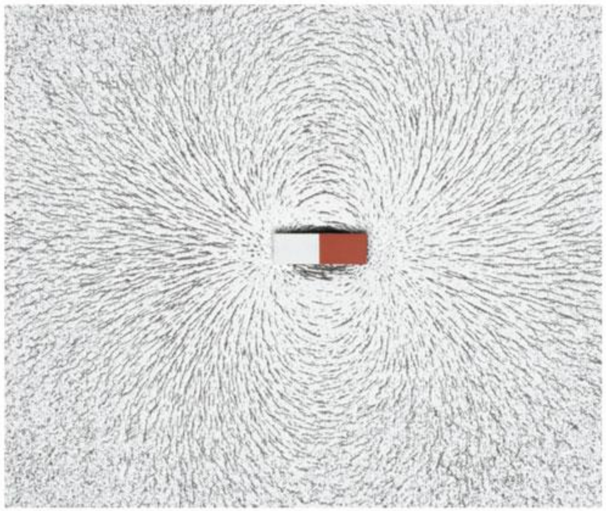
Magnetic Field Vectors and Field Lines

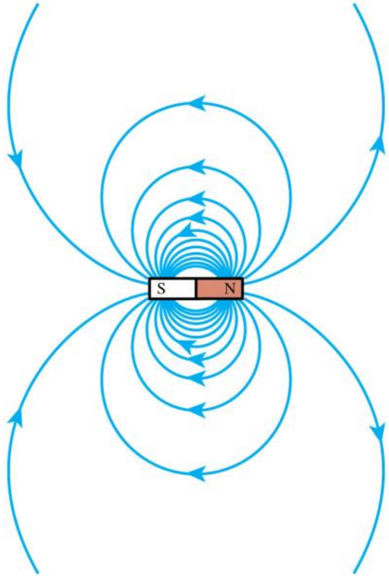
- Drawing the magnetic field lines of a bar magnet:



Magnetic Field Vectors and Field Lines

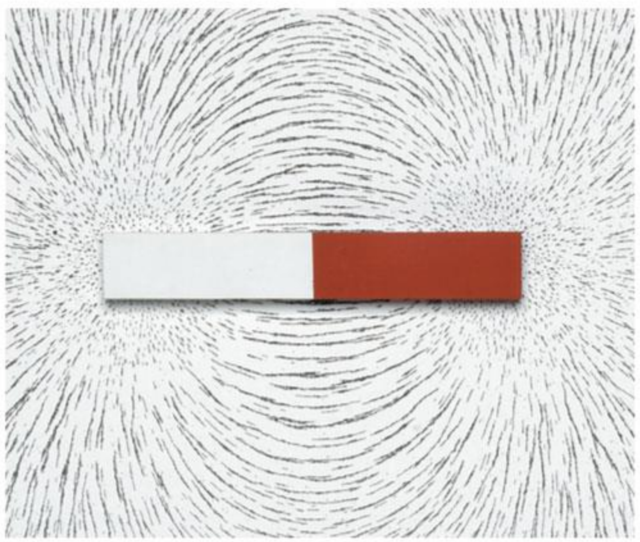
- **A single bar magnet:**
  - The magnetic field lines start on the north pole (red) and end on the south pole (white).
  - As you move away from the magnet, the field lines are farther apart, indicating a weaker field.

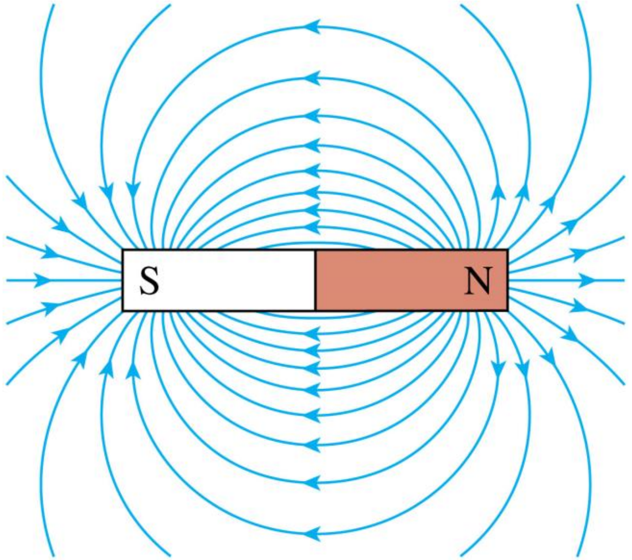




Magnetic Field Vectors and Field Lines

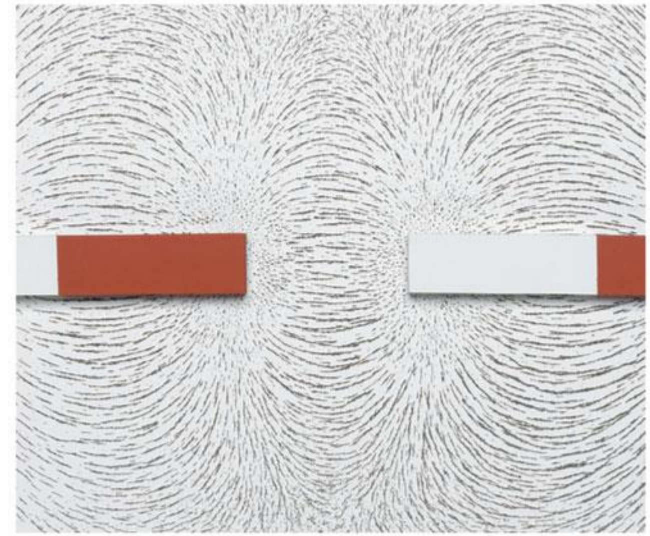
- **A single bar magnet (closeup):**
  - Closer to the magnet, we can more clearly see how the field lines always start on north poles and end on south poles.

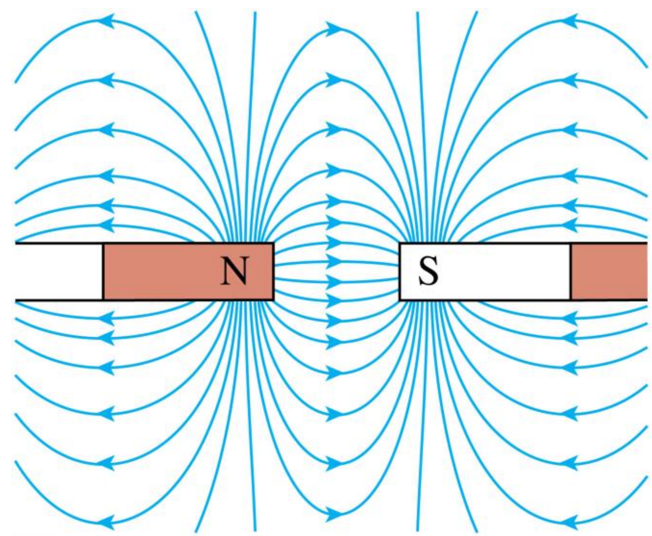




Magnetic Field Vectors and Field Lines

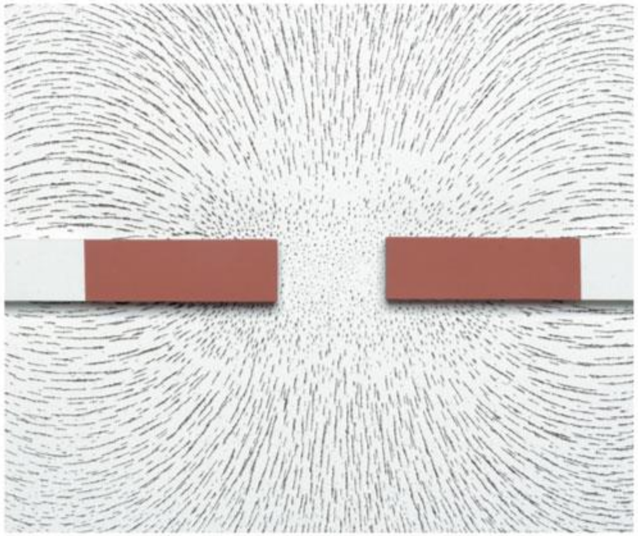
- **Two bar magnets, unlike poles facing:**
  - With more than one magnet, the field lines still start on a north pole and end on a south pole. But they can start on the north pole of one magnet, and end on the south pole of another.

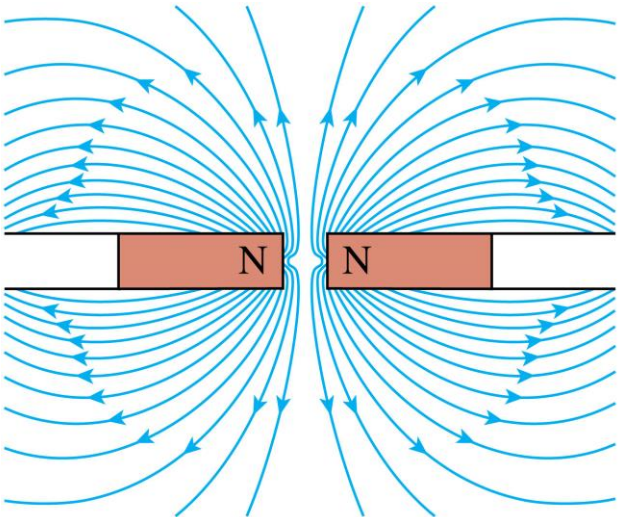




Magnetic Field Vectors and Field Lines

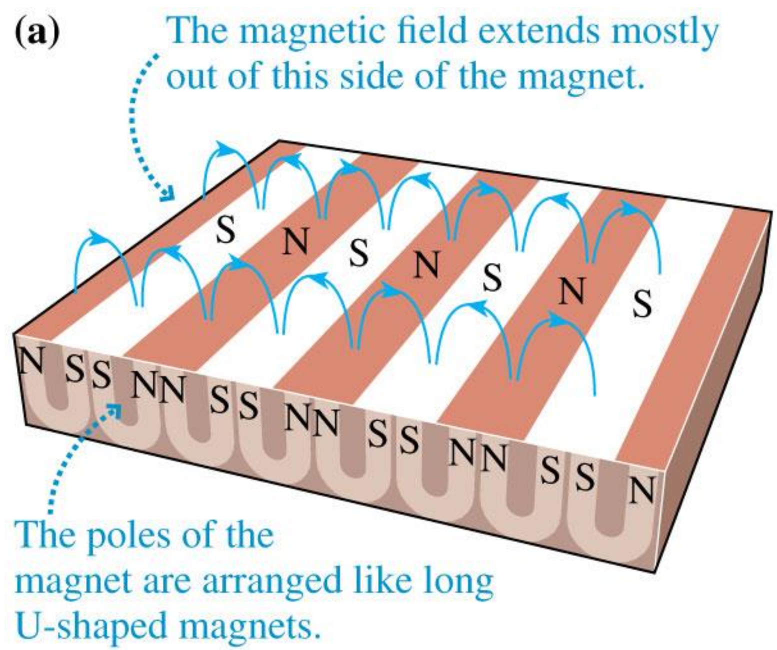
- **Two bar magnets, like poles facing:**
  - With two like poles placed nearby, the field lines starting on the north poles curve sharply toward their south poles in order to avoid the north pole of the other magnet.





Magnetic Field Vectors and Field Lines

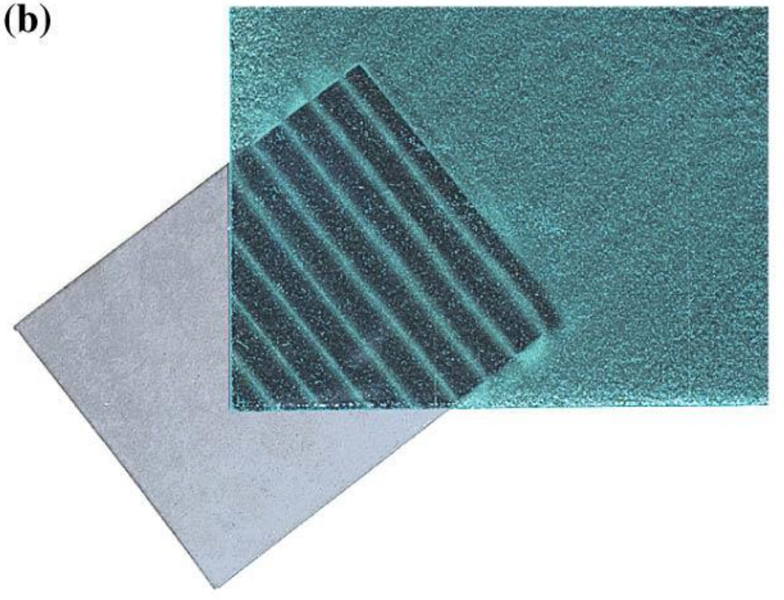
- Magnets can have more than one pair of north-south poles, and the poles do not need to be at the ends of the magnet.
- For example, the magnetic field of a refrigerator magnet:



Magnetic Field Vectors and Field Lines

- The pole structure of a refrigerator magnet can be revealed by a special film that contains fine iron filings.

(b)



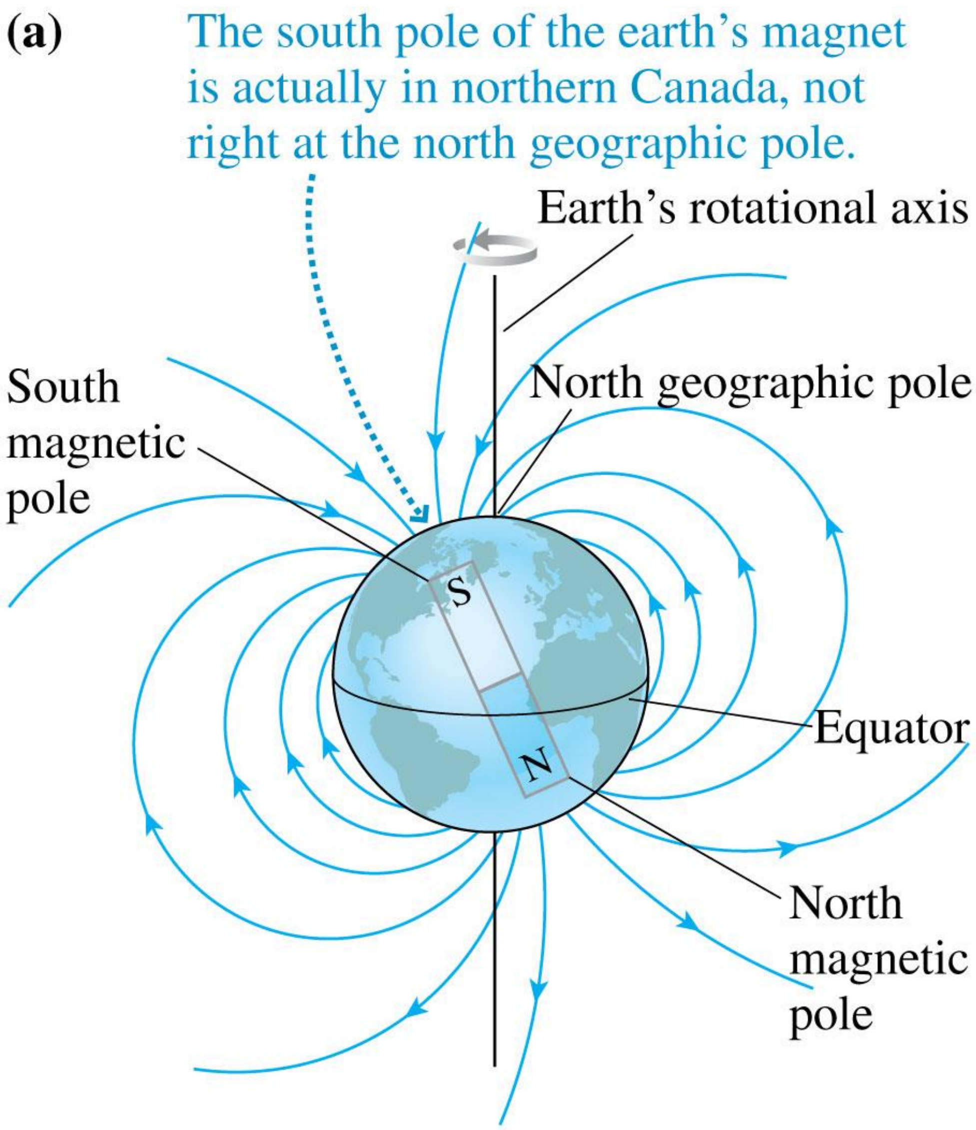
Try It Yourself: Buzzing Magnets

You can use two *identical* flexible refrigerator magnets for a nice demonstration of their alternating pole structure. Place the two magnets together, back to back, then quickly pull them across each other, noting the alternating attraction and repulsion from the alternating poles. If you pull them quickly enough, you will hear a buzz as the magnets are rapidly pushed apart and then pulled together.

The Magnetic Field of the Earth

- **The south pole of the earth's magnet is located near—but not exactly coincident with–the north geographic pole of the earth.**
- This is why the north pole of a compass points geographically north.

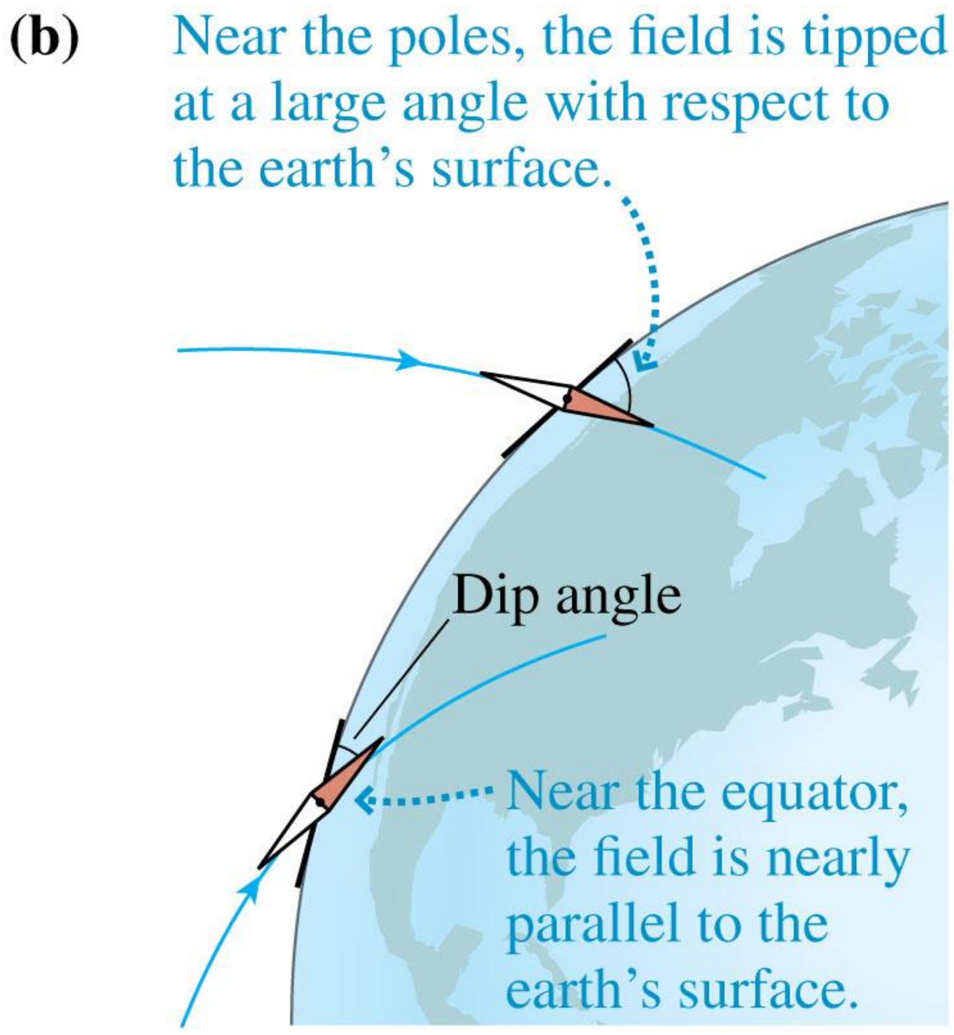
The Magnetic Field of the Earth



The Magnetic Field of the Earth

- The earth's magnetic field has components both parallel to the ground (horizontal) and perpendicular to the ground (vertical).
- An ordinary, north-pointing compass responds only to the horizontal component of the field, but a compass free to pivot vertically will tilt downward as well.
- The **dip angle** is the angle from the horizontal.

The Magnetic Field of the Earth



The Magnetic Field of the Earth

- Magnetotactic bacteria have strongly magnetized bits of iron in their bodies.
- Their bodies rotate to line up parallel to the earth's field, just like a compass.

- These bacteria prefer the low-oxygen zone near the bottom of bodies of water. If the water is disturbed and they are displaced upwards, they follow the vertical component of the earth's field downward.

Conceptual Example 24.1 Balancing a compass

Compasses made for use in northern latitudes are weighted so that the south pole of their needle is slightly heavier than the north pole. Explain why this is done.

Conceptual Example 24.1 Balancing a compass (cont.)

REASON Figure 24.7b shows that, at northern latitudes, the magnetic field of the earth has a large vertical component. A compass needle that pivots to line up with the field has its north pole pointing north, but the north pole also tips down to follow the field. To keep the compass balanced, there must be an extra force on the south end of the compass. A small weight on the south pole provides a force that keeps the needle balanced.

Conceptual Example 24.1 Balancing a compass (cont.)

ASSESS This strategy makes sense. Keeping the needle horizontal when the field is not horizontal requires some extra force.

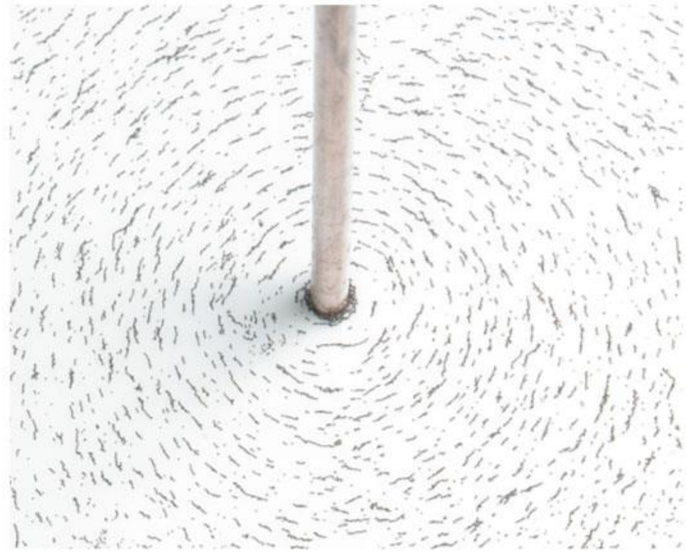
Section 24.3 Electric Currents Also Create Magnetic Fields

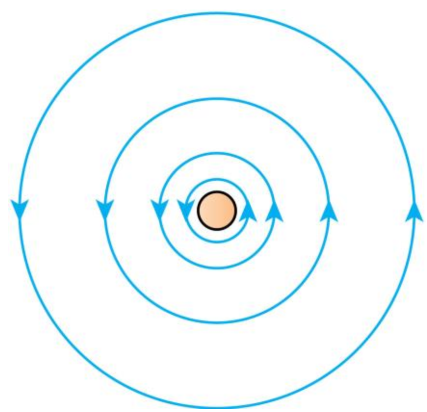
Electric Currents Also Create Magnetic Fields

- A compass will react to the presence of a bar magnet.
- A compass will also deflect if you place the compass near a wire and pass a current through the wire. When the current stops, the compass goes back to its original orientation.
- This means that an *electric* current produces a *magnetic* field.
- The shape of the field lines depends on the shape of the current-carrying wire.

Electric Currents Also Create Magnetic Fields

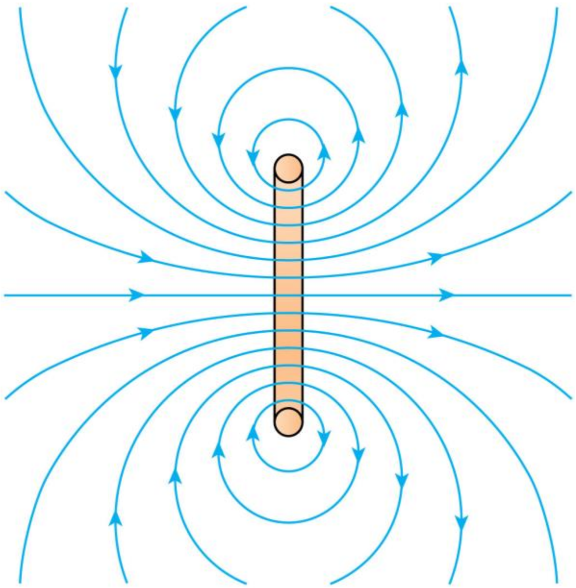
- The magnetic field lines form *circles* around the wire. The iron filings are less affected by the field as the distance from the wire increases, indicating that the field is getting weaker as the distance from the wire increases.





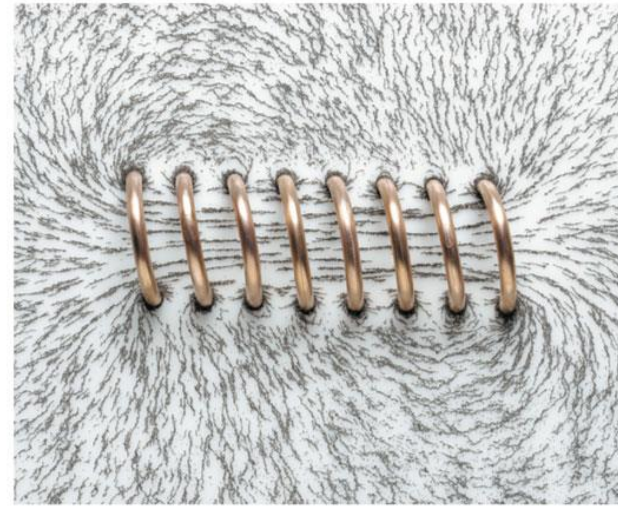
Electric Currents Also Create Magnetic Fields

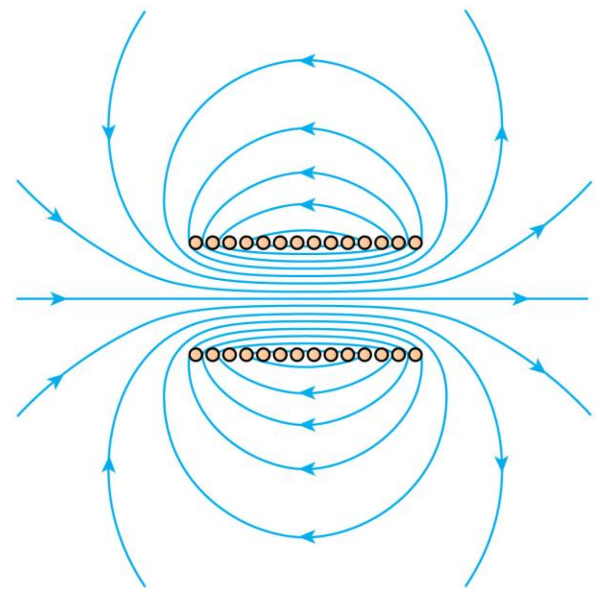
- The magnetic field lines curve through the center of the loop, around the outside, and back through the loop's center, forming complete closed curves. The field lines far from the loop look like the field lines far from a bar magnet.



Electric Currents Also Create Magnetic Fields

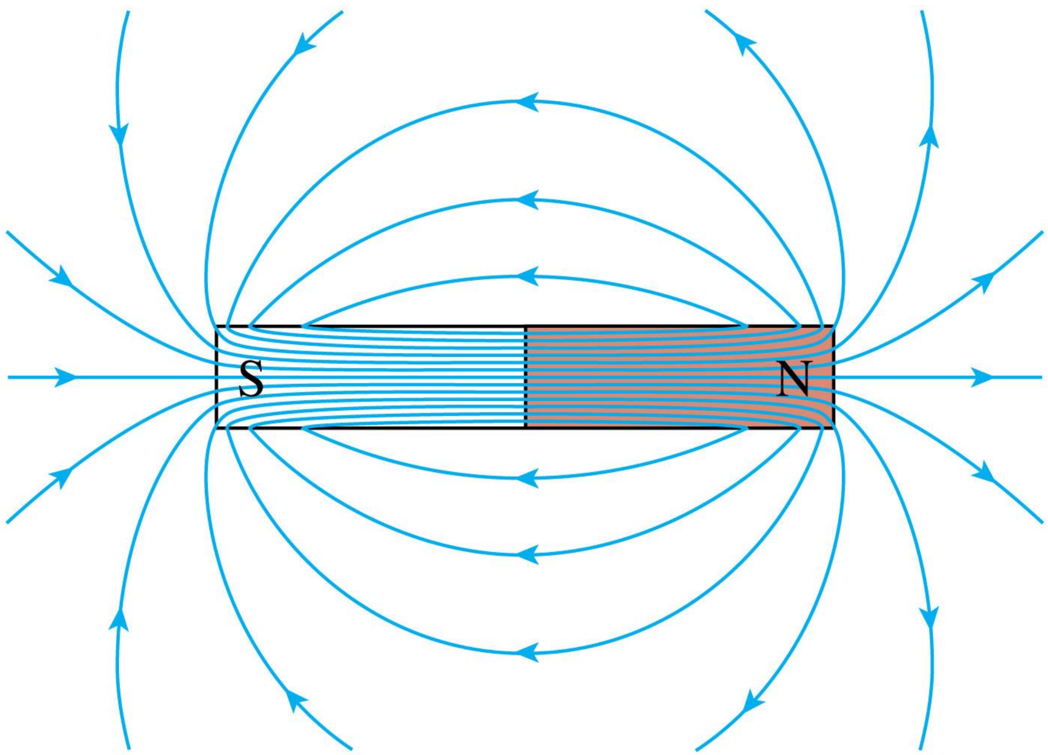
- A **solenoid** is a series of current loops placed along a common axis. The field outside is very weak compared to the field inside. Inside the solenoid, the magnetic field lines are reasonably evenly spaced; the field inside is nearly uniform.





Electric Currents Also Create Magnetic Fields

- Magnetic field lines due to currents have no start or end; they form complete closed curves.
- If we consider the field lines continuing *inside* a magnet, we find that these lines also form complete closed curves.

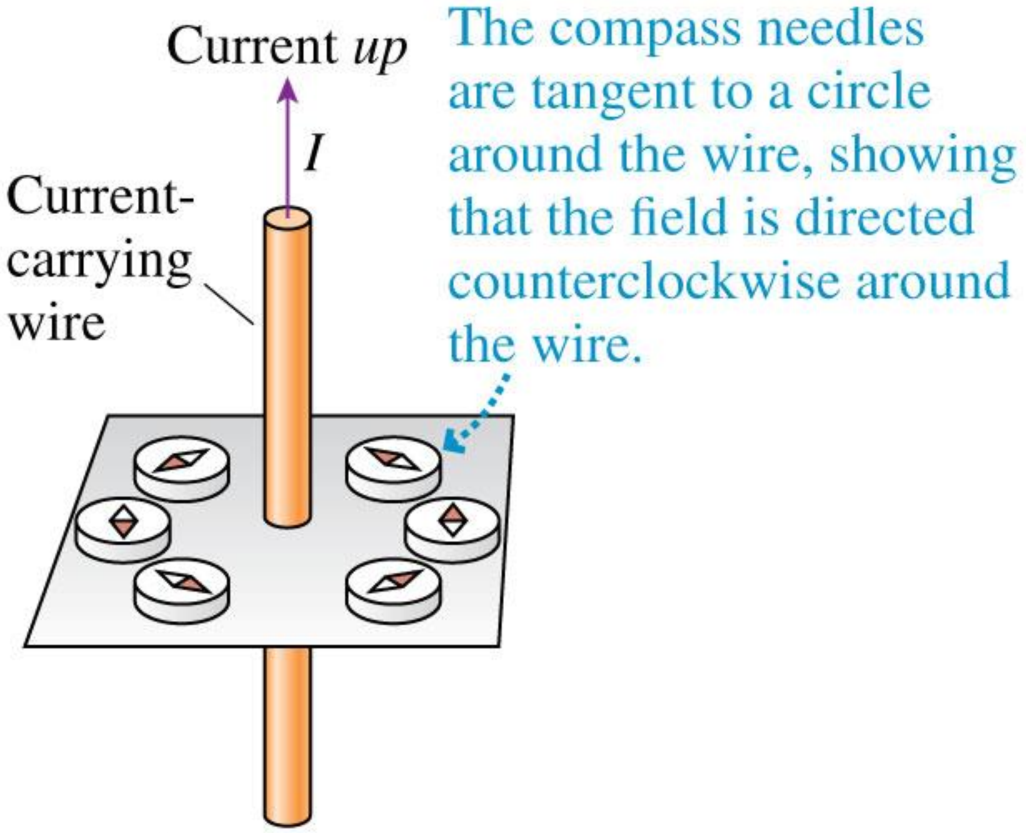


Electric Currents Also Create Magnetic Fields

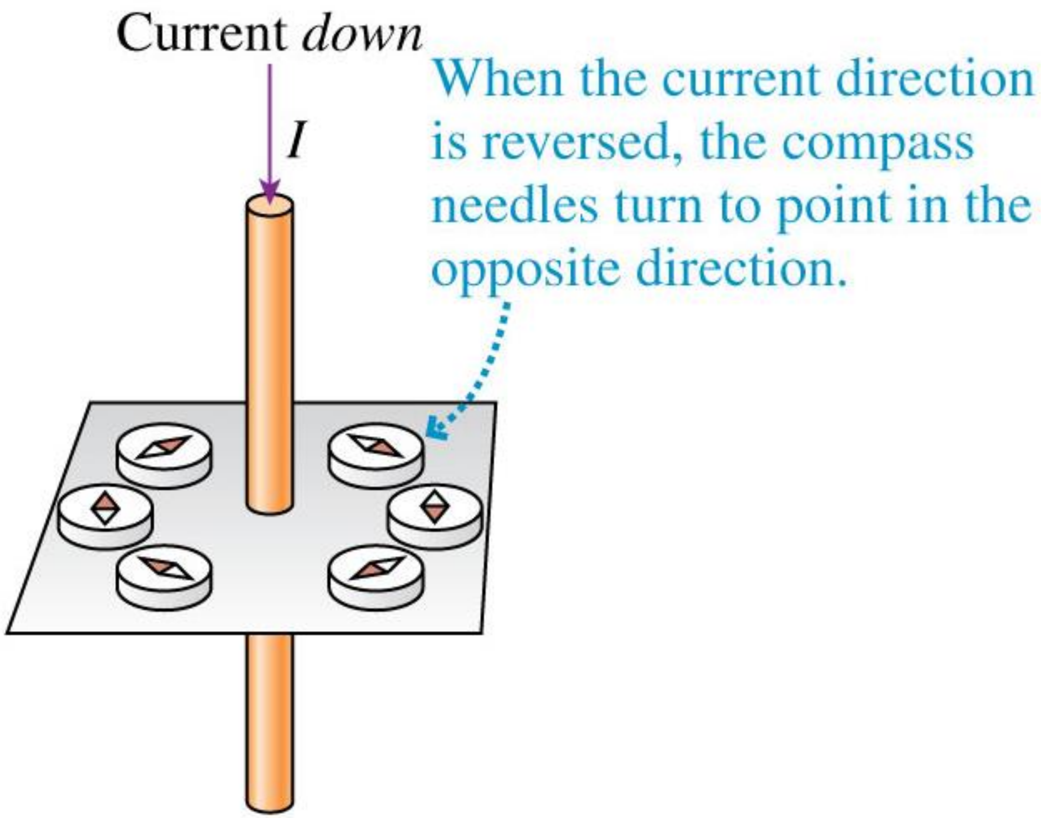
- Ordinary magnets are often called **permanent magnets** to distinguish their unchanging magnetism from that caused by currents that can be switched on and off.

The Magnetic Field of a Straight, Current-Carrying Wire

- The iron filings line up in *circles* around a straight, current carrying wire.



The Magnetic Field of a Straight, Current-Carrying Wire

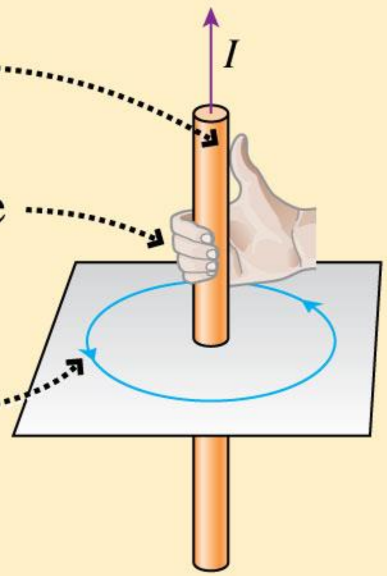


The Magnetic Field of a Straight, Current-Carrying Wire

- The **right-hand rule of fields** helps us remember which direction compasses will point.

TACTICS BOX 24.1 **Right-hand rule for fields**

1. Point your *right* thumb in the direction of the current.
2. Wrap your fingers around the wire to indicate a circle.
3. Your fingers curl in the direction of the magnetic field lines around the wire.

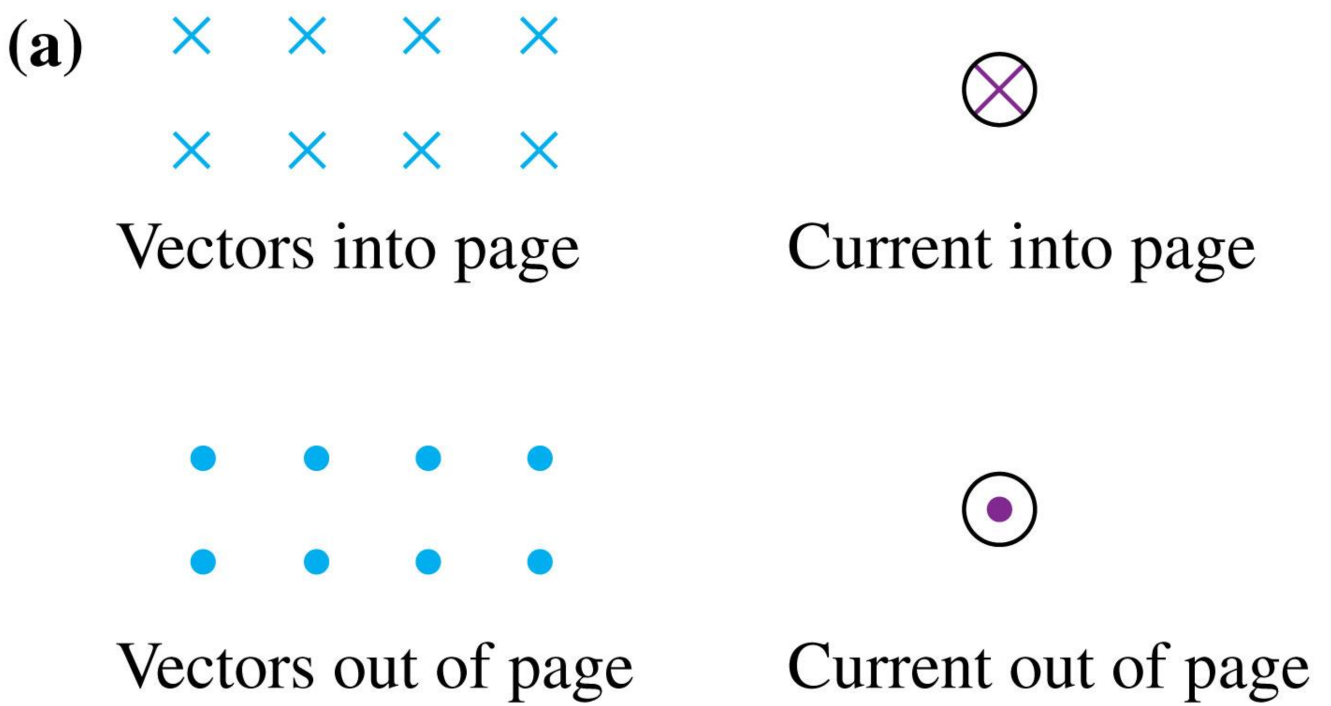


Exercises 6–11

Text: p. 771

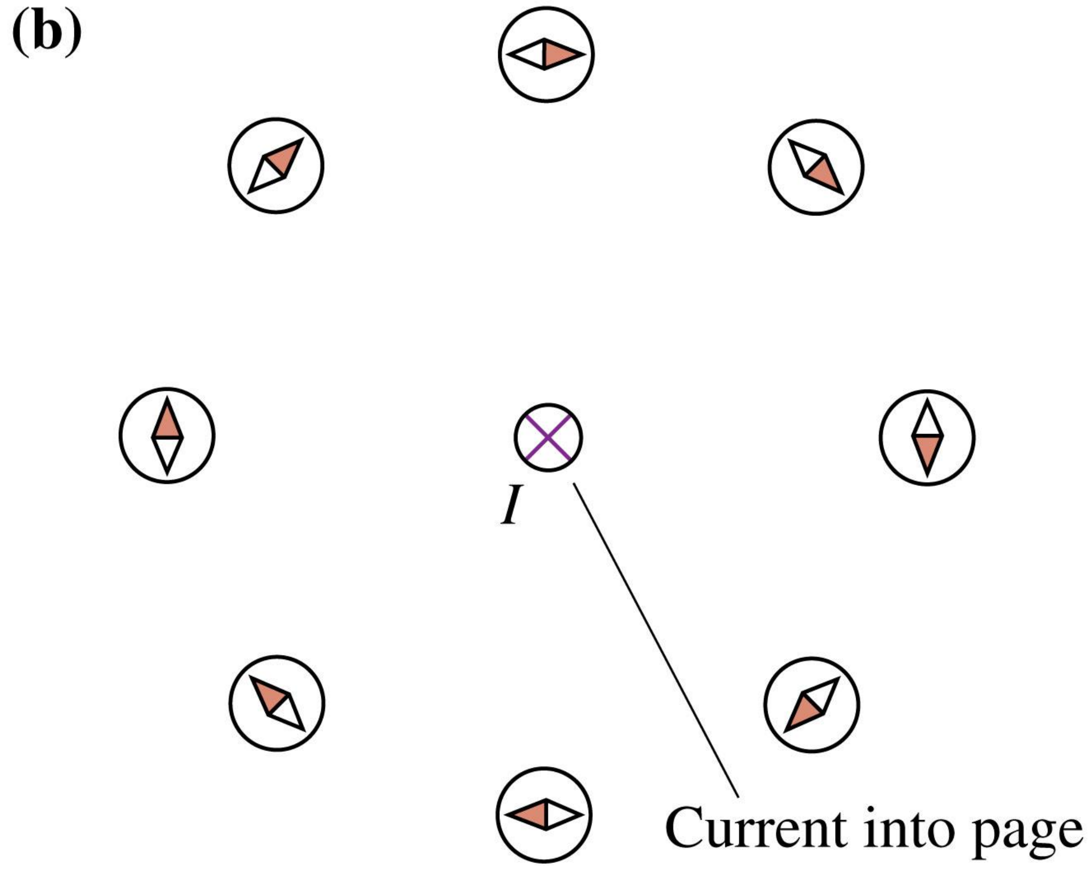
The Magnetic Field of a Straight, Current-Carrying Wire

- Magnetism often requires a three-dimensional perspective.
- To indicate field vectors or currents that are perpendicular to the page, we use



The Magnetic Field of a Straight, Current-Carrying Wire

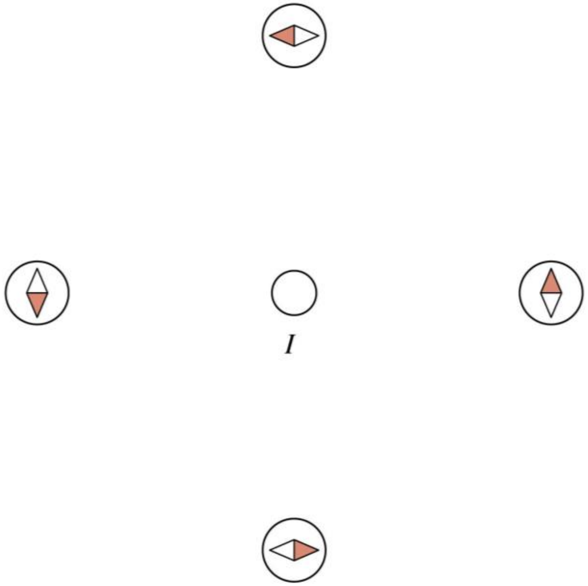
- Here is an example of the notation with compasses around a current that is directed into the page.



QuickCheck 24.7

A long, straight wire extends into and out of the screen. The current in the wire is

A. Into the screen.
B. Out of the screen.
C. There is no current in the wire.
D. Not enough info to tell the direction.

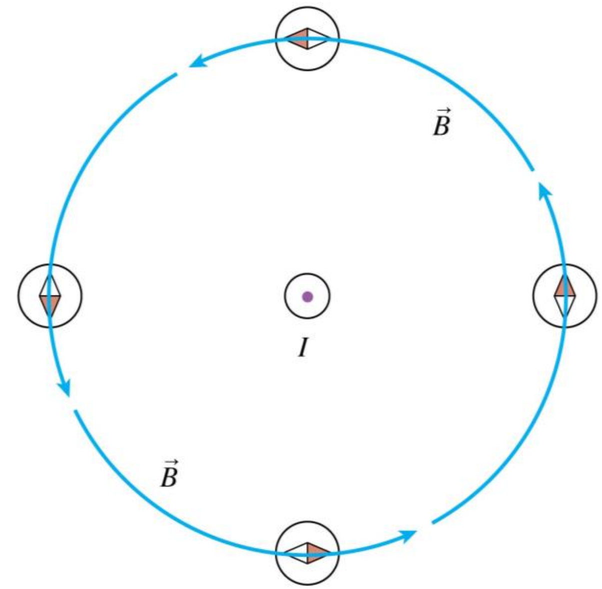


QuickCheck 24.7

A long, straight wire extends into and out of the screen. The current in the wire is

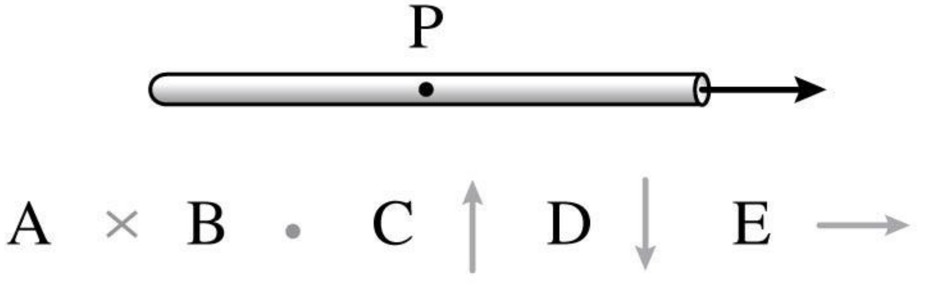
A. Into the screen.
✔ B. Out of the screen.
C. There is no current in the wire.
D. Not enough info to tell the direction.

Right-hand rule



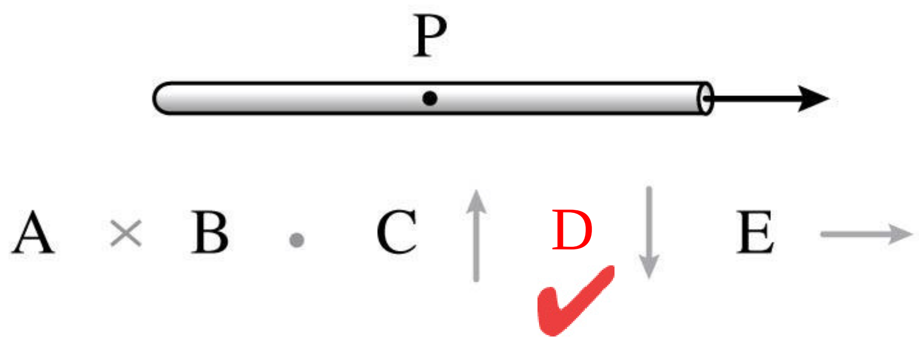
QuickCheck 24.8

Point P is 5 cm above the wire as you look straight down at it. In which direction is the magnetic field at P?



QuickCheck 24.8

Point P is 5 cm above the wire as you look straight down at it. In which direction is the magnetic field at P?



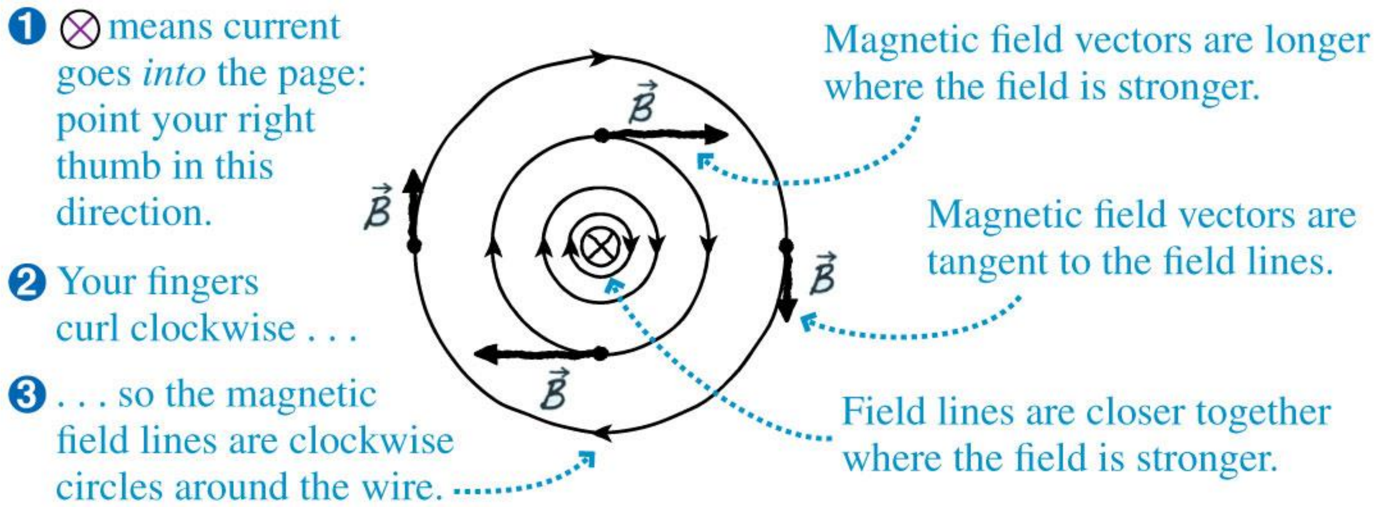
Conceptual Example 24.2 Drawing the magnetic field of a current-carrying wire

Sketch the magnetic field of a long, current-carrying wire, with the current going into the paper. Draw both magnetic field line and magnetic field vector representations.

Conceptual Example 24.2 Drawing the magnetic field f a current-carrying wire (cont.)

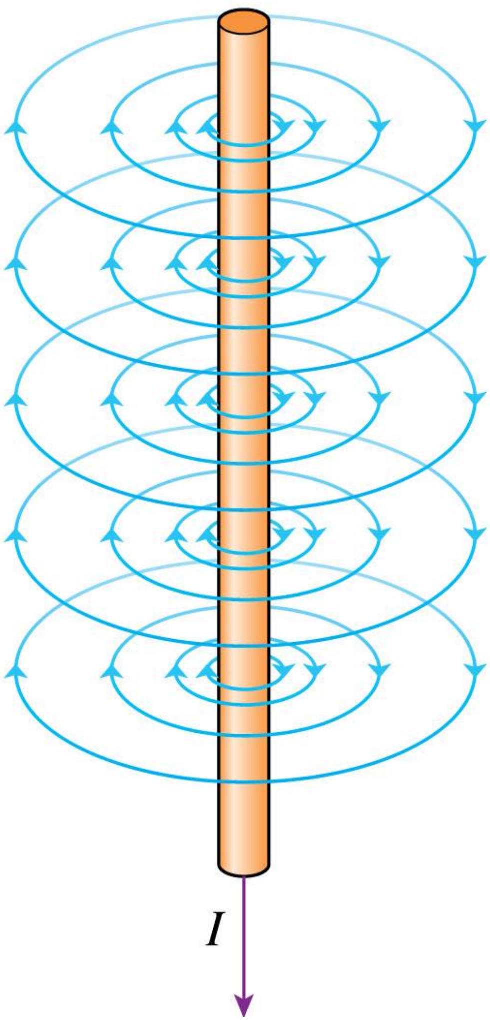
REASON From the iron filing picture in the atlas, we have seen that the field lines form circles around the wire, and the magnetic field becomes weaker as the distance from the wire is increased.

Conceptual Example 24.2 Drawing the magnetic field of a current-carrying wire (cont.)



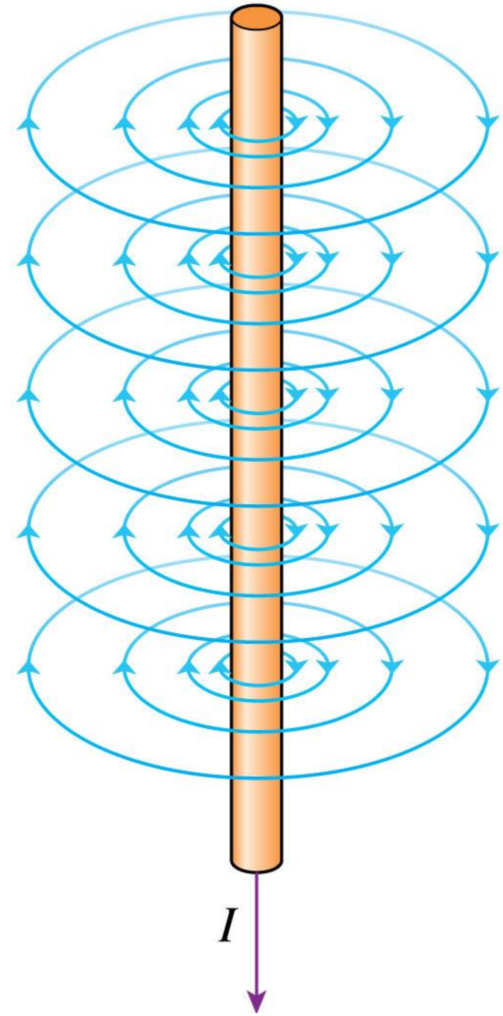
Conceptual Example 24.2 Drawing the magnetic field of a current-carrying wire (cont.)

ASSESS Figure 24.12 illustrates the key features of the field. The direction of the field vectors and field lines matches what we saw in Figure 24.11, and the field strength drops off with distance, as we learned in the atlas figure.



Conceptual Example 24.2 Drawing the magnetic field of a current-carrying wire (cont.)

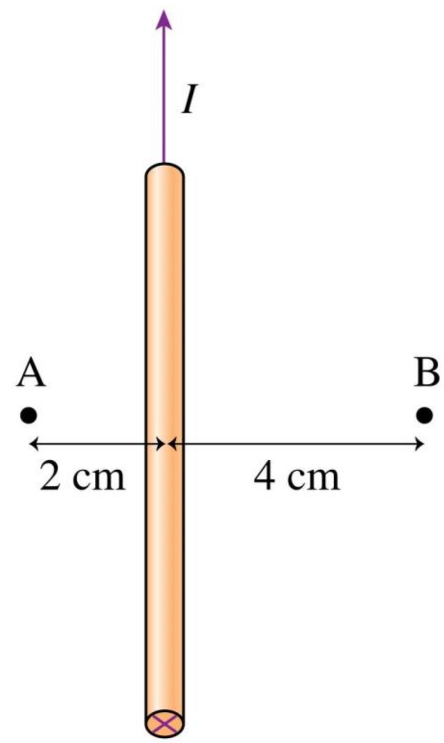
We don't expect you to draw such a figure, but it's worth looking at the full 3-D picture of the field in **FIGURE 24.13**. This conveys the idea that the field lines exist in every plane along the length of the wire.



QuickCheck 24.9

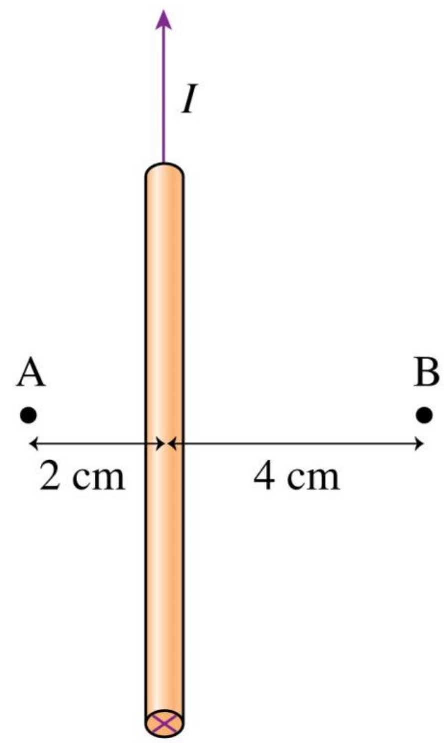
Compared to the magnetic field at point A, the magnetic field at point B is

A. Half as strong, same direction.
B. Half as strong, opposite direction.
C. One-quarter as strong, same direction.
D. One-quarter as strong, opposite direction.
E. Can't compare without knowing *I*.



QuickCheck 24.9

Compared to the magnetic field at point A, the magnetic field at point B is



A. Half as strong, same direction.

✔ B. Half as strong, opposite direction.

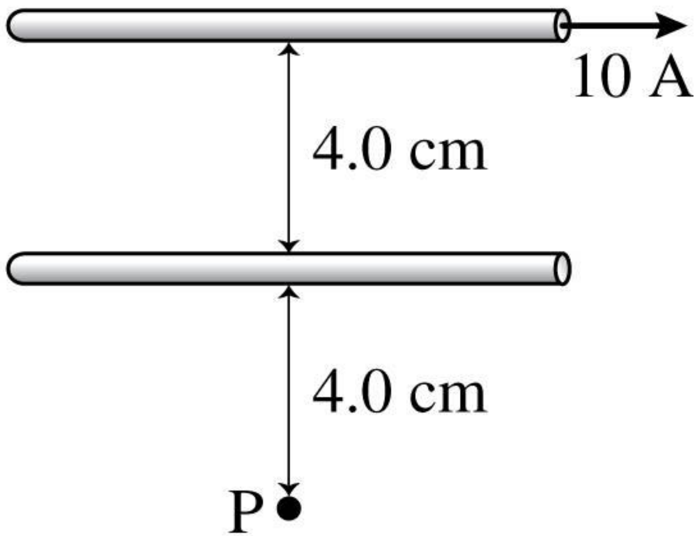
C. One-quarter as strong, same direction.

D. One-quarter as strong, opposite direction.

E. Can't compare without knowing *I*.

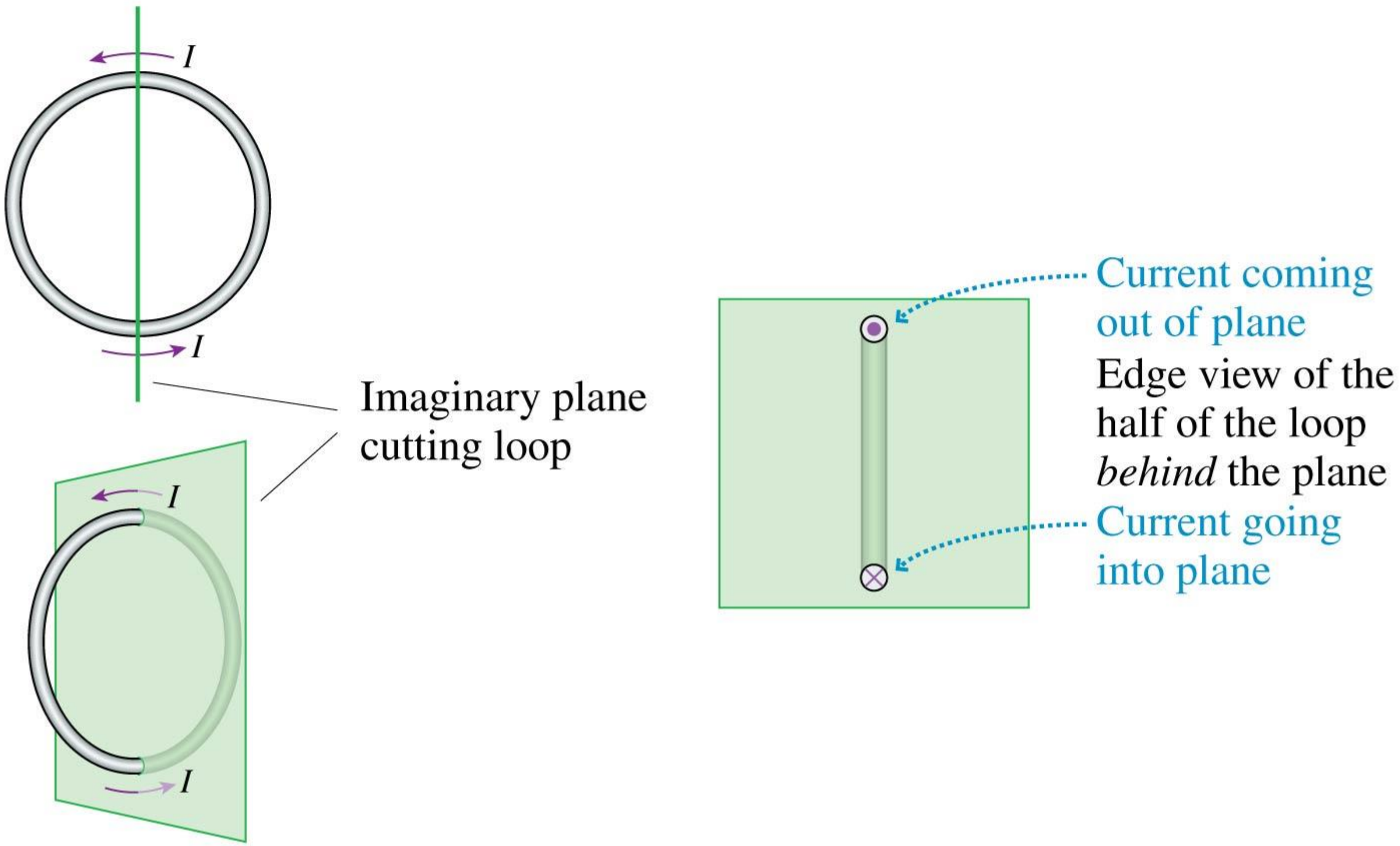
Example Problem

The magnetic field at point P is zero. What is the magnitude and direction of the current in the lower wire?



The Magnetic Field of a Current Loop

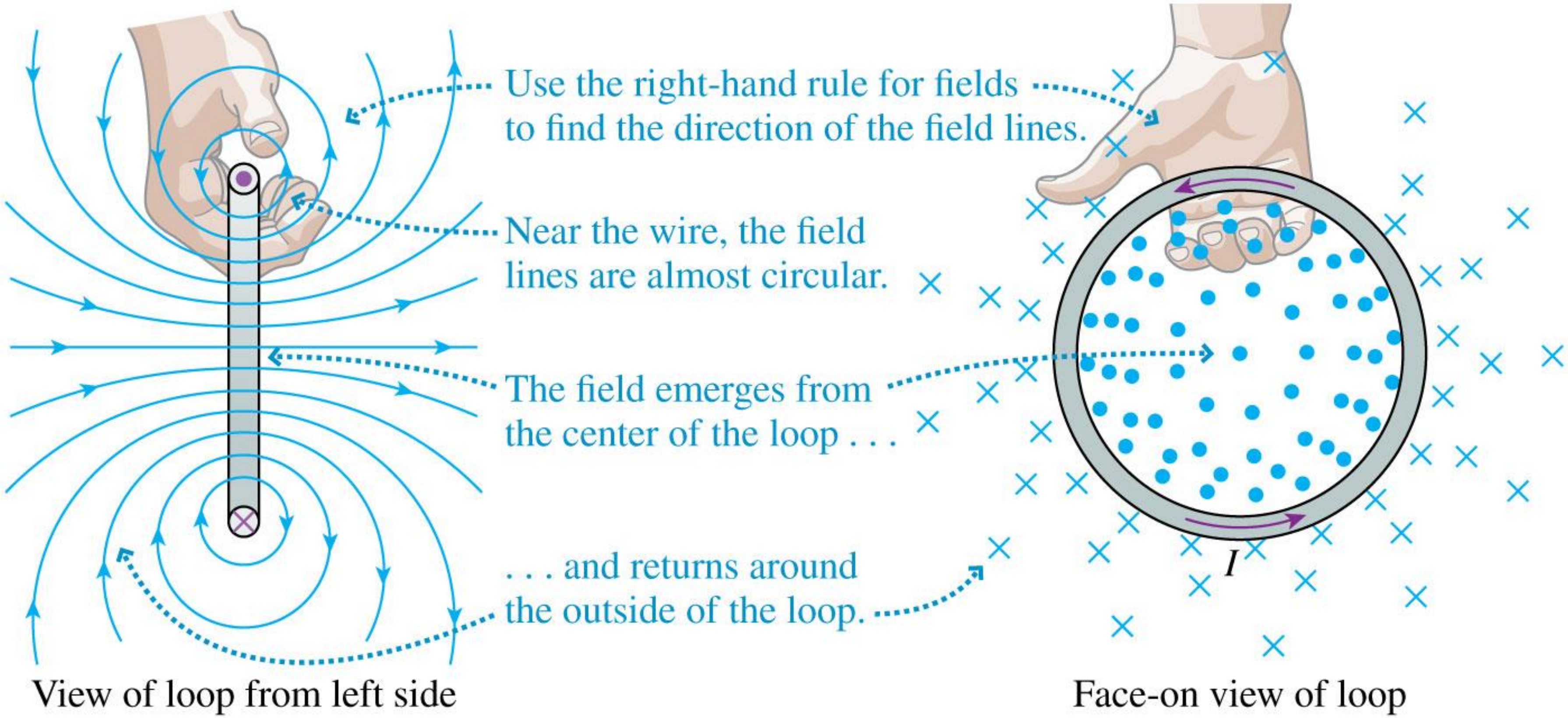
- Here we see three views of a current-carrying loop.



The Magnetic Field of a Current Loop

- To see what the field due to a current loop looks like, we can imagine bending a straight wire into a loop.
- The field lines near the wire will remain similar to what they looked like when the wire was straight: circles going around the wire.
- Farther from the wires, the field lines are no longer circles but they still curve through the center of the loop, back around the outside and then return through the center.
- If we reverse the direction of the current in the loop, all the field lines reverse direction as well.

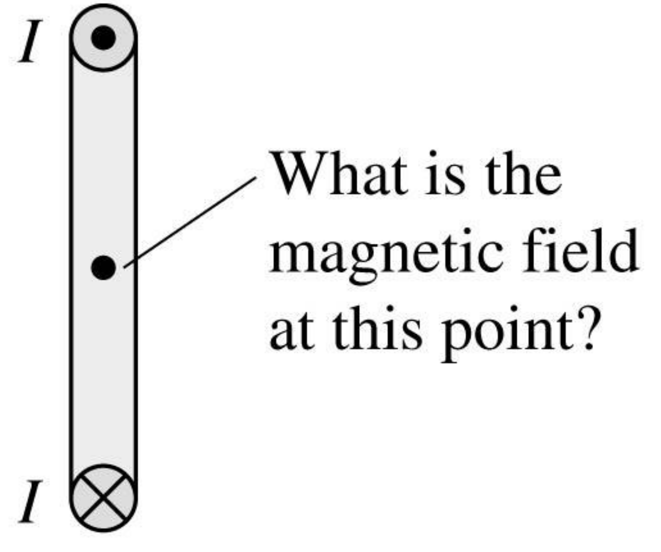
The Magnetic Field of a Current Loop



QuickCheck 24.10

The following diagram shows a current loop perpendicular to the page; the view is a "slice" through the loop. The direction of the current in the wire at the top and at the bottom is shown. What is the direction of the magnetic field at a point in the center of the loop?

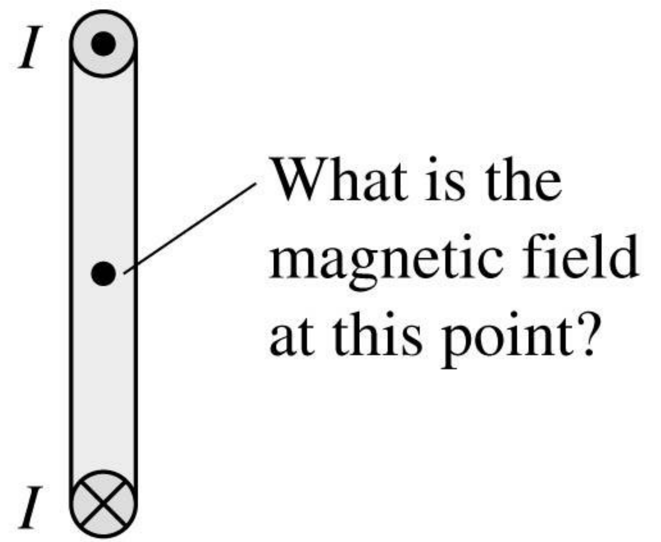
A. To the left
B. Up
C. To the right
D. Down



QuickCheck 24.10

The following diagram shows a current loop perpendicular to the page; the view is a "slice" through the loop. The direction of the current in the wire at the top and at the bottom is shown. What is the direction of the magnetic field at a point in the center of the loop?

A. To the left
B. Up
✔ C. To the right
D. Down



QuickCheck 24.11

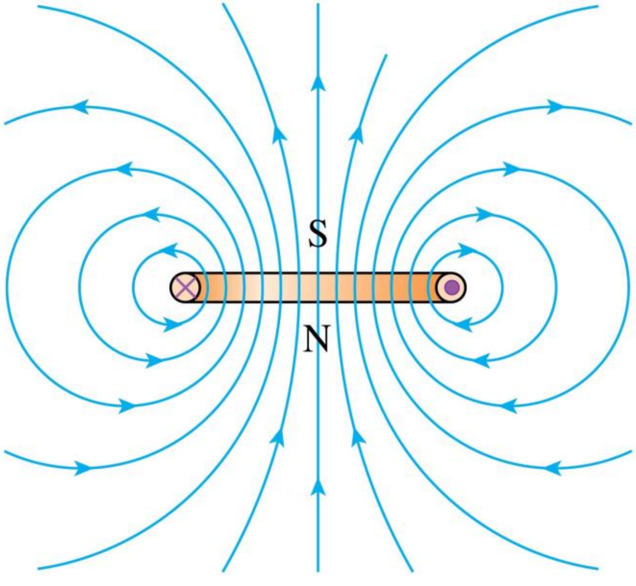
Where is the north magnetic pole of this current loop?

A. Top side
B. Bottom side
C. Right side
D. Left side
E. Current loops don't have north poles.

QuickCheck 24.11

Where is the north magnetic pole of this current loop?

A. Top side
✔ B. Bottom side
C. Right side
D. Left side
E. Current loops don't have north poles.



Example Problem

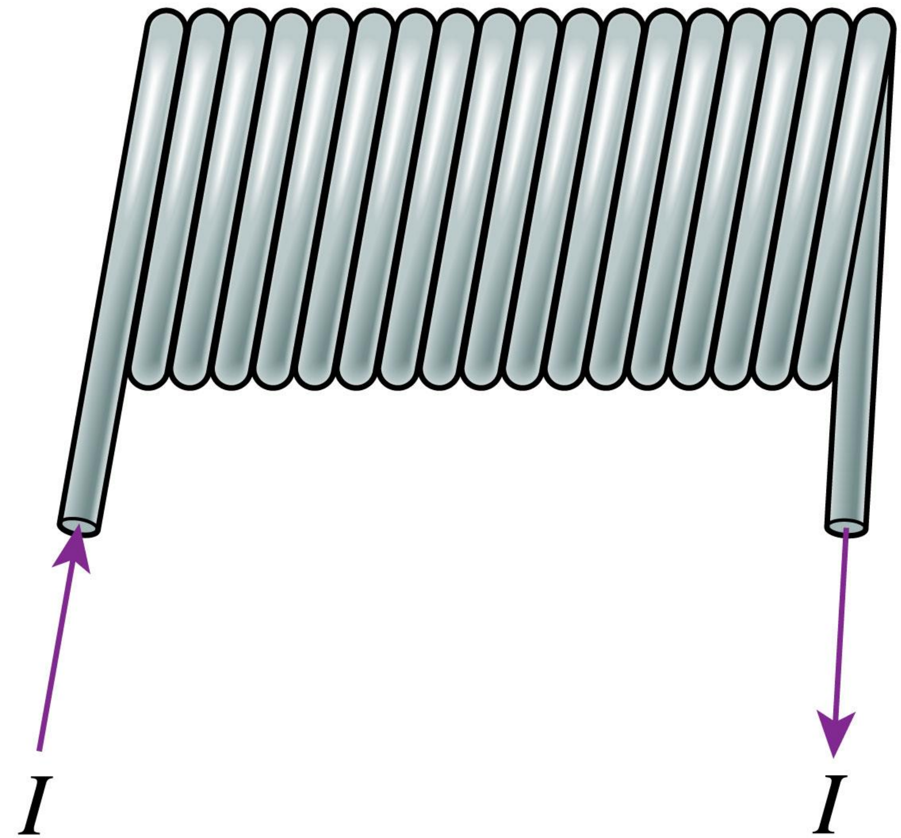
A physics instructor is creating a demonstration that shows the direction of the field at the center of a current loop. He takes a cardboard form 25 cm in diameter and wraps 20 turns of wire around it in a tight loop. He wants the field at the loop's center to be at least 10 times as large as the magnetic field of the earth, so that a compass will pivot convincingly to point in the direction of the field from the loop. How much current is needed to provide this field?

The Magnetic Field of a Solenoid

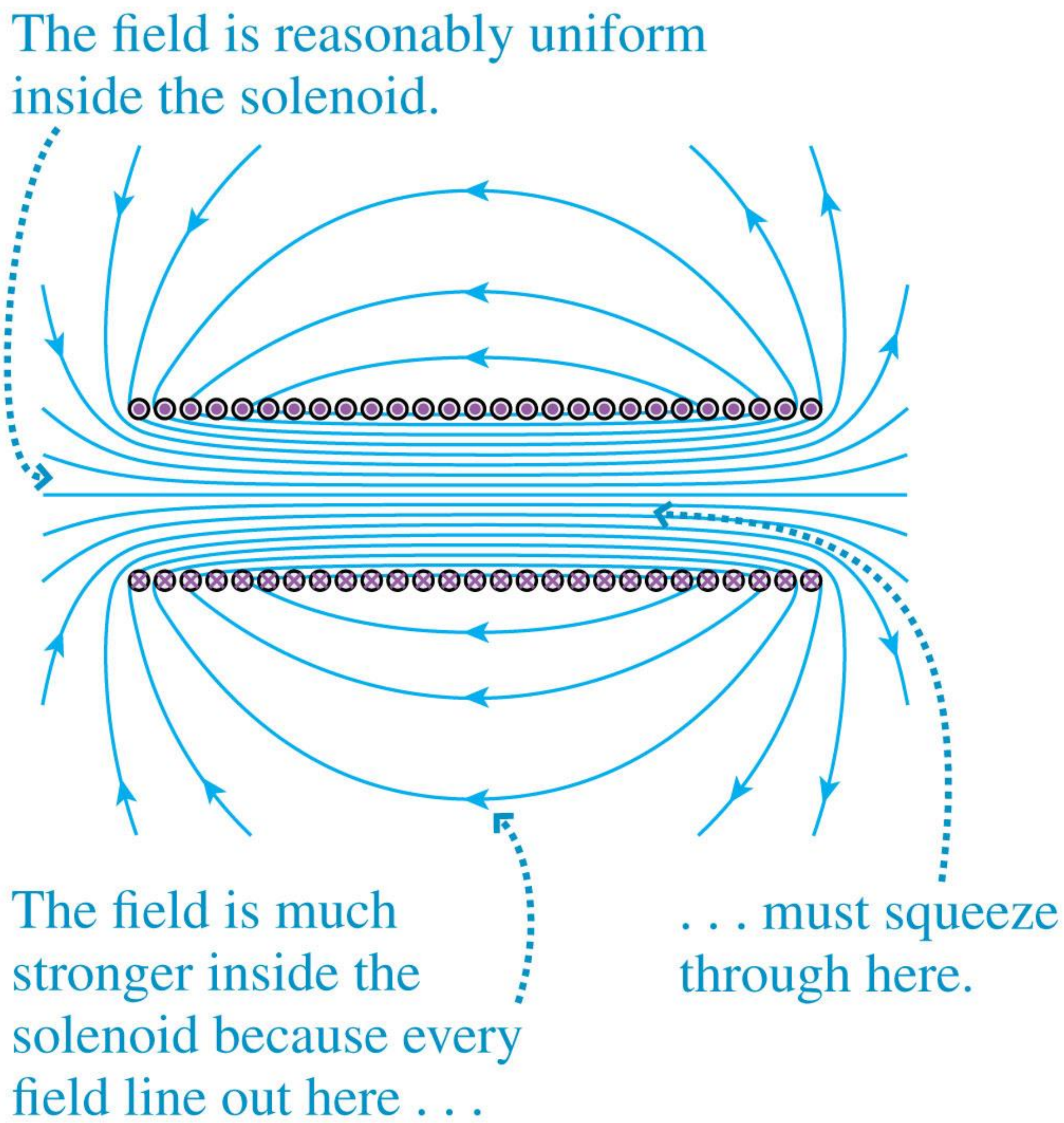
- There are many applications of magnetism for which we would like to generate a **uniform magnetic field,** a field that has the same magnitude and same direction at every point within some region of space.

The Magnetic Field of a Solenoid

- A solenoid is a long coil of wire with the same current I passing through each loop, or *turn*.
- **The field within the solenoid is strong, mainly parallel to the axis, and reasonably uniform, whereas the field outside the solenoid is very weak.**



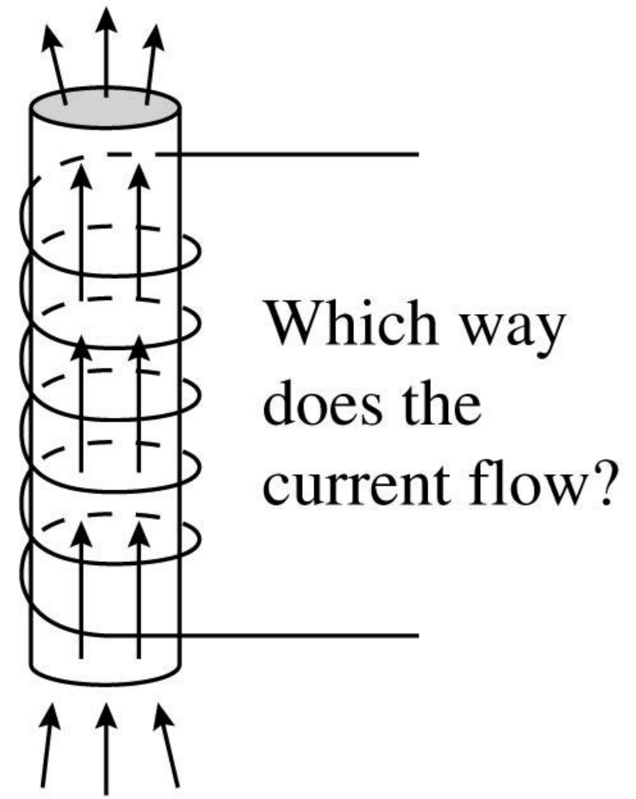
The Magnetic Field of a Solenoid



QuickCheck 24.12

What is the direction of the current in this solenoid, as viewed from the top?

A. Clockwise
B. Counterclockwise



QuickCheck 24.12

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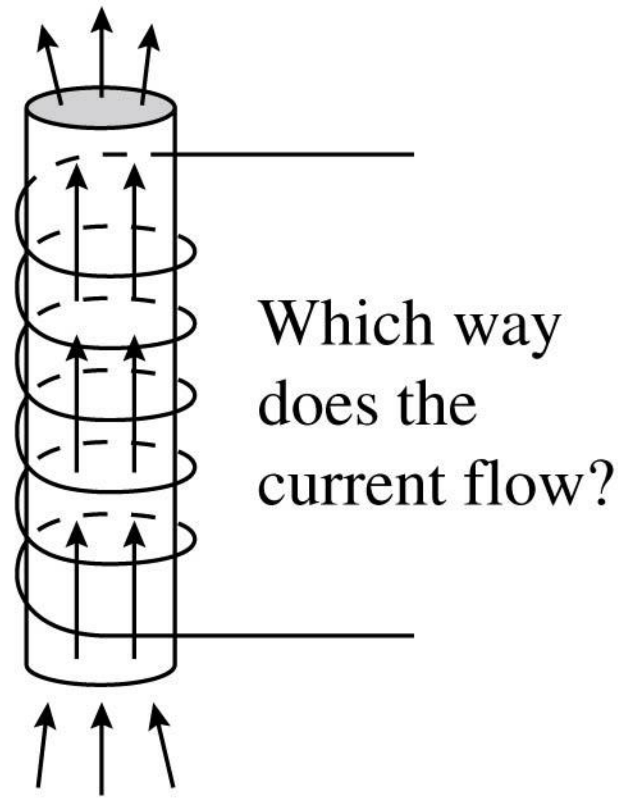
A. Clockwise

✔ B. Counterclockwise



Example Problem

An investigator needs a uniform 30 mT field, which she intends to produce with a solenoid. She takes a long 10-cm-diameter tube and wraps wire along the length of it, wrapping 1200 turns of wire along a 75 cm length of the tube. How much current must she pass through the wire to produce the desired field?

Section 24.4 Calculating the Magnetic Field Due to a Current

Calculating the Magnetic Field Due to a Current

- Magnetic field strengths are measured in **tesla**, T.
- The magnitude of the magnetic field around a long, straight current-carrying wire depends on the distance r from the wire and the *current I* through the wire:

$$B = \frac{\mu_0 I}{2\pi r}$$

Magnetic field due to a long, straight, current-carrying wire

- μ_0 is the **permeability constant**. It relates the strength of the magnetic field to the currents that produce it.

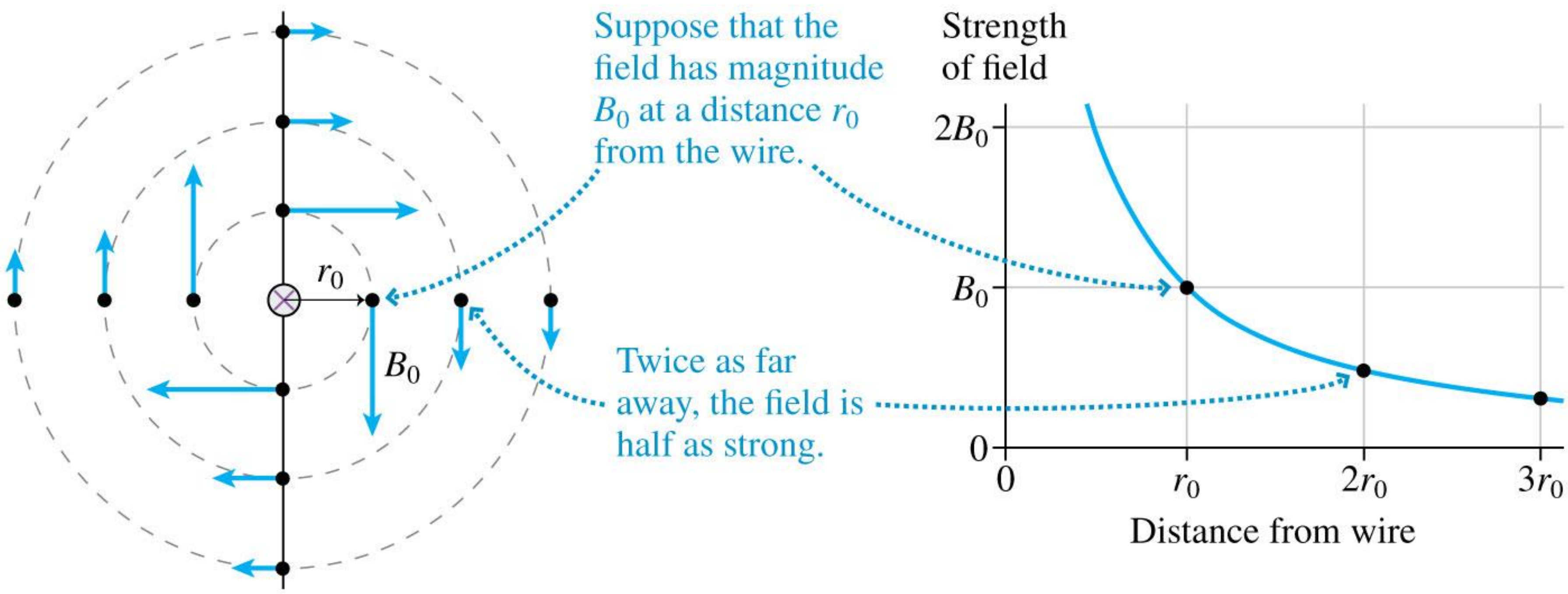
$$\mu_0 = 1.26 \times 10^{-6}\ \mathrm{T \cdot m/A}$$

Calculating the Magnetic Field Due to a Current

TABLE 24.1 Typical magnetic field strengths

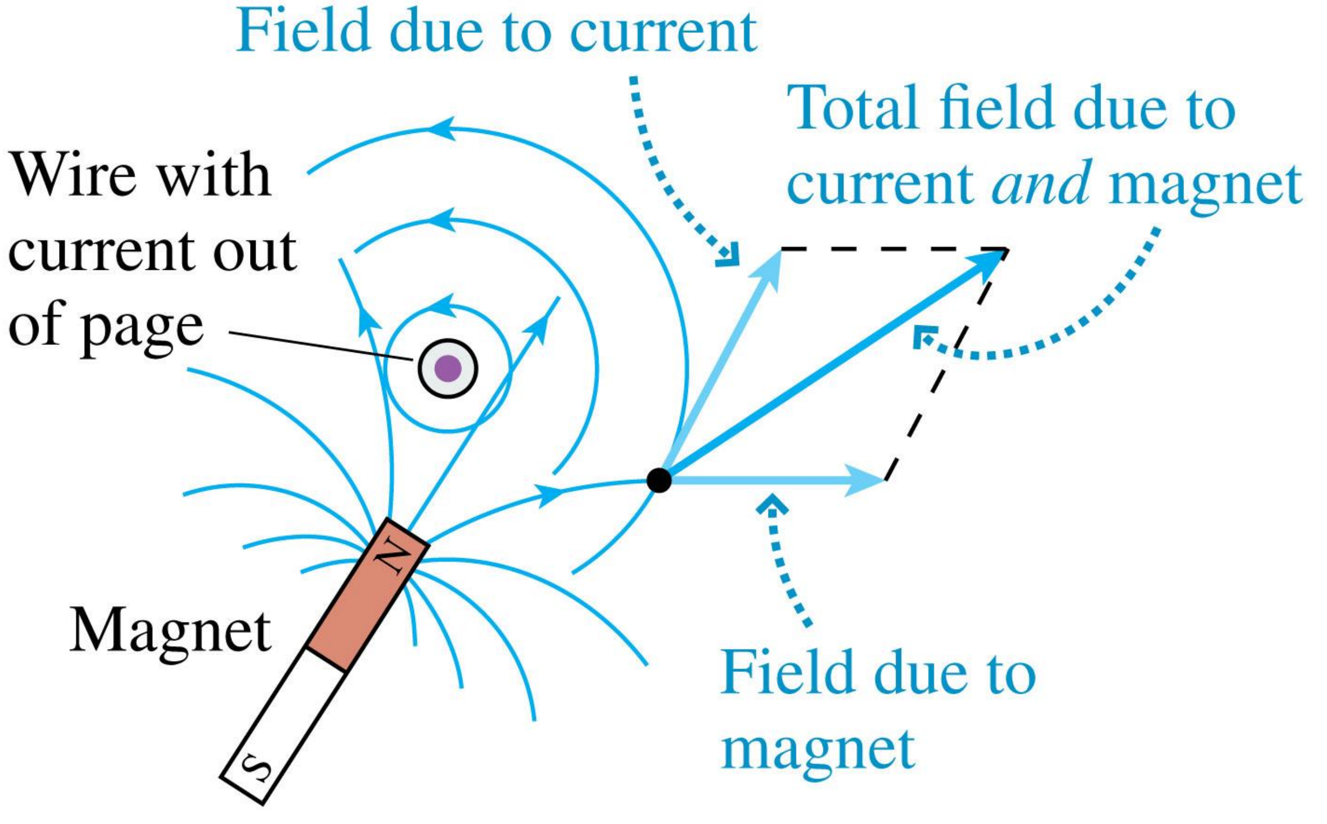
Field source and location	**Field strength (T)**
10 cm from a wire with 1 A current	2×10^{-6}
Surface of the earth	5×10^{-5}
1 cm from a wire with 10 A current	2×10^{-4}
Refrigerator magnet	5×10^{-3}
100-turn coil, 1 cm diameter, with 1 A current	1×10^{-2}
Surface of the sun, in a sunspot	1×10^{-1}
Near a rare-earth magnet	1
MRI solenoid	1

Calculating the Magnetic Field Due to a Current



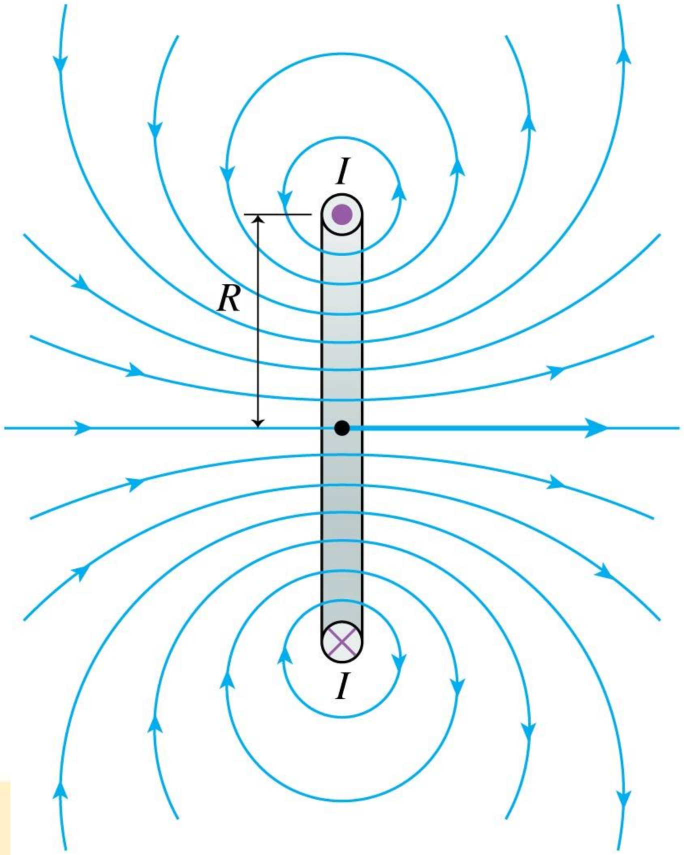
Magnetic Fields from More Than One Source

- The total magnetic field at any point is the *vector* sum of the individual fields at that point. This is the principle of superposition.



Current Loops

- The magnetic field due to a current loop is more complex than that of a straight wire.
- Because the loop can be thought of as a wire bent into a circle, the expression for the strength of the field at the *center* of the loop is similar to that of a wire.



$$B = \frac{\mu_0 I}{2R}$$

Magnetic field at the center of a current loop of radius R

Current Loops

- If N loops of wire carrying the same current I are all tightly wound into a single flat coil, then the magnitude of the field at the center is just N times bigger (since we're imposing N individual current loops):

$$B = \frac{\mu_0 NI}{2R}$$

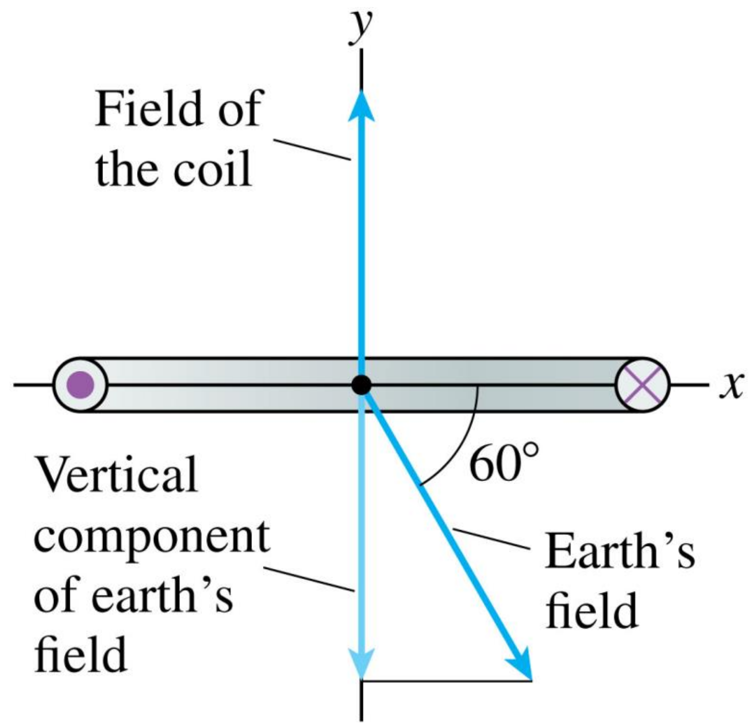
Magnetic field at the center of a thin coil with N turns

Example 24.4 Cancelling the earth's field

Green turtles are thought to navigate by using the dip angle of the earth's magnetic field. To test this hypothesis, green turtle hatchlings were placed in a 72-cm-diameter tank with a 60-turn coil of wire wrapped around the outside. A current in the coil created a magnetic field at the center of the tank that exactly canceled the vertical component of the earth's 50 μT field. At the location of the test, the earth's field was directed 60° below the horizontal. What was the current in the coil?

Example 24.4 Cancelling the earth's field (cont.)

PREPARE FIGURE 24.23 shows the earth's field passing downward through the coil. To cancel the vertical component of this field, the current in the coil must generate an upward field of equal magnitude. We can use the right-hand rule (see Figure 24.15) to find that the current must circulate around the coil as shown. Viewed from above, the current will be counterclockwise.



Example 24.4 Cancelling the earth's field (cont.)

SOLVE The vertical component of the earth's field is

$$(B_{\text{earth}})_y = -(50 \times 10^{-6}\ \text{T})\sin(60°) = -4.33 \times 10^{-5}\ \text{T}$$

The field of the coil, given by Equation 24.3, must have the same magnitude at the center.

Example 24.4 Cancelling the earth's field (cont.)

The 2R in the equation is just the diameter of the coil, 72 cm or 0.72 m. Thus

$$B_{\text{coil}} = \frac{\mu_0 NI}{2R} = 4.33 \times 10^{-5}\ \text{T}$$

$$I = \frac{(4.33 \times 10^{-5}\ \text{T})(2R)}{(\mu_0 N)}$$

$$= \frac{(4.33 \times 10^{-5}\ \text{T})(0.72\ \text{m})}{(1.26 \times 10^{-6}\ \text{T} \cdot \text{m/A})(60)} = 0.41\ \text{A}$$

As noted, this current is counterclockwise as viewed from above.

Example 24.4 Cancelling the earth's field (cont.)

ASSESS Equation 24.3 shows that the field in the center of a coil is proportional to the number of turns in the coil, proportional to the current, and inversely proportional to the radius of the coil. Table 24.1 gives 0.01 T for the field in the center of a 100-turn coil that is 1 cm in diameter and carries a current of 1.0 A.

Example 24.4 Cancelling the earth's field (cont.)

The coil in this problem is nearly 100 times larger, carries about half as much current, and has about half as many turns. We'd therefore predict a field that is less than the Table 24.1 value by a factor of a few hundred, which it is. A rough estimate of the answer agrees with our result, so it seems reasonable.

Solenoids

- The field inside a solenoid is fairly uniform.
- The field outside is quite small.
- The greater the solenoid’s length in comparison to its diameter, the better these statements hold.
- Solenoids can be built quite large; the cylinder that surrounds a patient undergoing magnetic resonance imaging (MRI) contains a large solenoid.

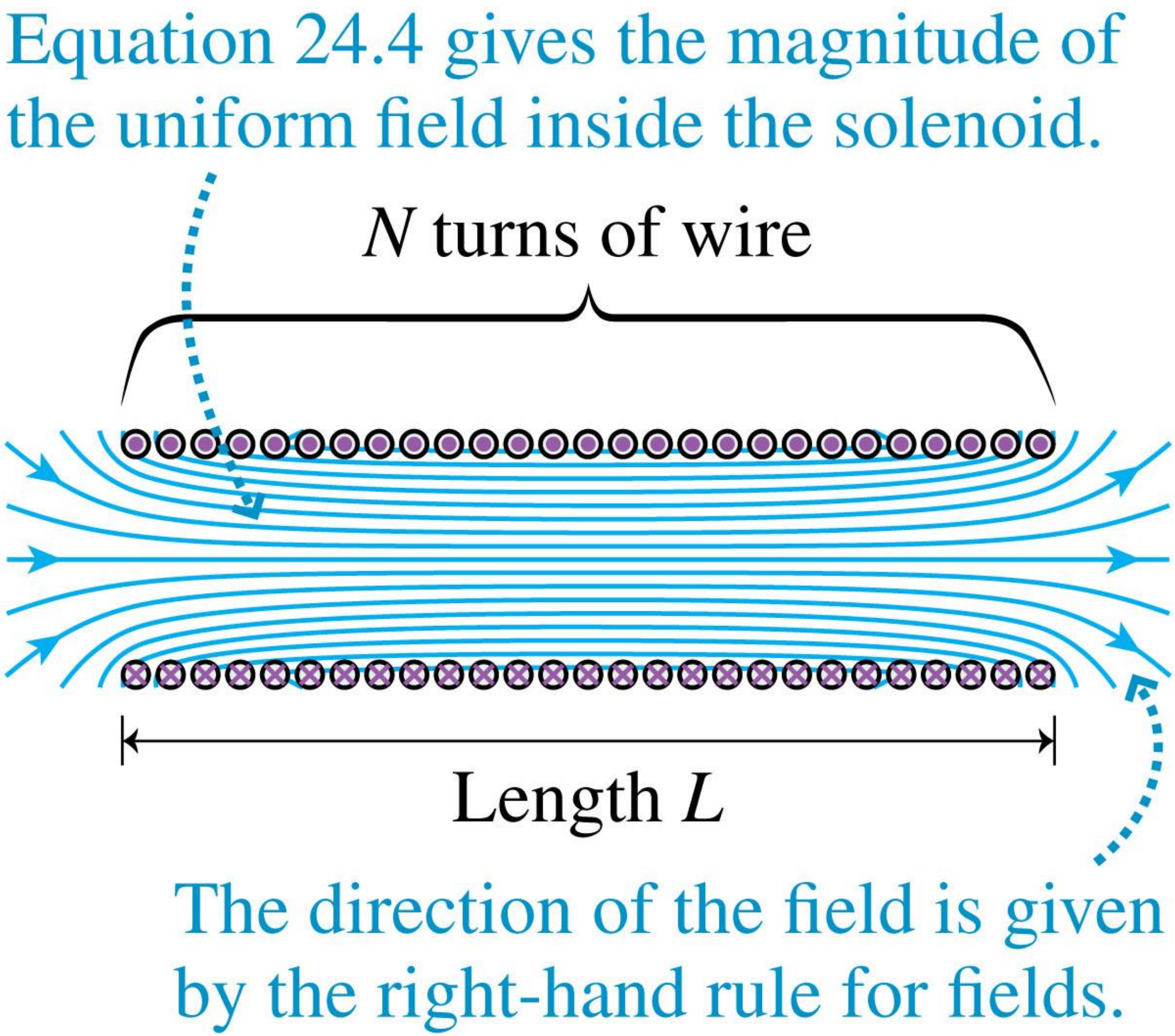
Solenoids

- The greater the ratio of N turns of wire to the length L of the solenoid (N/L), the stronger the field inside will be.
- The strength of the field will also be proportional to the current.
- The field does not depend on the radius of the solenoid.

$$B = \frac{\mu_0 NI}{L}$$

Magnetic field inside a solenoid of length L with N turns

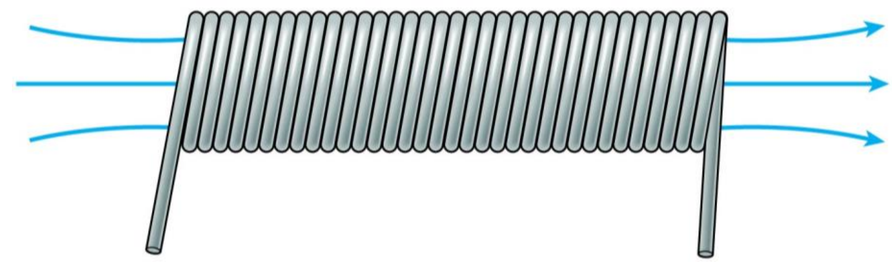
Solenoids


Equation 24.4 gives the magnitude of the uniform field inside the solenoid.
N turns of wire
Length L
The direction of the field is given by the right-hand rule for fields.

QuickCheck 24.13

The current in this solenoid

A. Enters on the left, leaves on the right.
B. Enters on the right, leaves on the left.
C. Either A or B would produce this field.



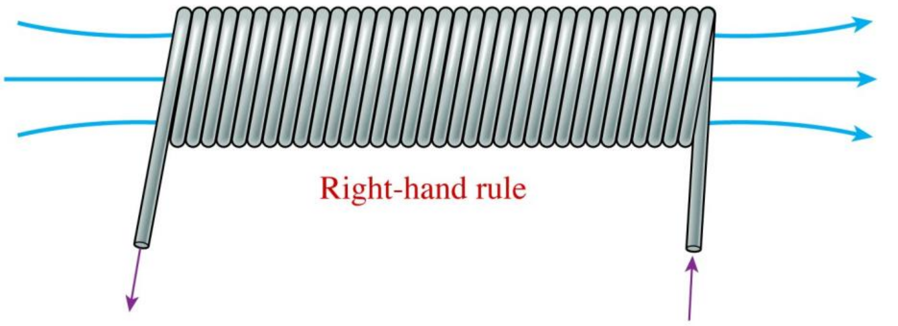
QuickCheck 24.13

The current in this solenoid

A. Enters on the left, leaves on the right.

✔ B. Enters on the right, leaves on the left.

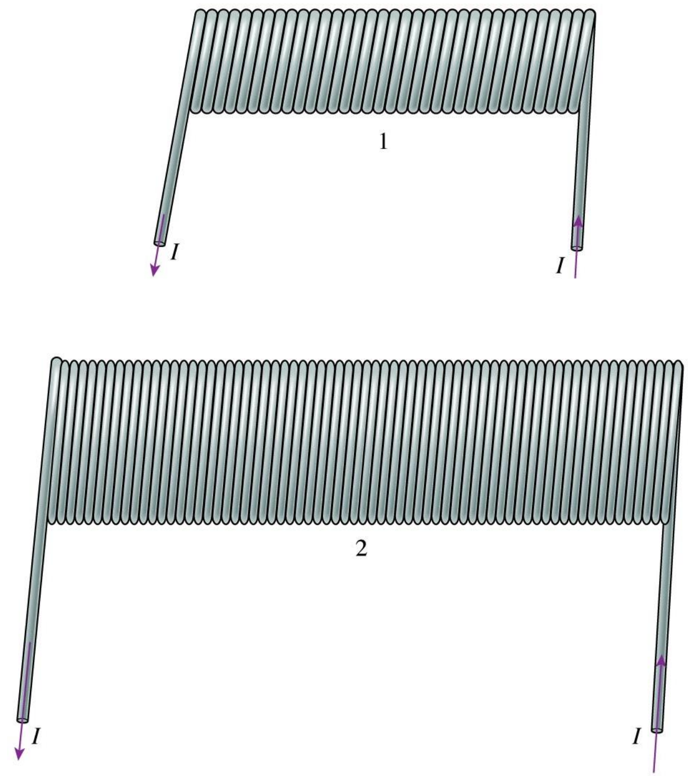
C. Either A or B would produce this field.



QuickCheck 24.14

Solenoid 2 has twice the diameter, twice the length, and twice as many turns as solenoid 1. How does the field B_2 at the center of solenoid 2 compare to B_1 at the center of solenoid 1?

A. $B_2 = B_1/4$
B. $B_2 = B_1/2$
C. $B_2 = B_1$
D. $B_2 = 2B_1$
E. $B_2 = 4B_1$



QuickCheck 24.14

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A. $B_2 = B_1/4$

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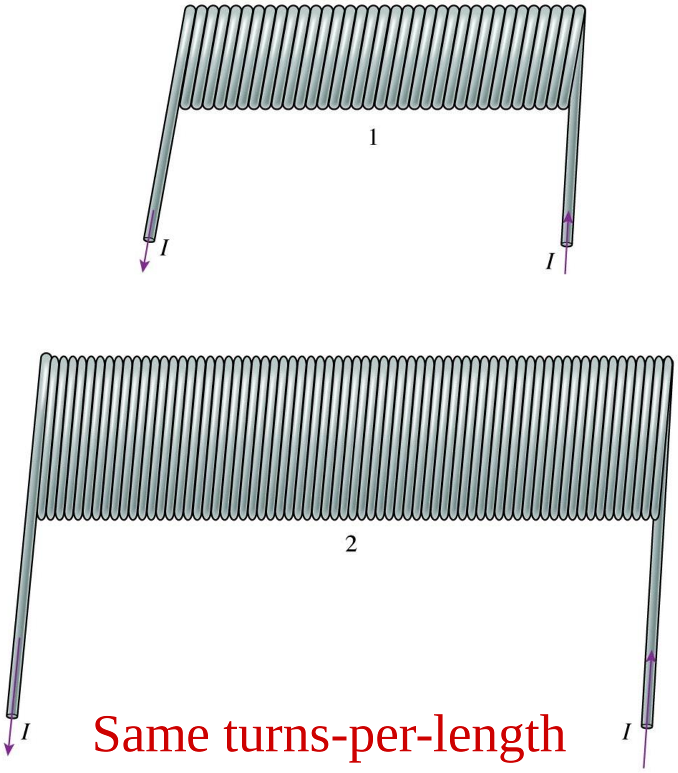
✔ C. $B_2 = B_1$

D. $B_2 = 2B_1$

E. $B_2 = 4B_1$



Same turns-per-length

Example 24.5 Generating an MRI magnetic field

A typical MRI solenoid has a length of about 1 m and a diameter of about 1 m. A typical field inside such a solenoid is about 1 T. How many turns of wire must the solenoid have to produce this field if the largest current the wire can carry is 100 A?

Example 24.5 Generating an MRI magnetic field (cont.)

PREPARE This solenoid is not very long compared to its diameter, so using Equation 24.4 will give only an approximate result. This is acceptable, since we have only rough estimates of the field B and the length L.

Example 24.5 Generating an MRI magnetic field (cont.)

Equation 24.4 gives the magnetic field B of a solenoid in terms of the current I, the number of turns N, and the length L. Here, however, we want to find the number of turns in terms of the other variables. We'll need $B = 1$ T, $I = 100$ A, and $L = 1$ m.

Example 24.5 Generating an MRI magnetic field (cont.)

SOLVE We can solve Equation 24.4 for N to get

$$N = \frac{LB}{\mu_0 I} = \frac{(1\ \text{m})(1\ \text{T})}{(1.26 \times 10^{-6}\ \text{T}\cdot\text{m/A})(100\ \text{A})} = 8000\ \text{turns}$$

to one significant figure.

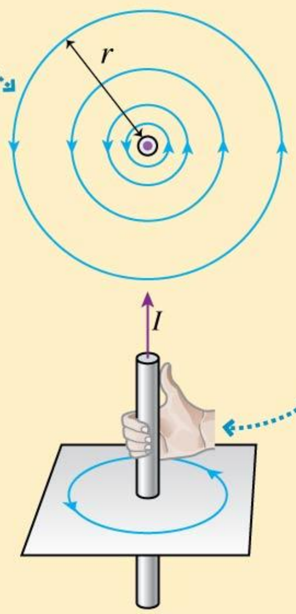
ASSESS The number of turns required is quite large, but the field is quite large, so this makes sense.

Fields from currents

SYNTHESIS 24.1 Fields from currents

An electric current produces a magnetic field. The geometry of the field depends on the geometry of the conductor.

Current in a **long, straight wire** creates a magnetic field that encircles the wire.



Current (A)

$$B = \frac{\mu_0 I}{2\pi r}$$

Distance from wire (m)

Direction given by the right-hand rule for fields

Permittivity constant

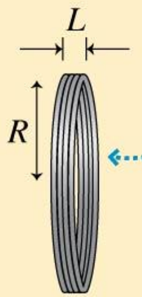
$$\mu_0 = 1.26 \times 10^{-6}\ \mathrm{T \cdot m/A}$$

Text: p. 777

Fields from currents

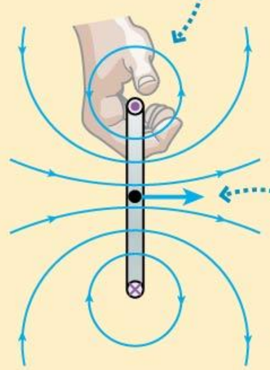
SYNTHESIS 24.1 Fields from currents

An electric current produces a magnetic field. The geometry of the field depends on the geometry of the conductor.



A **coil** is a stack of loops with the length small compared to the radius. We treat this as a loop with multiple turns of wire.

For current in a coil or a loop, field lines emerge from the center of the loop and wrap around it in a direction given by the right-hand rule for fields.



Number of turns. For a loop, $N = 1$.

Current (A)

Field (T) at the center

$$B = \frac{\mu_0 N I}{2R}$$

Radius of the loop or coil (m)

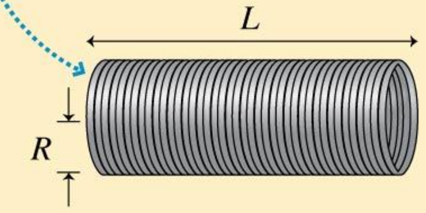
Text: p. 777

Fields from currents

SYNTHESIS 24.1 Fields from currents

An electric current produces a magnetic field. The geometry of the field depends on the geometry of the conductor.

A **solenoid** is a stack of loops with the length much greater than the radius.



The field (T) inside a solenoid is uniform.

Number of turns

Current (A)

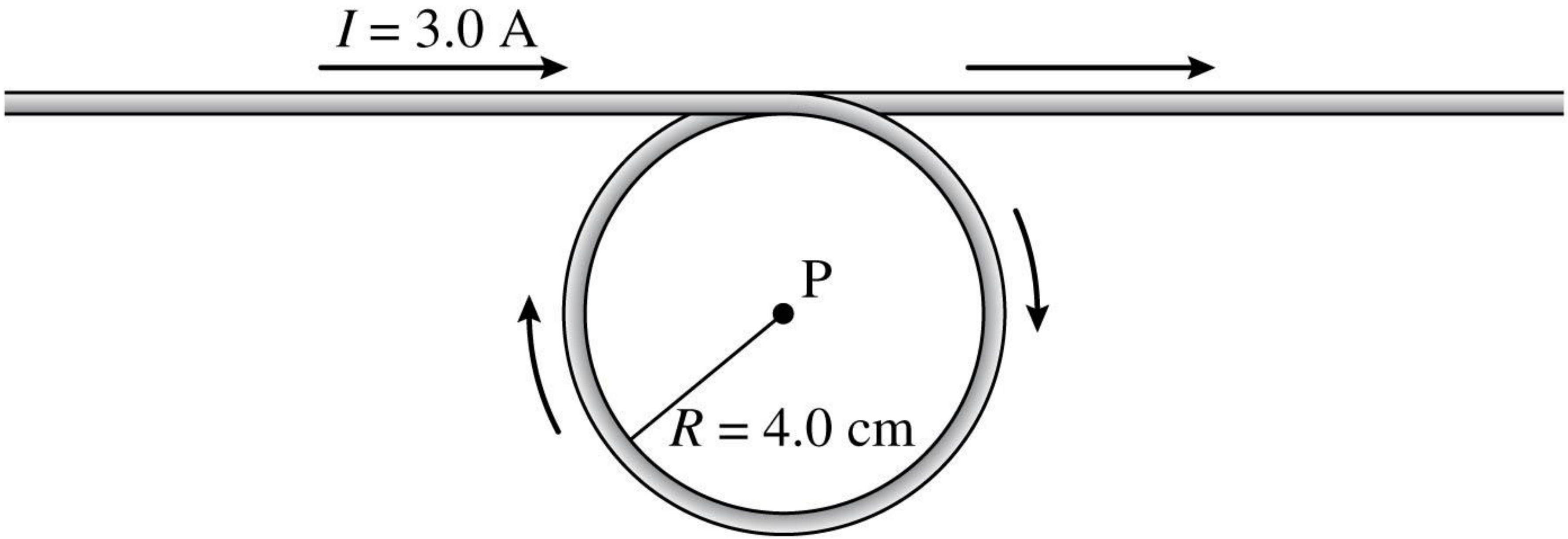
$$B = \frac{\mu_0 N I}{L}$$

Length of the solenoid (m)

Text: p. 777

Example Problem

What is the direction and magnitude of the magnetic field at point P, at the center of the loop?

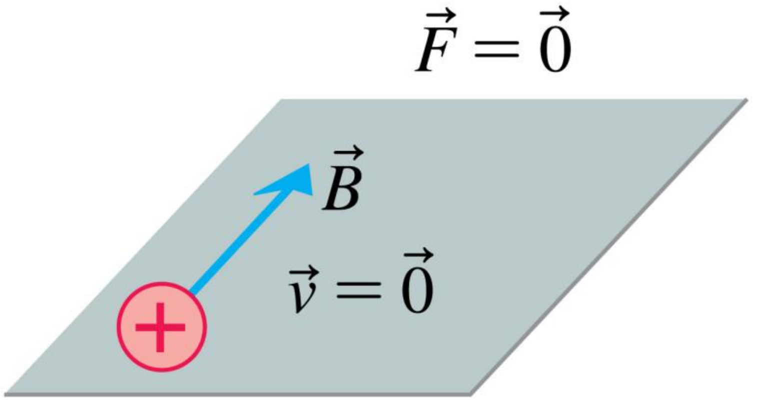


Section 24.5 Magnetic Fields Exert Forces on Moving Charges

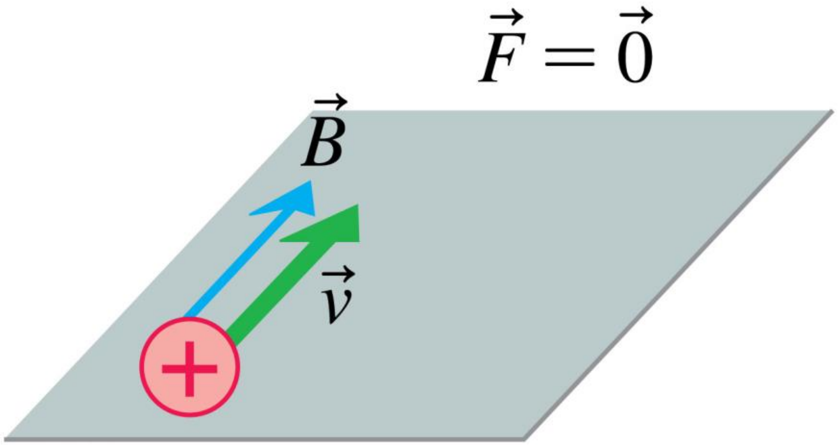
Magnetic Fields Exert Forces on Moving Charges

- Magnetic fields also exert forces on moving charged particles and on electric currents in wires.

Magnetic Fields Exert Forces on Moving Charges

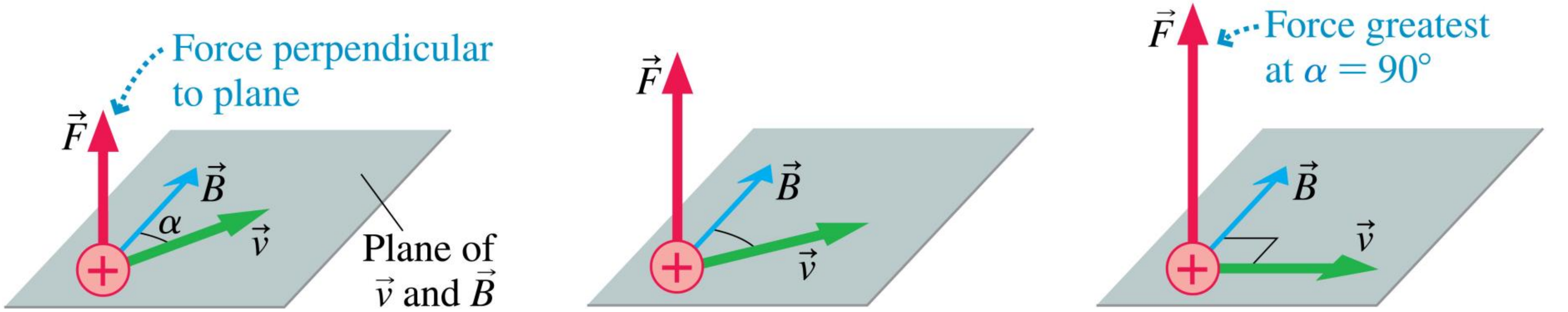


There is no magnetic force on a charged particle at rest.



There is no magnetic force on a charged particle moving parallel to a magnetic field.

Magnetic Fields Exert Forces on Moving Charges



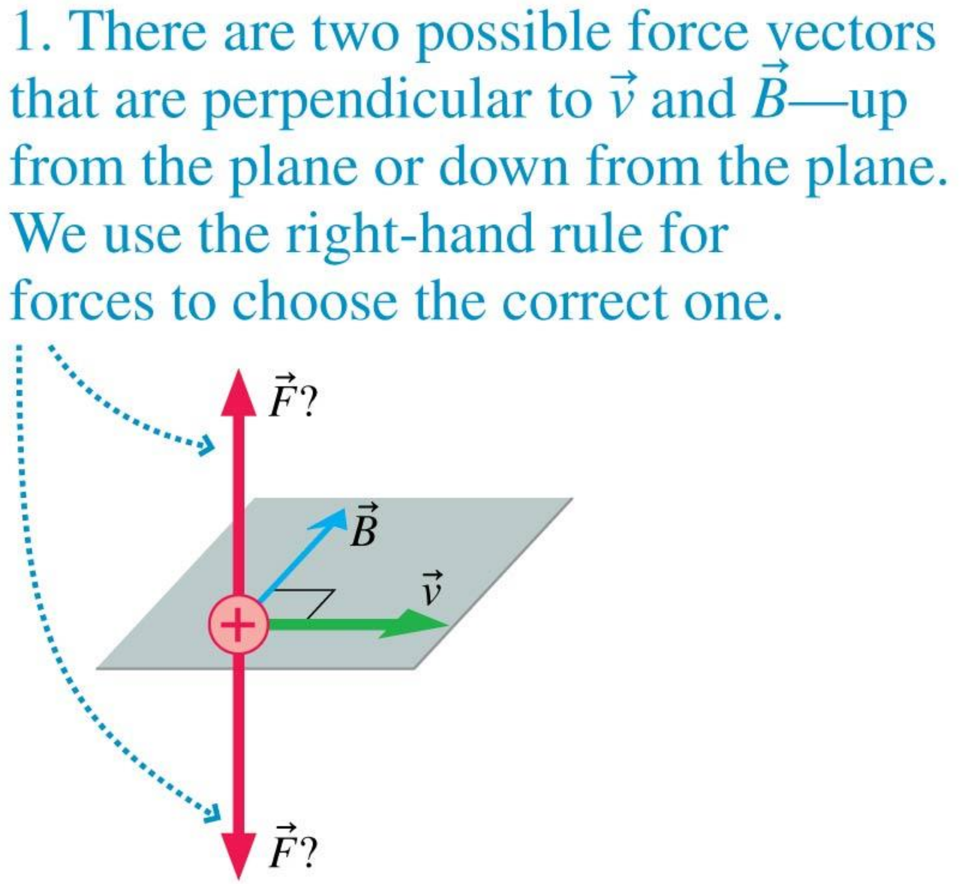
As the angle α between the velocity and the magnetic field increases, the magnetic force also increases. The force is greatest when the angle is 90°. The magnetic force is always perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.

Magnetic Fields Exert Forces on Moving Charges

- The magnetic force is different from the electric force.
- There is no magnetic force if the charged particle is at rest or if it is moving parallel to the magnetic field.
- The force is always *perpendicular* to the plane containing $\vec{v}$ and $\vec{B}$.

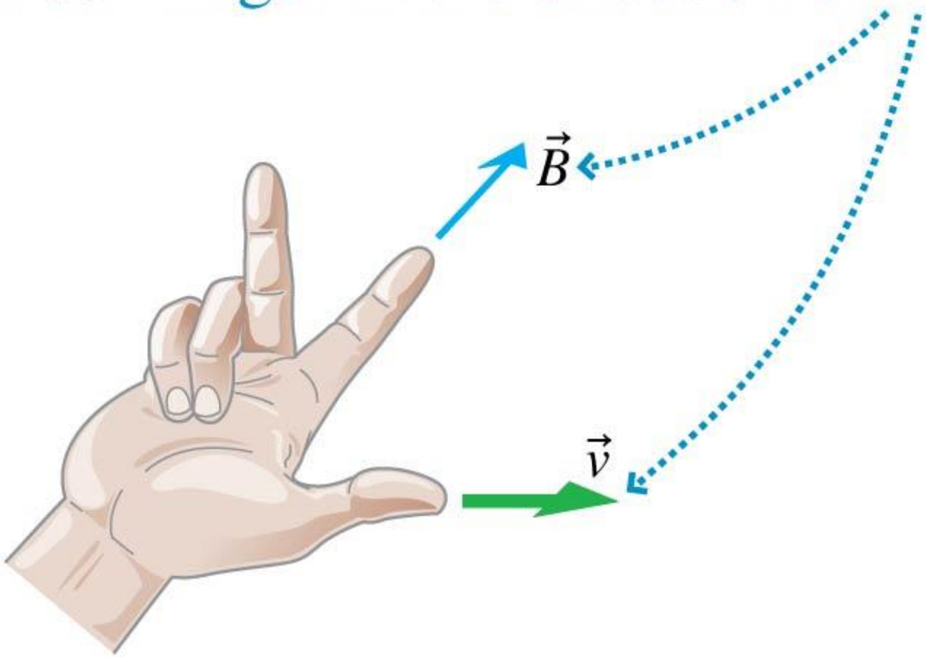
Magnetic Fields Exert Forces on Moving Charges

- We determine the correct direction of the force using the **right-hand rule for forces.**

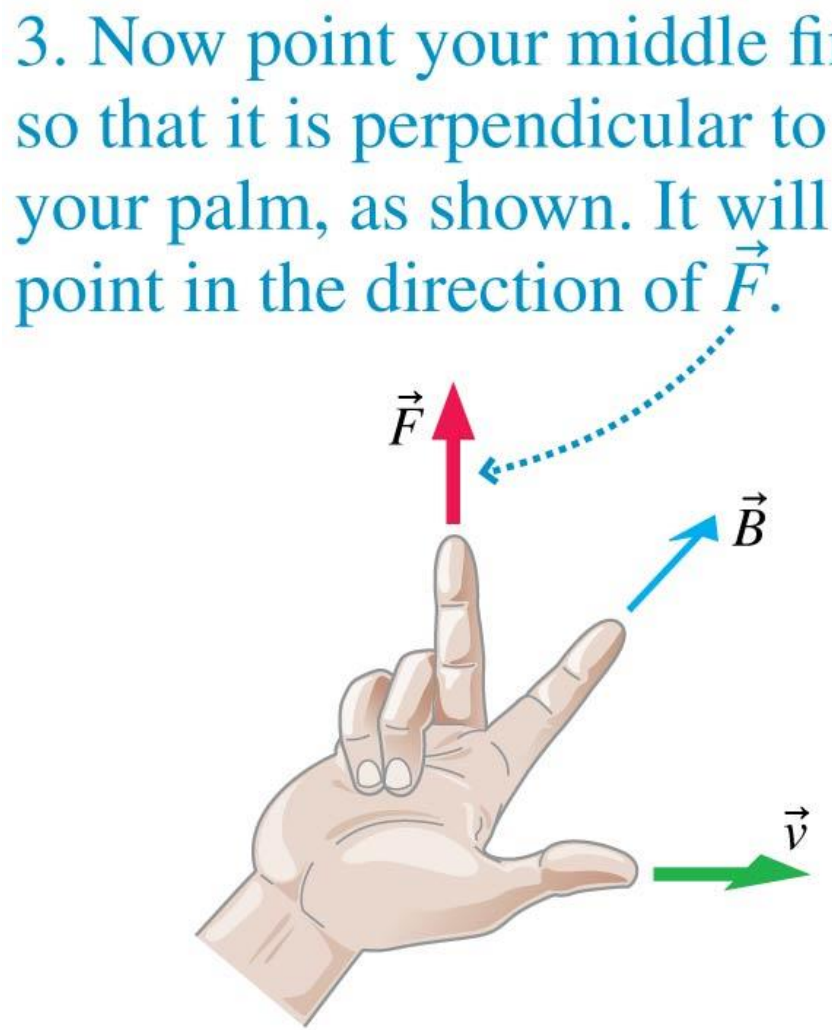


Magnetic Fields Exert Forces on Moving Charges

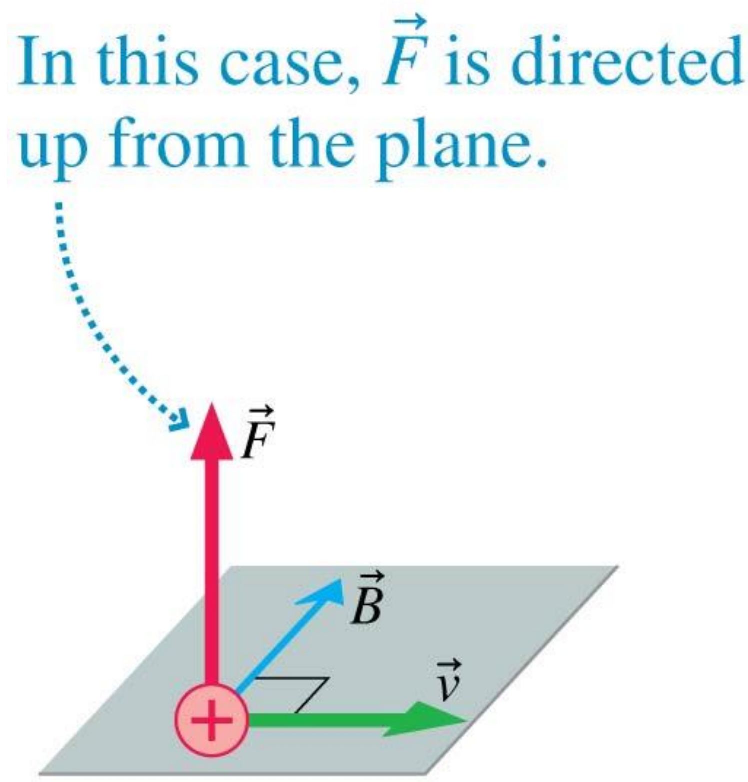
2. Spread the fingers of your right hand so that your index finger and thumb point out from your hand as shown. Rotate your hand to point your thumb in the direction of $\vec{v}$ and your index finger in the direction of $\vec{B}$.



Magnetic Fields Exert Forces on Moving Charges

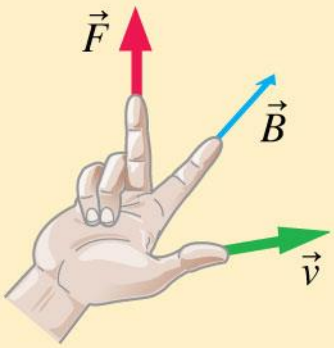


Magnetic Fields Exert Forces on Moving Charges



Magnetic Fields Exert Forces on Moving Charges

The *direction* of the force



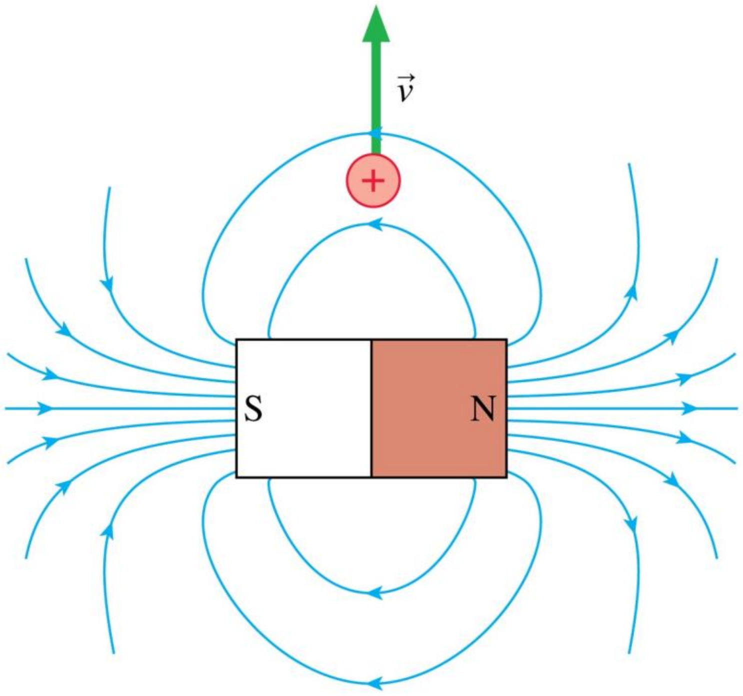
The *magnitude* of the force

$$F = |q| vB \sin\alpha$$

QuickCheck 24.15

The direction of the magnetic force on the proton is

A. To the right.
B. To the left.
C. Into the screen.
D. Out of the screen.
E. The magnetic force is zero.



QuickCheck 24.15

The direction of the magnetic force on the proton is

A. To the right.
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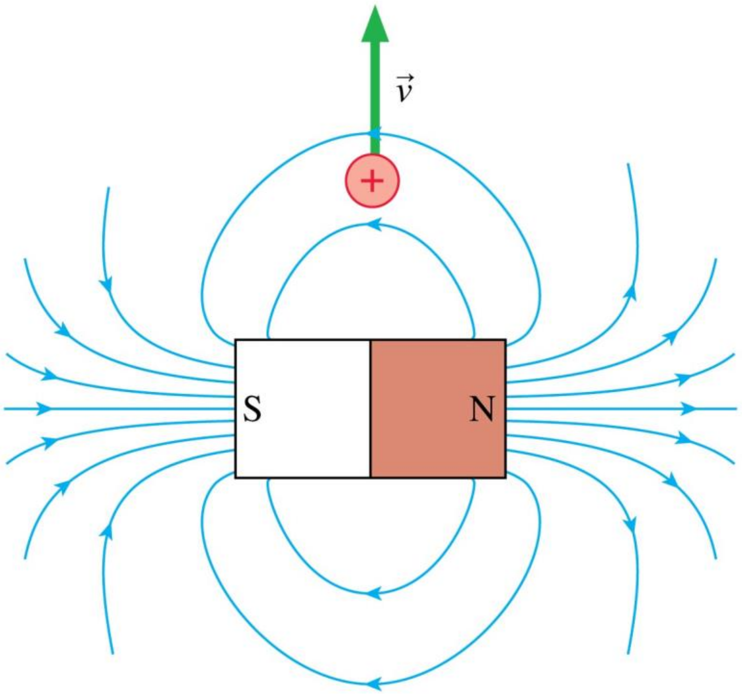
✔ D. Out of the screen.
E. The magnetic force is zero.



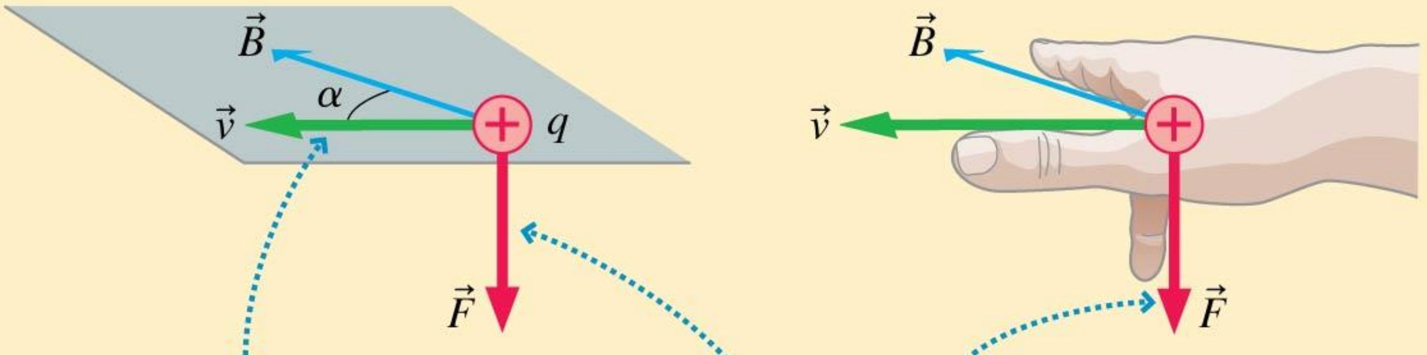
Magnetic Fields Exert Forces on Moving Charges

- The velocity and the magnetic field are perpendicular in many practical situations. In this case, α is 90°, and the magnitude of the magnetic field simplifies to

$$F = |q|vB$$

Magnetic Fields Exert Forces on Moving Charges

TACTICS BOX 24.2 **Determining the magnetic force on a moving charged particle**

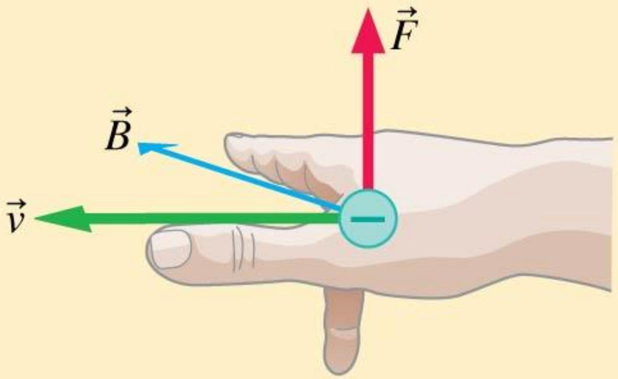


1. Note the direction of $\vec{v}$ and $\vec{B}$, and find the angle α between them.
2. The force is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$. The direction of $\vec{F}$ is given by the right-hand rule.

Text: p. 778

Magnetic Fields Exert Forces on Moving Charges

TACTICS BOX 24.2 Determining the magnetic force on a moving charged particle



$$F = |q| vB \sin \alpha$$

$$F = |q| vB$$

❸ For a negative charge, the force is in the direction opposite that predicted by the right-hand rule.

❹ The magnitude of the force is given by Equation 24.5 or Equation 24.6.

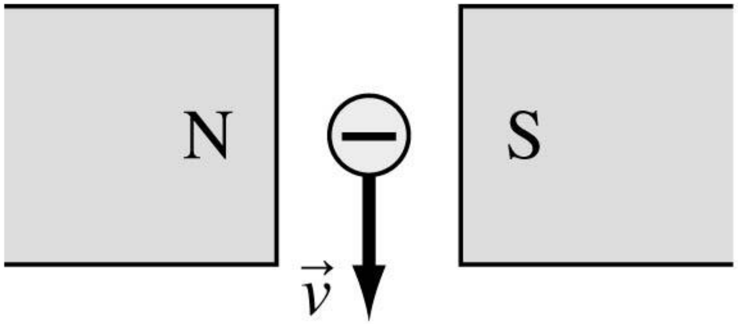
Exercises 18, 19

Text: p. 778

QuickCheck 24.16

The diagram shows a top view of an electron beam passing between the poles of a magnet. The beam will be deflected

A. Toward the north pole of the magnet.
B. Toward the south pole of the magnet.
C. Out of the plane of the figure
D. Into the plane of the figure.



QuickCheck 24.16

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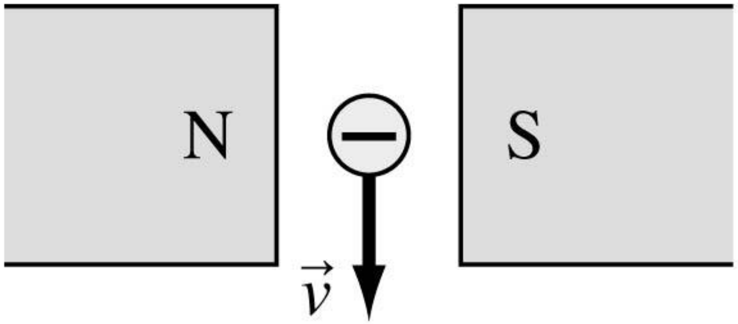
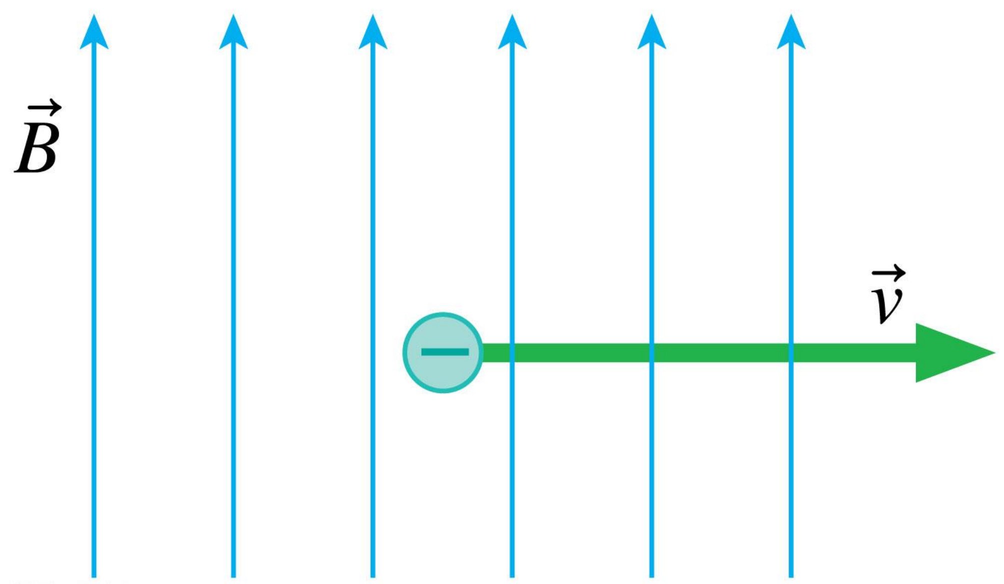
A. Toward the north pole of the magnet.
B. Toward the south pole of the magnet.
C. Out of the plane of the figure
✔ D. Into the plane of the figure.



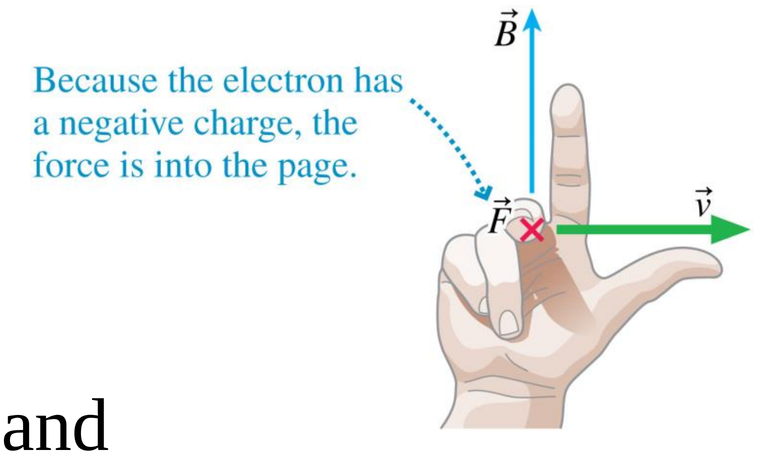
Conceptual Example 24.6 Determining the force on a moving electron

An electron is moving to the right in a magnetic field that points upward, as in **FIGURE 24.26**. What is the direction of the magnetic force?



Conceptual Example 24.6 Determining the force on a moving electron (cont.)

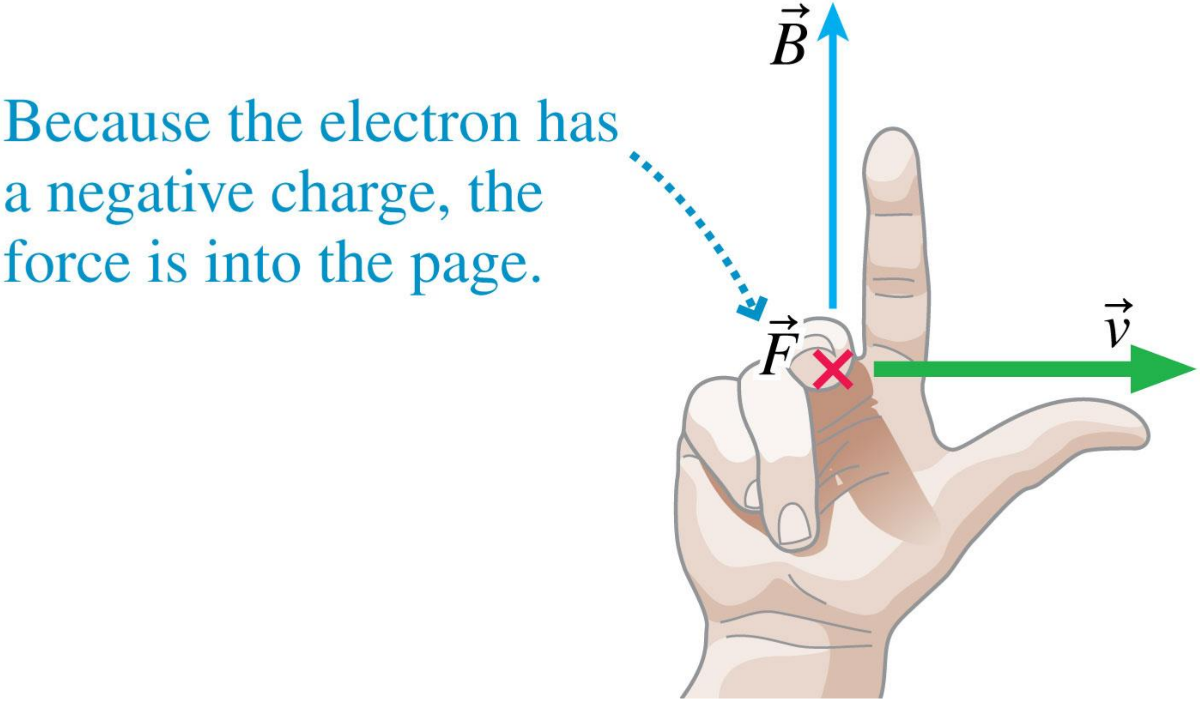
REASON **FIGURE 24.27** shows how the right-hand rule for forces is applied to this situation:



- Point your right thumb in the direction of the electron's velocity and your index finger in the direction of the magnetic field.
- Bend your middle finger to be perpendicular to your index finger. Your middle finger, which now points out of the page, is the direction of the force on a positive charge. But the electron is negative, so the force on the electron is *into* the page.

Conceptual Example 24.6 Determining the force on a moving electron (cont.)

ASSESS The force is perpendicular to both the velocity and the magnetic field, as it must be. The force on an electron is into the page; the force on a proton would be out of the page.

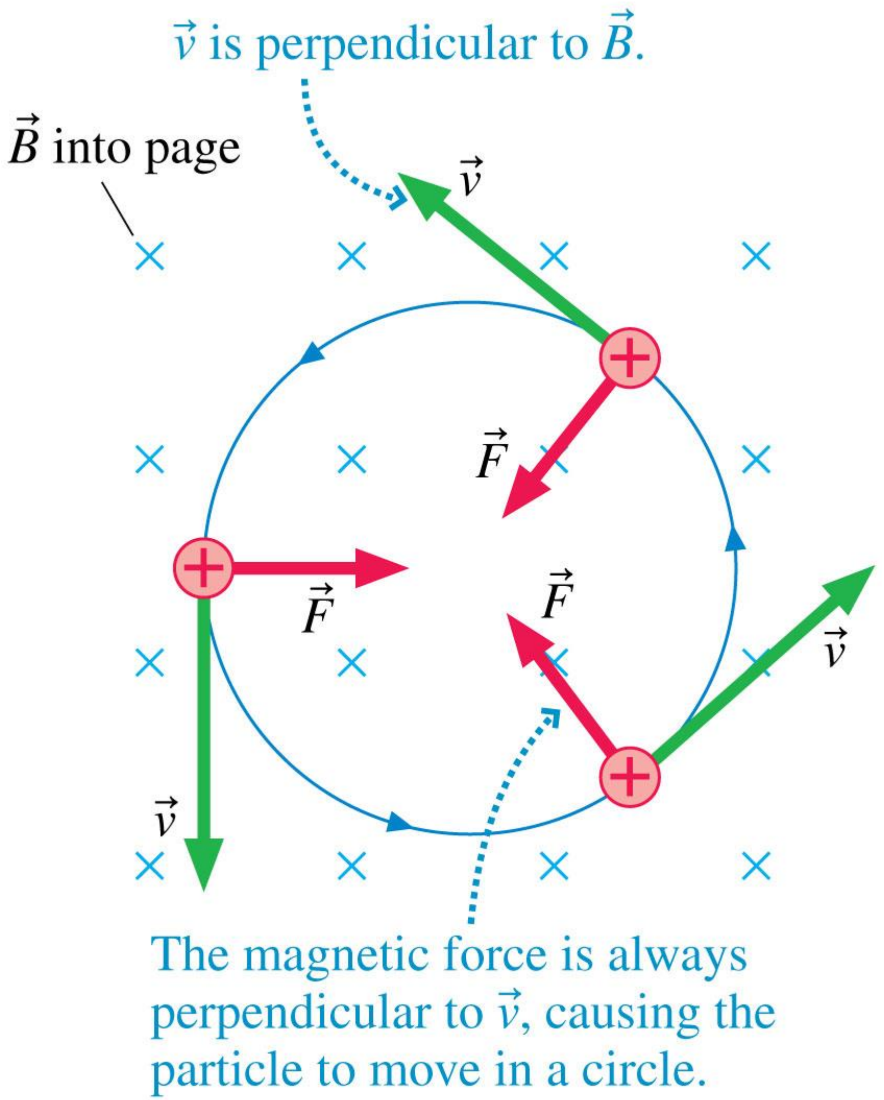


Paths of Charged Particles in Magnetic Fields

- When we studied the motion of objects subject to a force that was always perpendicular to the velocity, the result was *circular motion at a constant speed*. For example, a ball moved at the end of a string moved in a circle due to the perpendicular force of tension in the string.
- For a charged particle moving in a magnetic field, the magnetic force is always perpendicular to $\vec{v}$ and so it causes the particle to move in a circle.

Paths of Charged Particles in Magnetic Fields

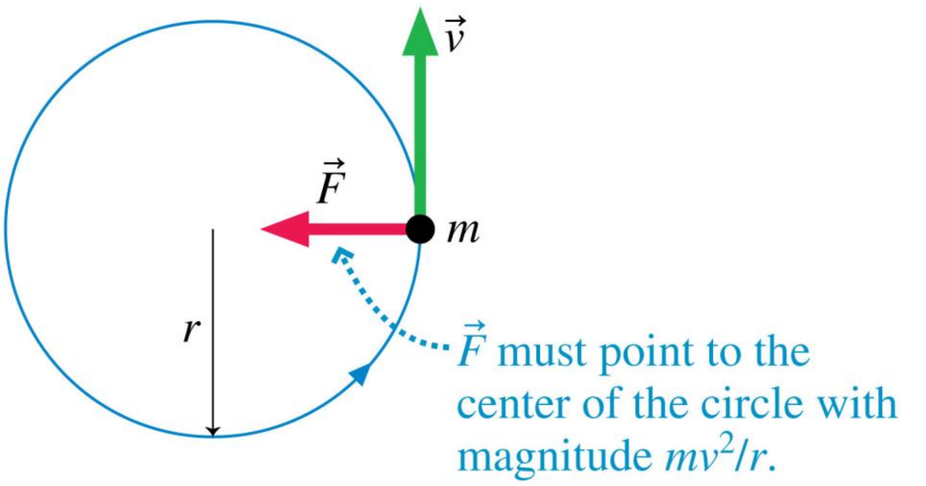
- **A particle moving perpendicular to a uniform magnetic field undergoes uniform circular motion at constant speed.**



Paths of Charged Particles in Magnetic Fields

- In Chapter 6 we found that circular motion requires a force directed toward the center of the circle with magnitude:

$$F = \frac{mv^2}{r}$$



- For a charged particle moving in a magnetic field, the force is provided by the magnetic force:

$$F = |q|vB = \frac{mv^2}{r}$$

Paths of Charged Particles in Magnetic Fields

- We find that the radius of the circular orbit for a charged particle moving in a magnetic field is given by

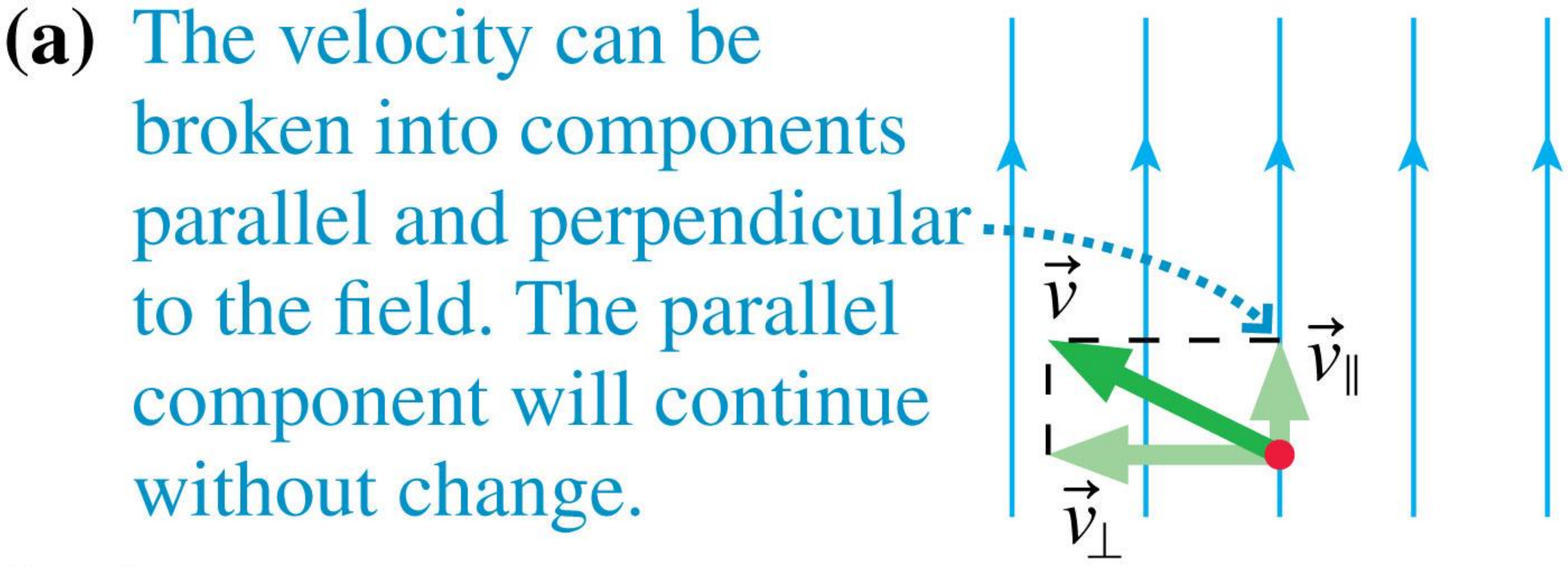
Particle mass (kg) → m; Particle velocity (m/s) → v

$$r = \frac{mv}{|q|B}$$

Particle charge (C) → q; Magnetic field strength (T) → B

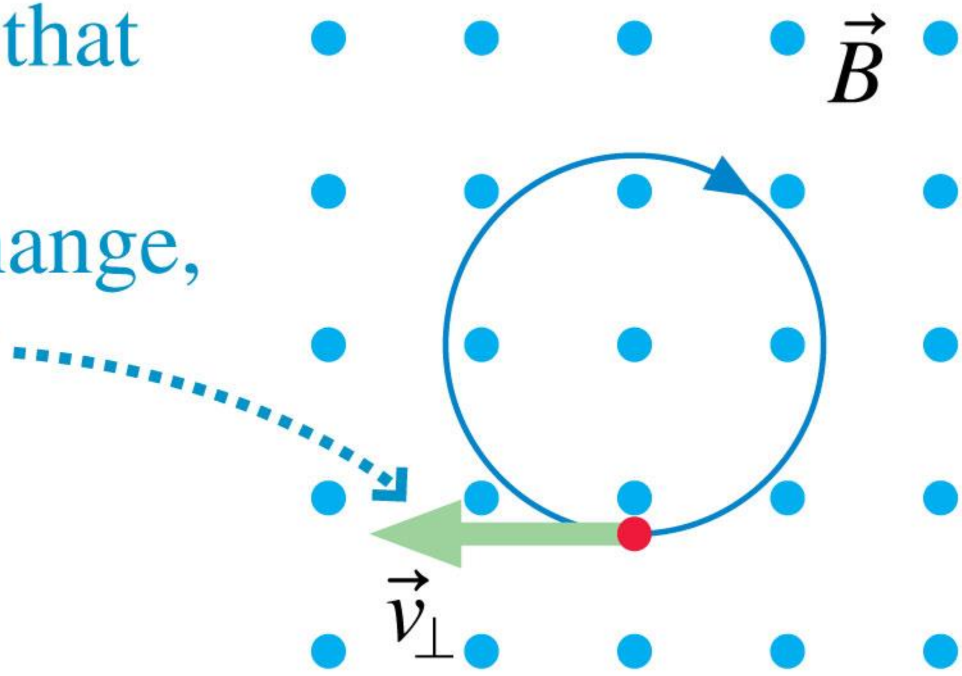
Paths of Charged Particles in Magnetic Fields

- The motion of a charged particle when its velocity is neither parallel nor perpendicular to the magnetic field:



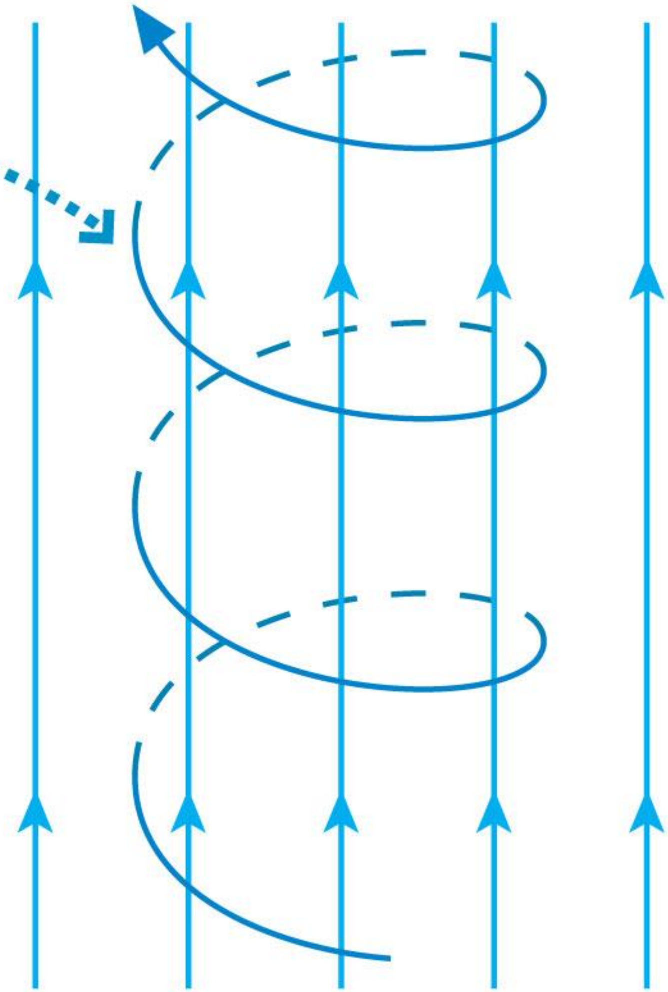
Paths of Charged Particles in Magnetic Fields

(b) A top view shows that the perpendicular component will change, leading to circular motion.



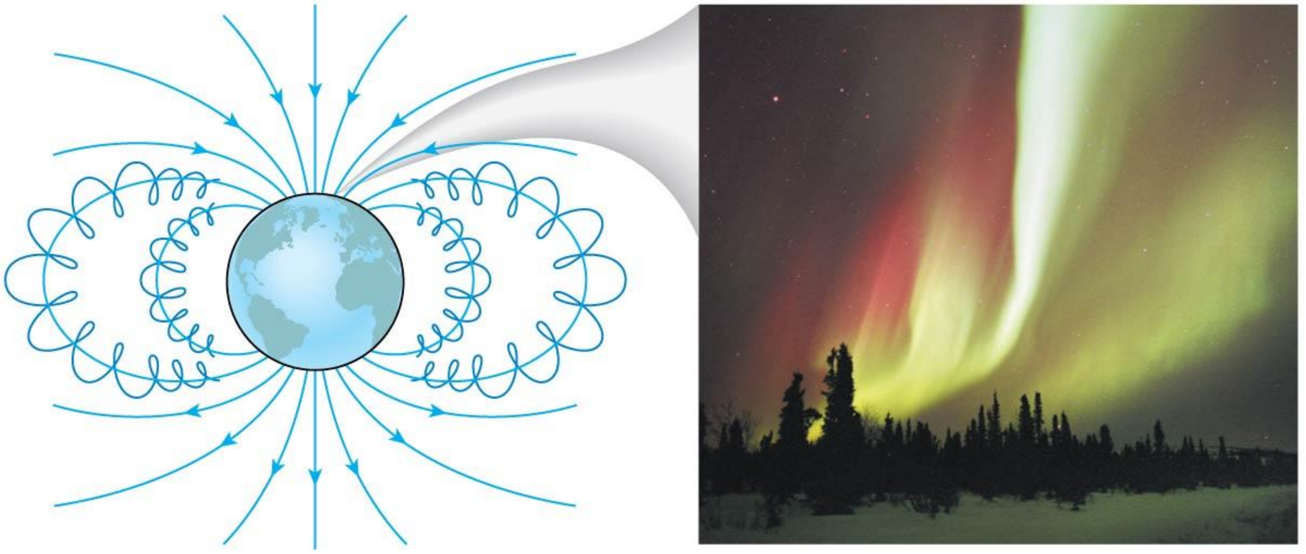
Paths of Charged Particles in Magnetic Fields

(c) The net result is a helical path that spirals around the field lines.



Paths of Charged Particles in Magnetic Fields

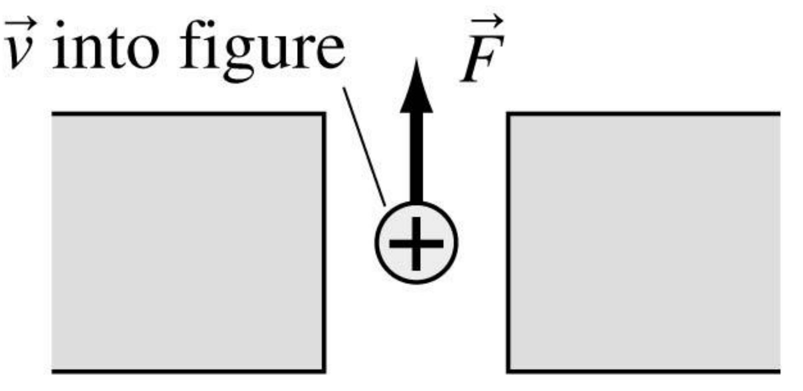
- High-energy particles stream out from the sun in the solar wind, some of which becomes trapped in the earth's magnetic field.
- The particles spiral in helical trajectories along the earth's magnetic field lines. When they enter the atmosphere at the poles, they ionize gas, creating the **aurora.**



QuickCheck 24.17

A beam of positively charged particles passes between the poles of a magnet as shown in the figure; the force on the particles is noted in the figure. The magnet's north pole is on the ______, the south pole on the ______.

A. Left, right
B. Right, left
C. There's not enough information to tell.



QuickCheck 24.17

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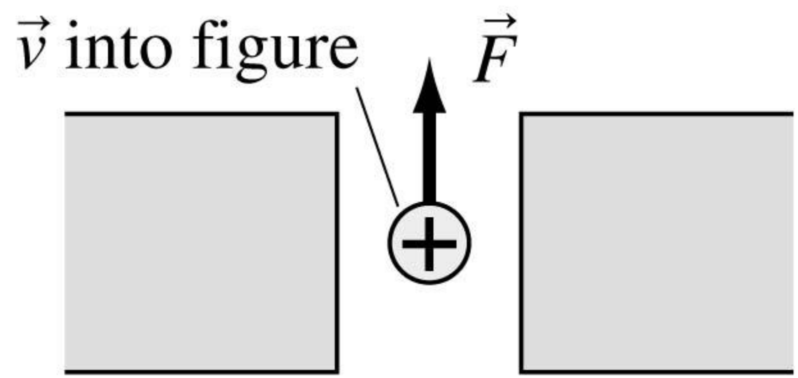
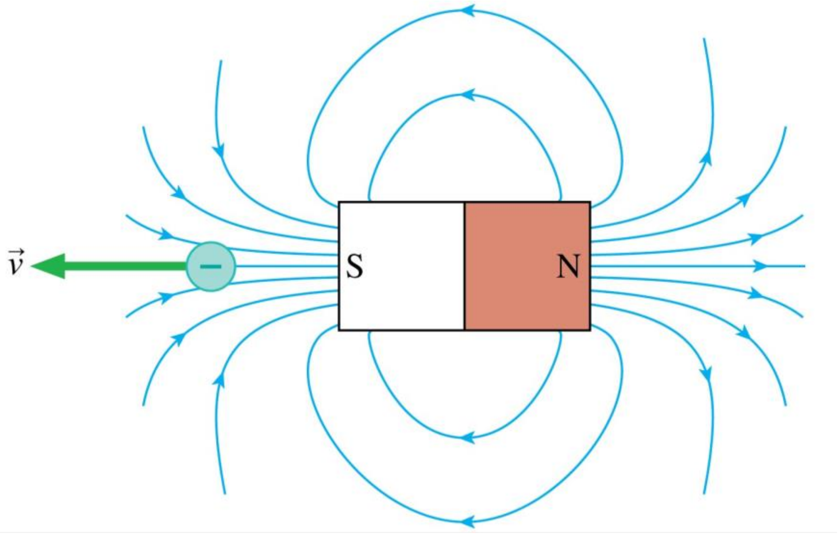
A. Left, right
✔ B. Right, left
C. There's not enough information to tell.



QuickCheck 24.18

The direction of the magnetic force on the electron is

A. Upward.
B. Downward.
C. Into the screen.
D. Out of the screen.
E. The magnetic force is zero.



QuickCheck 24.18

The direction of the magnetic force on the electron is

A. Upward.
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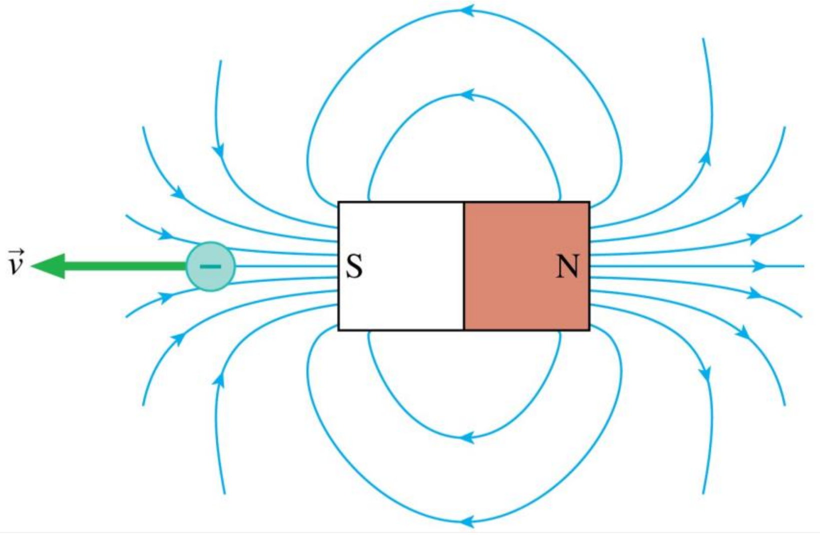
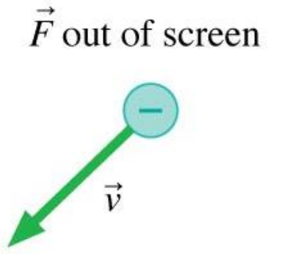
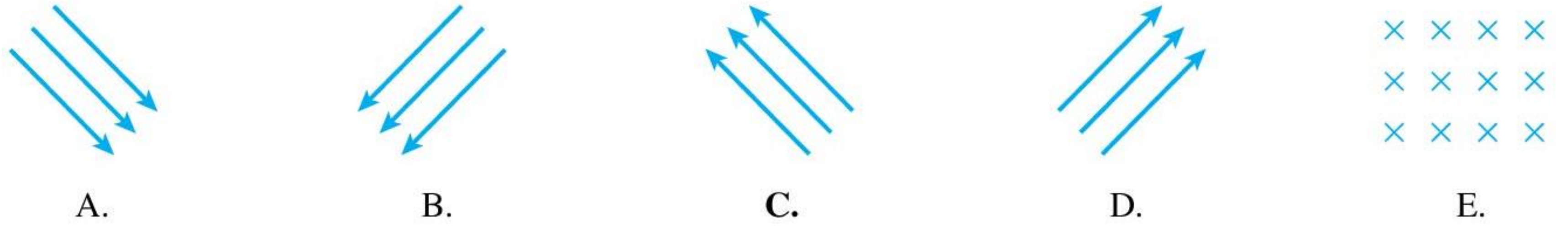
C. Into the screen.
D. Out of the screen.
✔ E. The magnetic force is zero.



QuickCheck 24.19

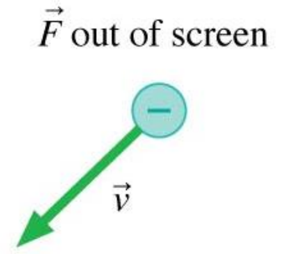
Which magnetic field causes the observed force?

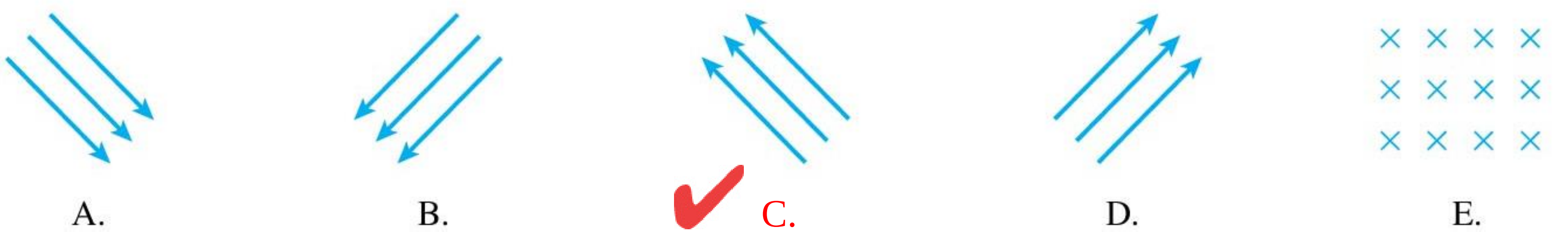




QuickCheck 24.19

Which magnetic field causes the observed force?

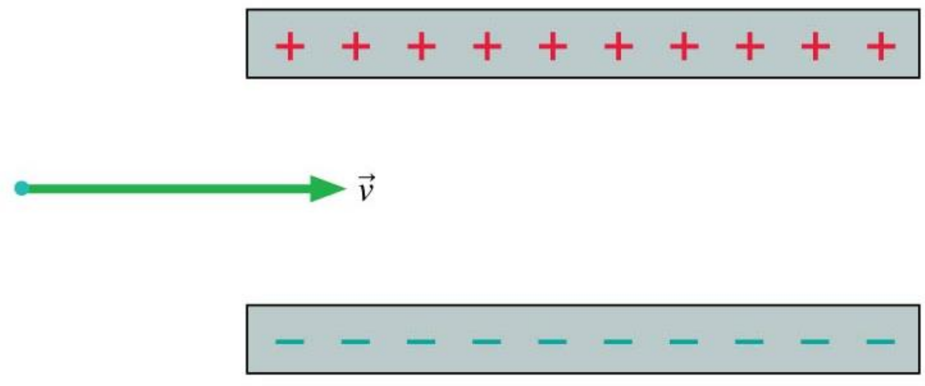


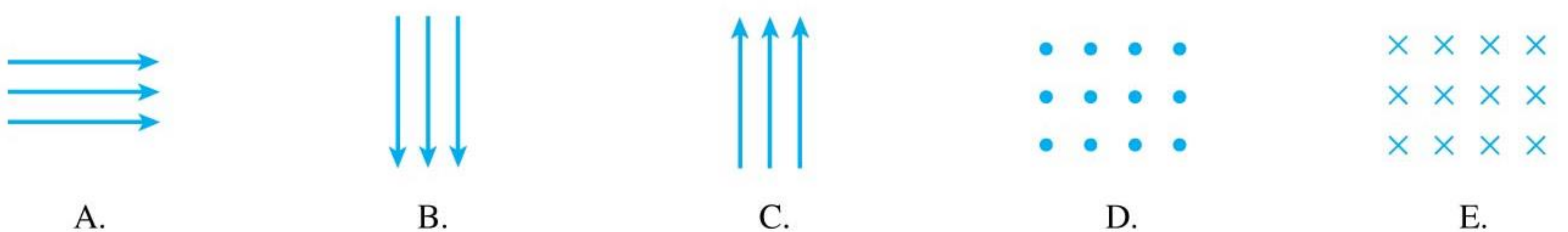


A. B. ✔ C. D. E.

QuickCheck 24.20

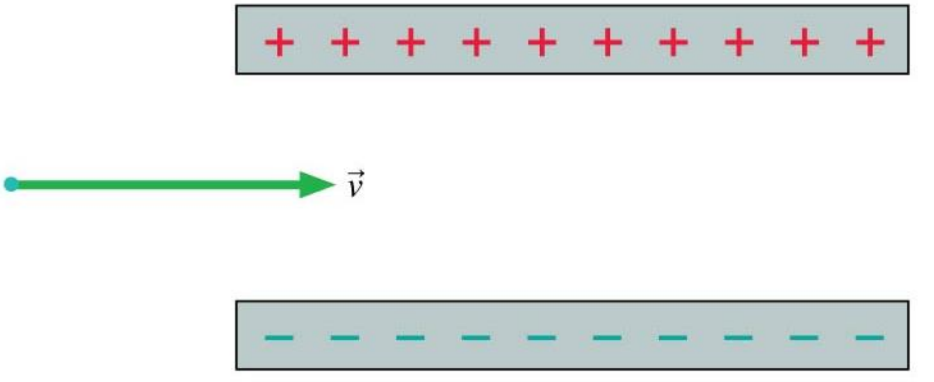
Which magnetic field (if it's the correct strength) allows the electron to pass through the charged electrodes without being deflected?

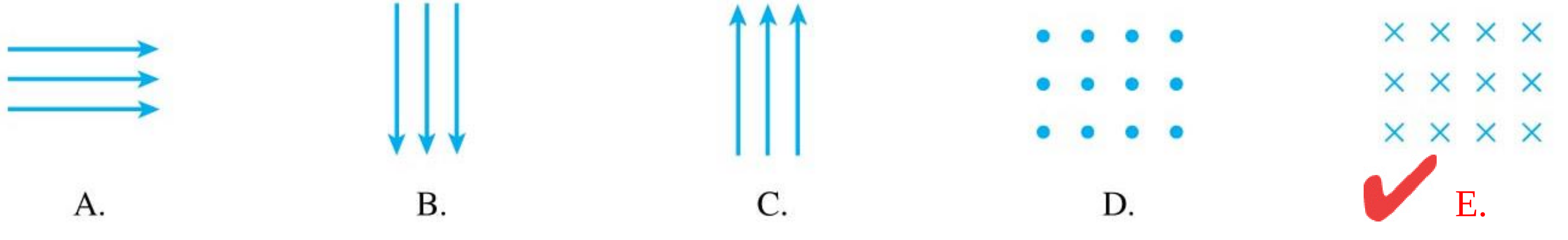




QuickCheck 24.20

Which magnetic field (if it's the correct strength) allows the electron to pass through the charged electrodes without being deflected?

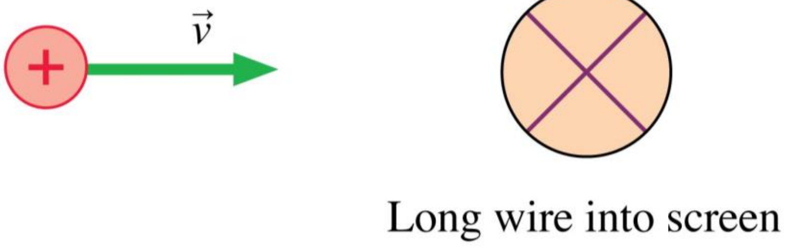




QuickCheck 24.21

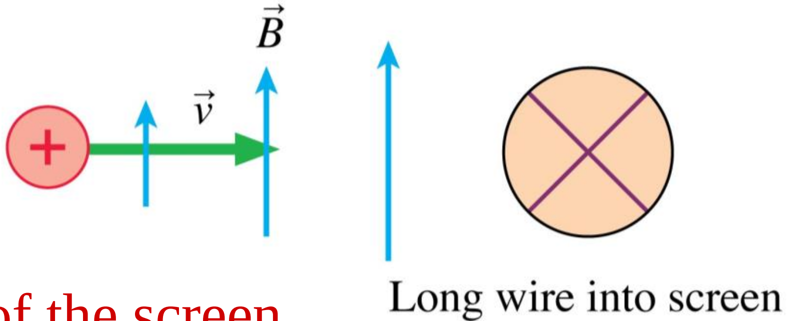
A proton is shot straight at the center of a long, straight wire carrying current into the screen. The proton will

A. Go straight into the wire.
B. Hit the wire in front of the screen.
C. Hit the wire behind the screen.
D. Be deflected over the wire.
E. Be deflected under the wire.



QuickCheck 24.21

A proton is shot straight at the center of a long, straight wire carrying current into the screen. The proton will



A. Go straight into the wire.

✔ B. Hit the wire in front of the screen. $\vec{v} \times \vec{B}$ points out of the screen

C. Hit the wire behind the screen.

D. Be deflected over the wire.

E. Be deflected under the wire.

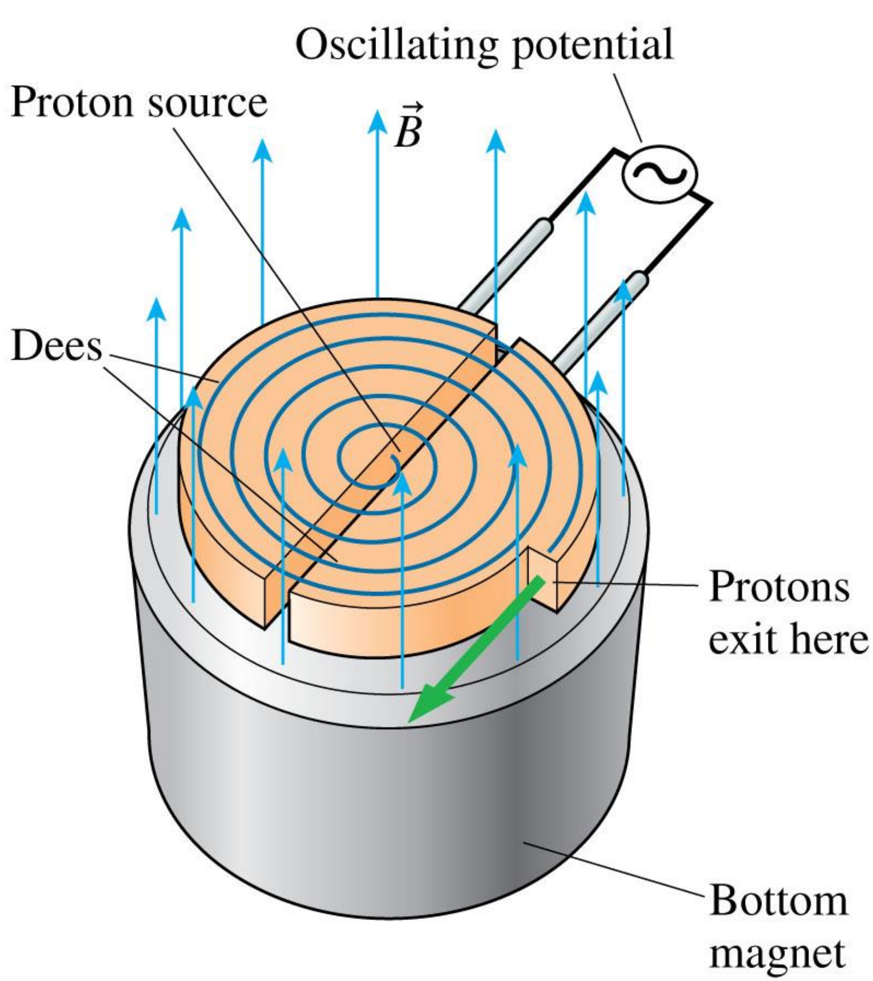
The Cyclotron

- The medical imaging technique of *positron-emission tomography* (PET) is used to make images of the internal *biological activity* of the body.
- A **cyclotron** fires energetic protons at ^{18}O atoms in water, creating ^{18}F, which is needed for PET.

The Cyclotron

- A cyclotron consists of an evacuated chamber within a large, uniform magnetic field. Inside the chamber are two hollow conductors called "dees," separated by a small gap.

(a) Interior view of a cyclotron



The Cyclotron

- The cyclotron uses an oscillating electric potential to create a strong electric field in the gap between the dees, which accelerates the protons passing through the gap.
- The protons travel in a circular path in the magnetic field. When they reach the opposite gap, the potential has changed signs so the electric field again accelerates the protons.
- The protons' orbital radius must be proportional to their speed, so as they increase in speed, they move toward the outer edge of the magnet, where they eventually exit as a high-energy beam.

Example 24.10 A medical cyclotron

It takes a proton with a kinetic energy of 11 MeV to efficiently change ^{18}O nuclei into ^{18}F. If the magnetic field inside the cyclotron is 1.2 T, what is the radius of the protons' orbit just before they exit the cyclotron?

PREPARE Equation 24.8 relates the radius of a charged particle's orbit to its speed. We can find the speed of the protons from their kinetic energy; to do so, we'll first need to convert their energy from MeV to J.

Example 24.10 A medical cyclotron (cont.)

SOLVE An 11 MeV proton's kinetic energy in J is

$$K = (11 \times 10^6 \text{ eV}) \times \frac{1.60 \times 10^{-19} \text{ J}}{1 \text{ eV}} = 1.76 \times 10^{-12} \text{ J}$$

The kinetic energy of a particle is $K = (1/2)mv^2$, so the proton's speed is

$$v = \sqrt{\frac{2K}{m}} = \sqrt{\frac{2(1.76 \times 10^{-12} \text{ J})}{1.67 \times 10^{-27} \text{ kg}}} = 4.59 \times 10^7 \text{ m/s}$$

Example 24.10 A medical cyclotron (cont.)

We can then find the radius of the orbit corresponding to this speed from Equation 24.8:

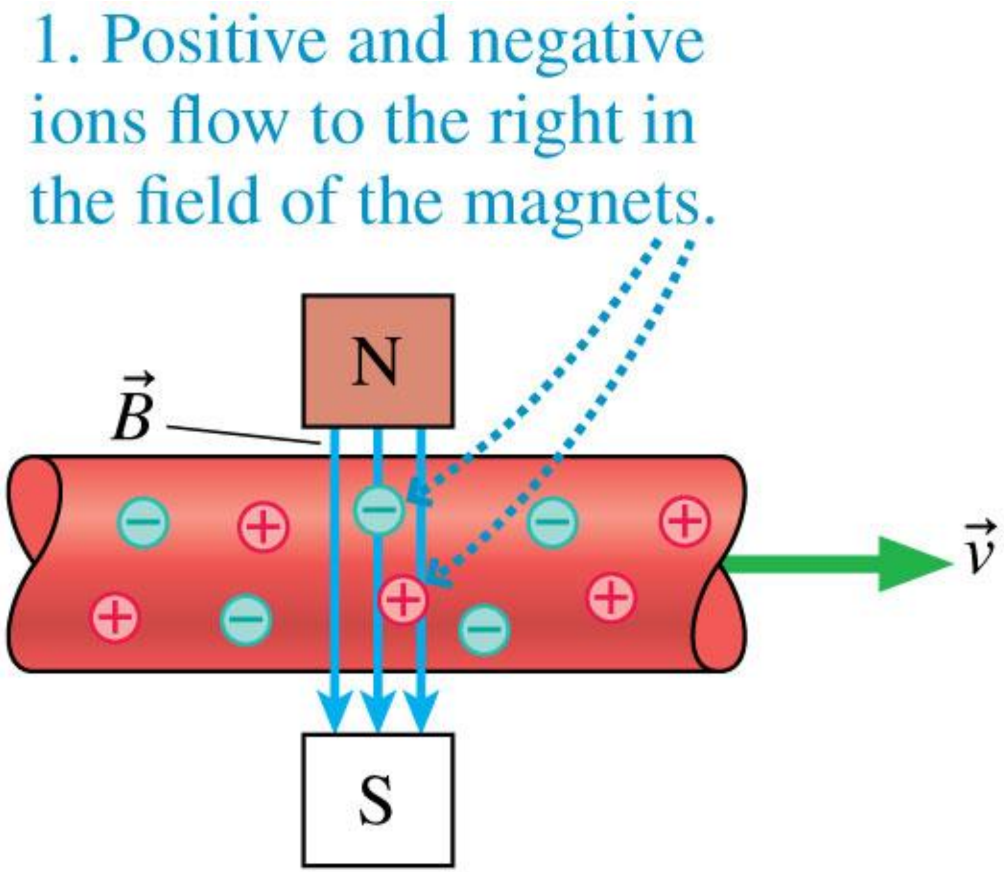
$$r = \frac{mv}{|q|B} = \frac{(1.67 \times 10^{-27}\ \text{kg})(4.59 \times 10^{7}\ \text{m/s})}{(1.60 \times 10^{-19}\ \text{C})(1.2\ \text{T})} = 0.40\ \text{m}$$

ASSESS The woman next to the cyclotron in **FIGURE 24.35B** is roughly 2 m tall, so a 0.80 m diameter for a proton's orbit as it exits the cyclotron seems reasonable.

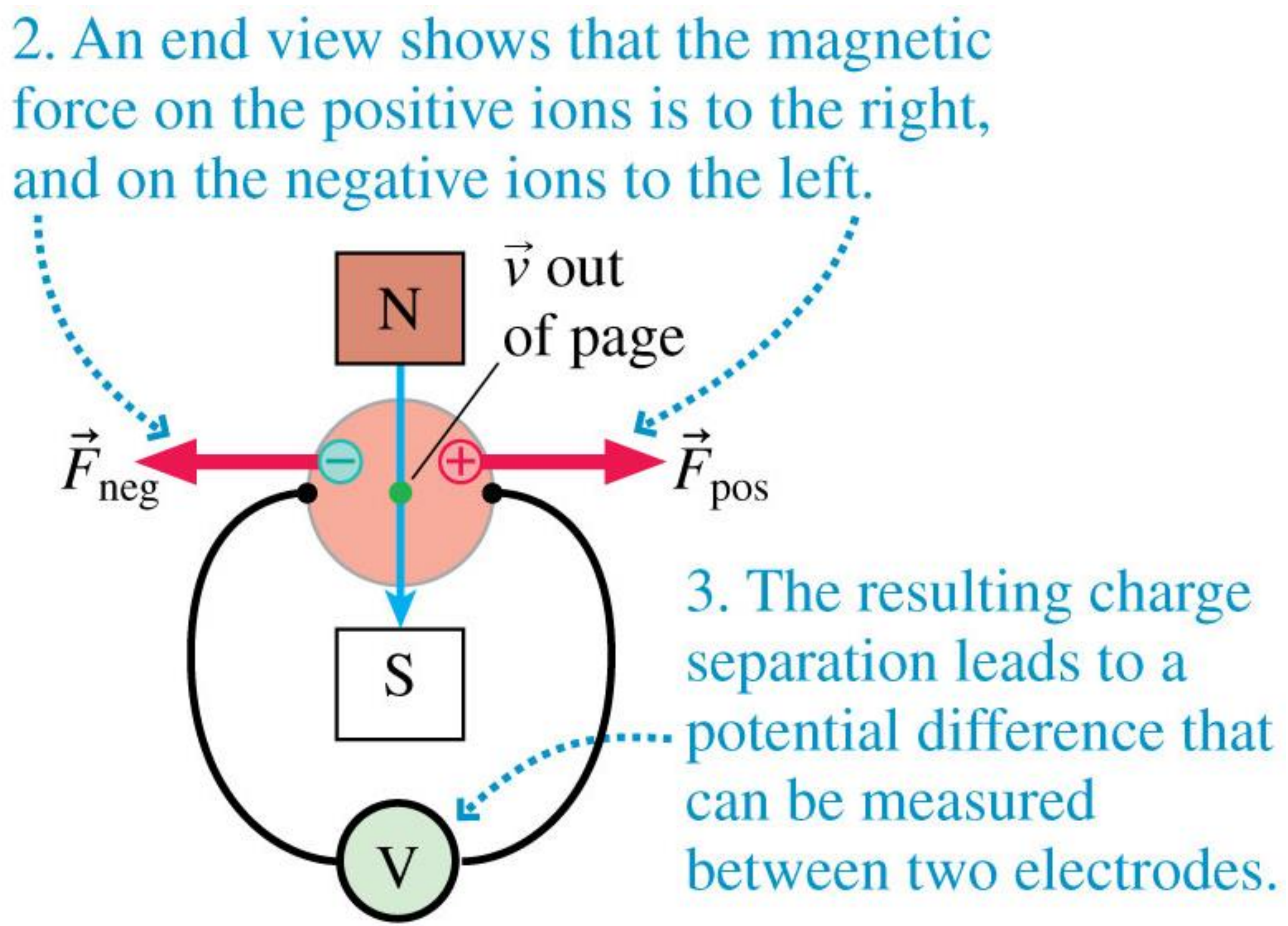
Electromagnetic Flowmeters

- An *electromagnetic flowmeter* is a device that can be used to measure the blood flow in an artery.
- It applies a magnetic field across the artery, which separates the positive and negative ions in the blood.
- The flowmeter measures the potential difference due to the separation of the ions.
- The faster the blood's ions are moving, the greater the forces separating the ions become, therefore generating a higher voltage.
- Therefore, the measured voltage is proportional to the velocity of the blood.

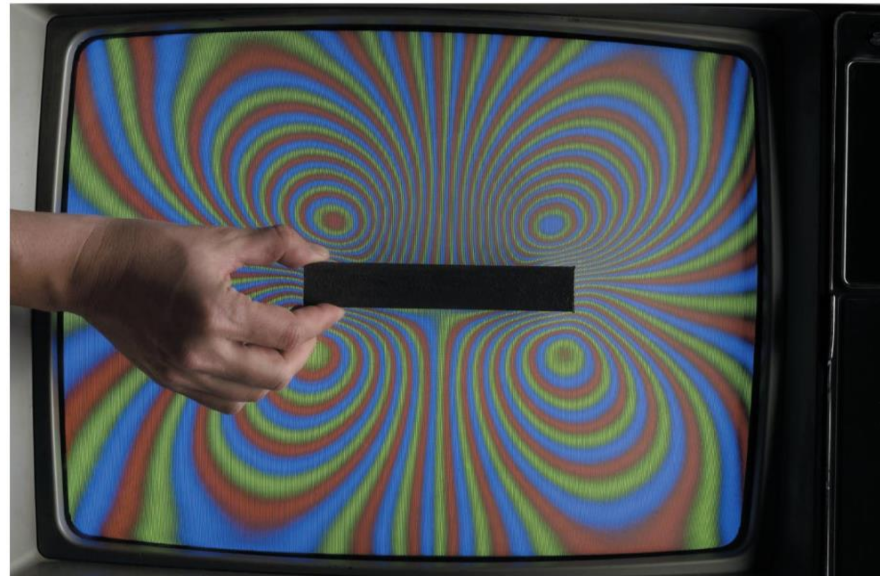
Electromagnetic Flowmeters



Electromagnetic Flowmeters



Don't Try It Yourself: Magnets and Television Screens



The image on a cathode-ray tube television screen is drawn by an electron beam that is steered by magnetic fields from coils of wire. Other magnetic fields can also exert forces on the moving electrons. If you place a strong magnet near the TV screen, the electrons will be forced along altered trajectories and will strike different places on the screen than they are supposed to, producing an array of bright colors. *(The magnet can magnetize internal components and permanently alter the image, so do not do this to your television!)*

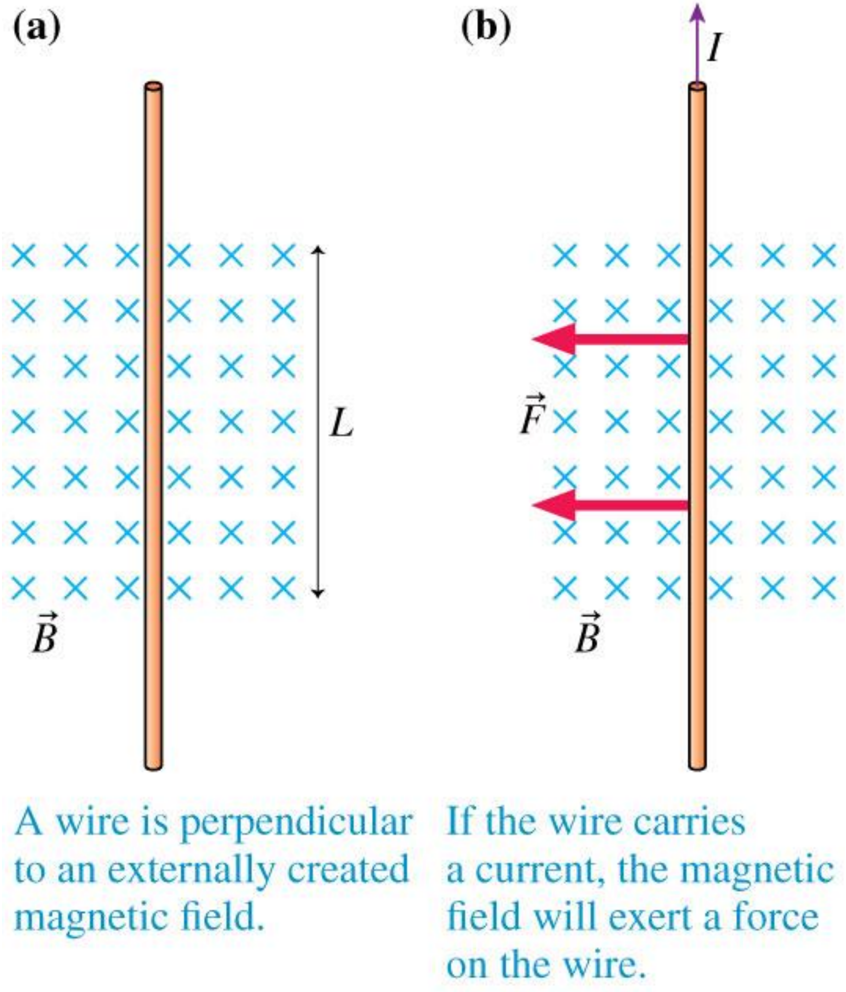
Section 24.6 Magnetic Fields Exert Forces on Currents

The Form of the Magnetic Force on a Current

- We learned that the magnetic field exerts no force on a charged particle moving parallel to a magnetic field.
- If a current-carrying wire is *parallel* to a magnetic field, we also find that the force on it is zero.

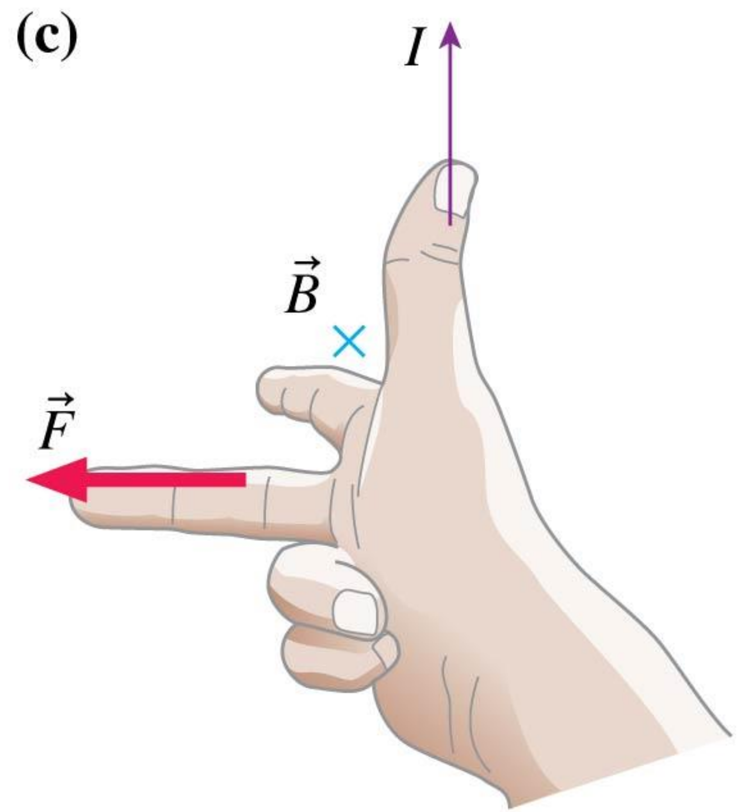
The Form of the Magnetic Force on a Current

- There is a force on a current-carrying wire that is *perpendicular* to a magnetic field.



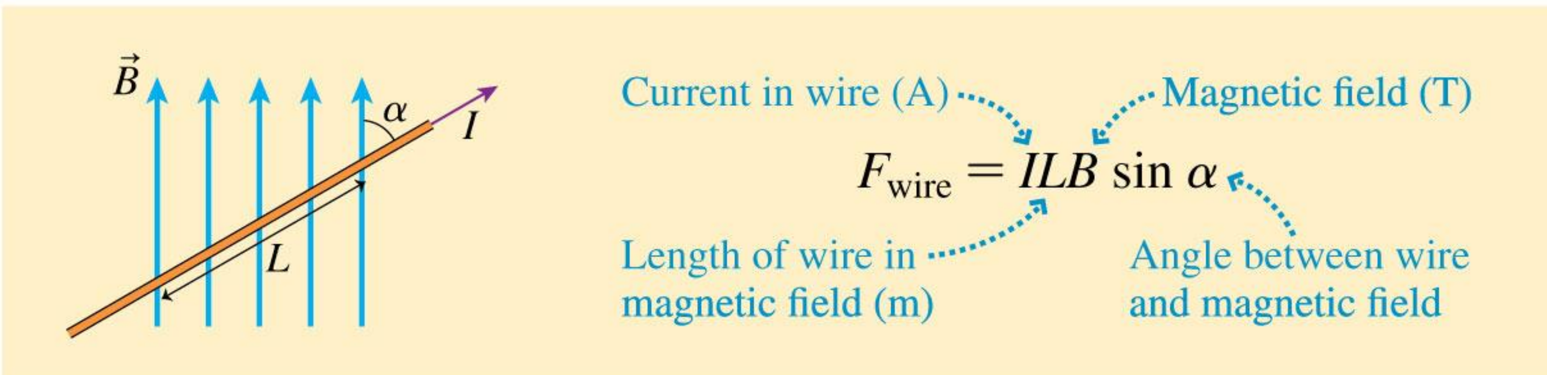
The Form of the Magnetic Force on a Current

- The direction of the force on the current is found by considering the force on each charge in the current.
- **The right-hand rule for forces applies to currents in the same way it does for moving charges.**



The Form of the Magnetic Force on a Current

- The length of the wire L, the current I, and the magnetic field B affect the magnitude of the force on the wire:



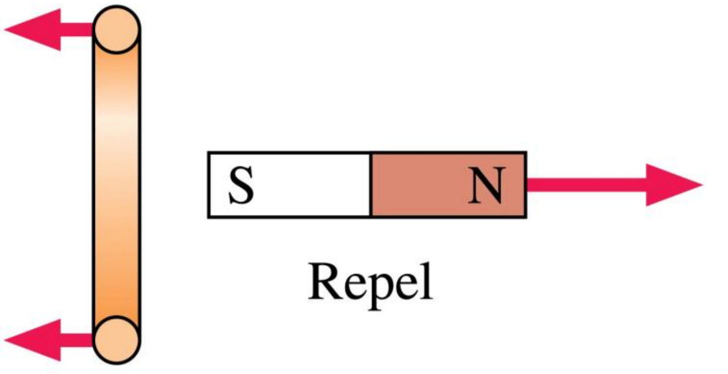
- When the wire is perpendicular to the field, $\alpha = 90°$ so

$$F_{\text{wire}} = ILB$$

QuickCheck 24.22

What is the current direction in the loop?

A. Out at the top, in at the bottom
B. In at the top, out at the bottom
C. Either A or B would cause the current loop and the bar magnet to repel each other.



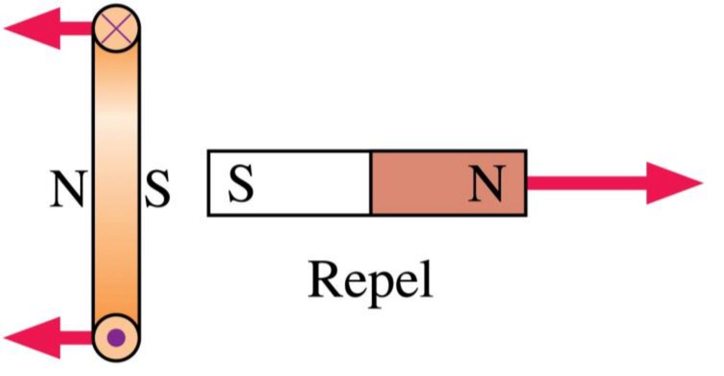
QuickCheck 24.22

What is the current direction in the loop?

A. Out at the top, in at the bottom

✔ B. In at the top, out at the bottom

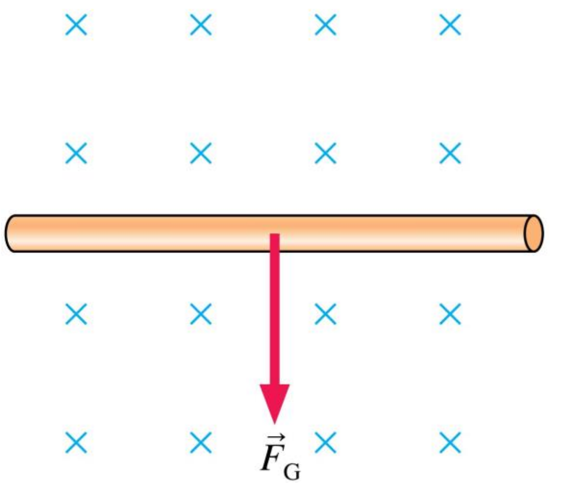
C. Either A or B would cause the current loop and the bar magnet to repel each other.



QuickCheck 24.23

The horizontal wire can be levitated—held up against the force of gravity—if the current in the wire is

A. Right to left.
B. Left to right.
C. It can't be done with this magnetic field.



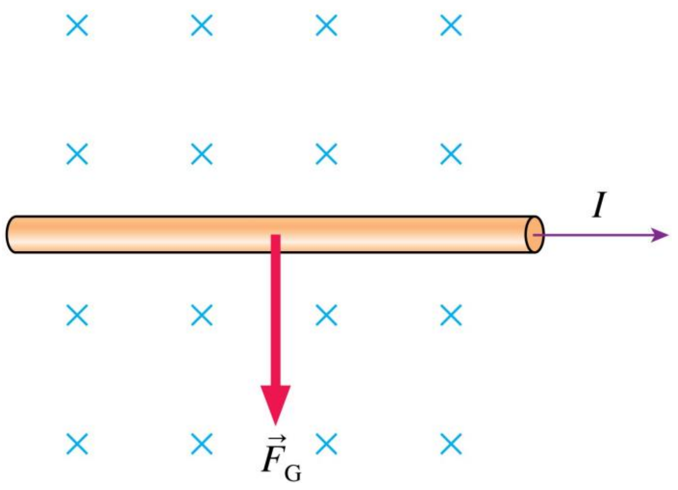
QuickCheck 24.23

The horizontal wire can be levitated—held up against the force of gravity—if the current in the wire is

A. Right to left.

✔ B. Left to right.

C. It can't be done with this magnetic field.

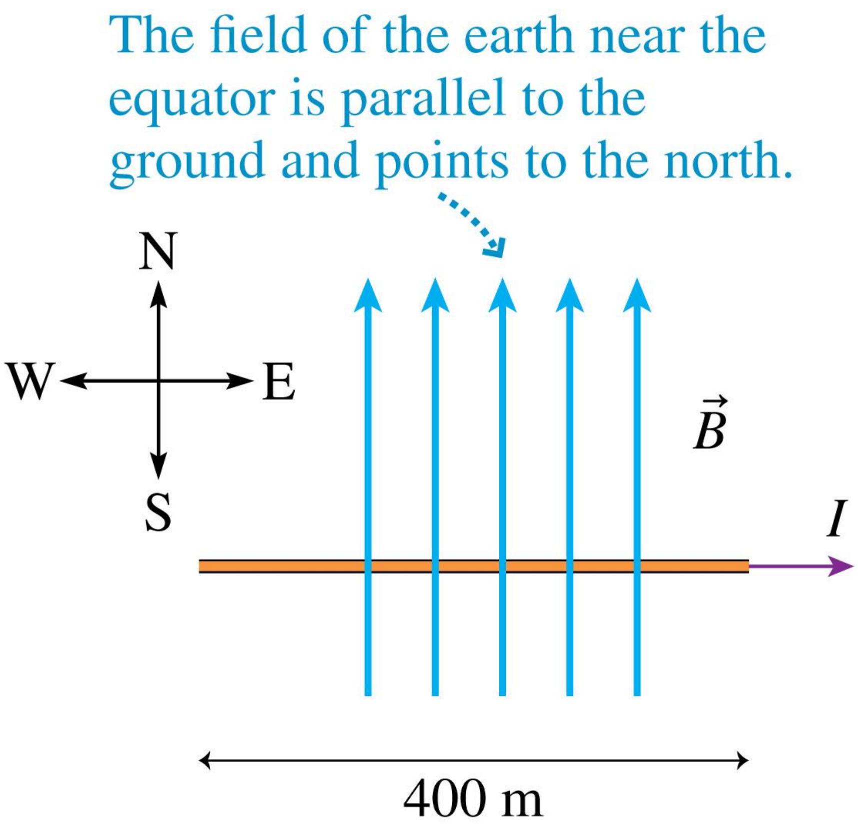


Example 24.11 Magnetic force on a power line

A DC power line near the equator runs east-west. At this location, the earth's magnetic field is parallel to the ground, points north, and has magnitude 50 μT. A 400 m length of the heavy cable that spans the distance between two towers has a mass of 1000 kg. What direction and magnitude of current would be necessary to offset the force of gravity and "levitate" the wire? (The power line will actually carry a current that is much less than this; 850 A is a typical value.)

Example 24.11 Magnetic force on a power line (cont.)

PREPARE First, we sketch a top view of the situation, as in **FIGURE 24.38**. The magnetic force on the wire must be opposite that of gravity. An application of the right-hand rule for forces shows that a current to the east will result in an upward force—out of the page.



Example 24.11 Magnetic force on a power line (cont.)

SOLVE The magnetic field is perpendicular to the current, so the magnitude of the magnetic force is given by Equation 24.10. To levitate the wire, this force must be opposite to the weight force but equal in magnitude, so we can write

$$mg = ILB$$

where m and L are the mass and length of the wire and B is the magnitude of the earth's field. Solving for the current, we find

$$I = \frac{mg}{LB} = \frac{(1000 \text{ kg})(9.8 \text{ m/s}^2)}{(400 \text{ m})(50 \times 10^{-6} \text{ T})} = 4.9 \times 10^5 \text{ A}$$

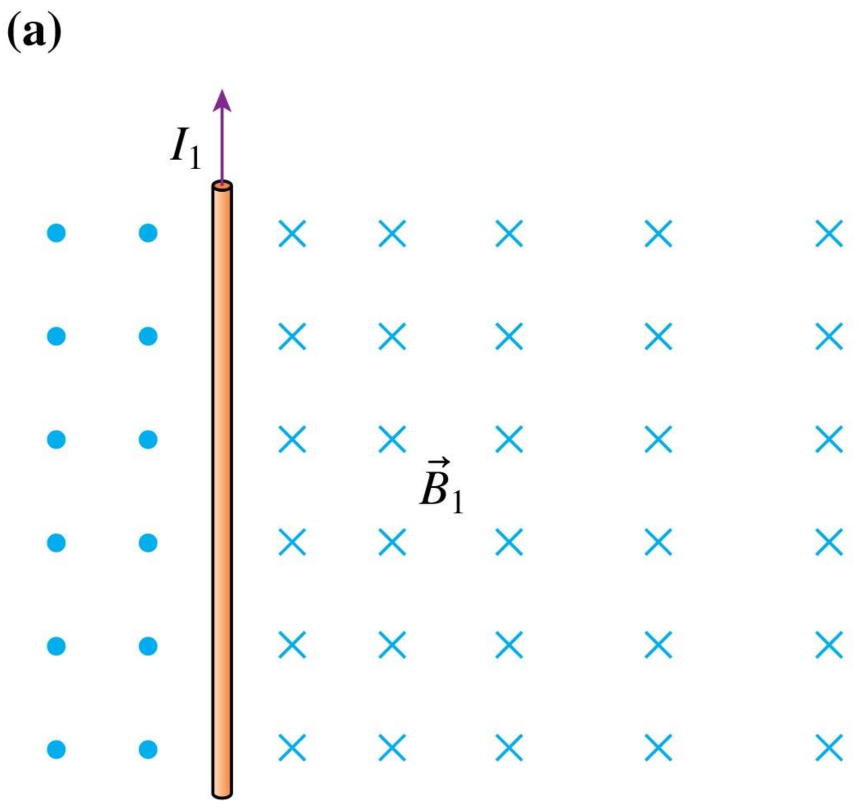
directed to the east.

Example 24.11 Magnetic force on a power line (cont.)

ASSESS The current is much larger than a typical current, as we expected.

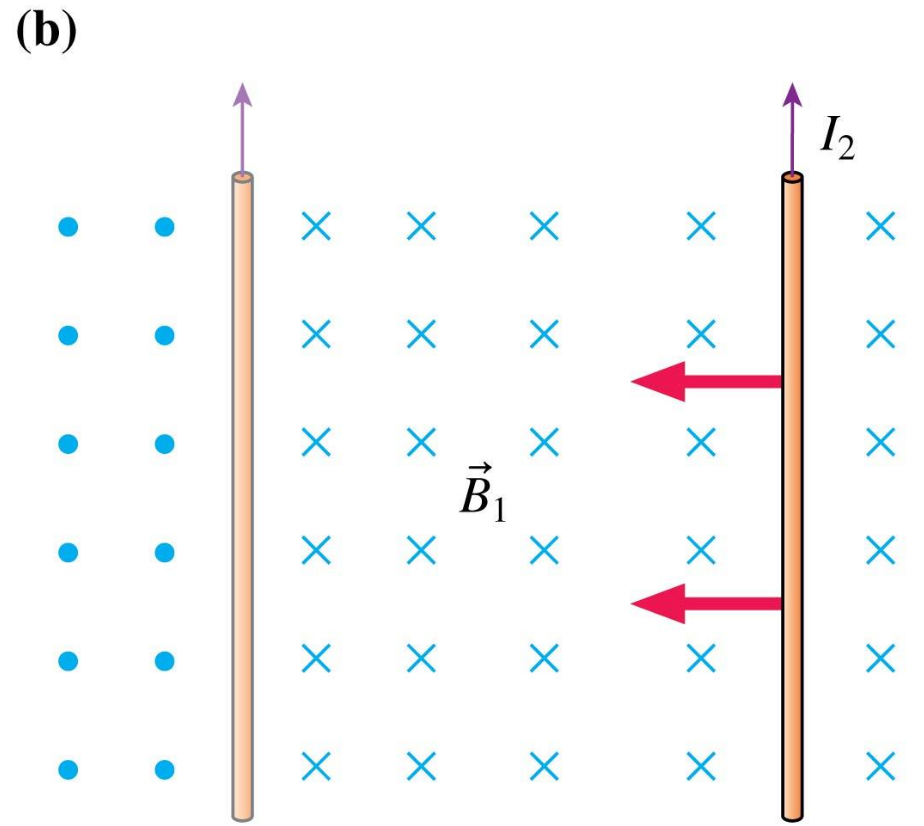
Forces Between Currents

- Because a current produces a magnetic field, and a magnetic field exerts a force on a current, it follows that two current-carrying wires will exert forces on each other.
- A wire carrying a current I_1 will create a magnetic field $\vec{B}_1$.



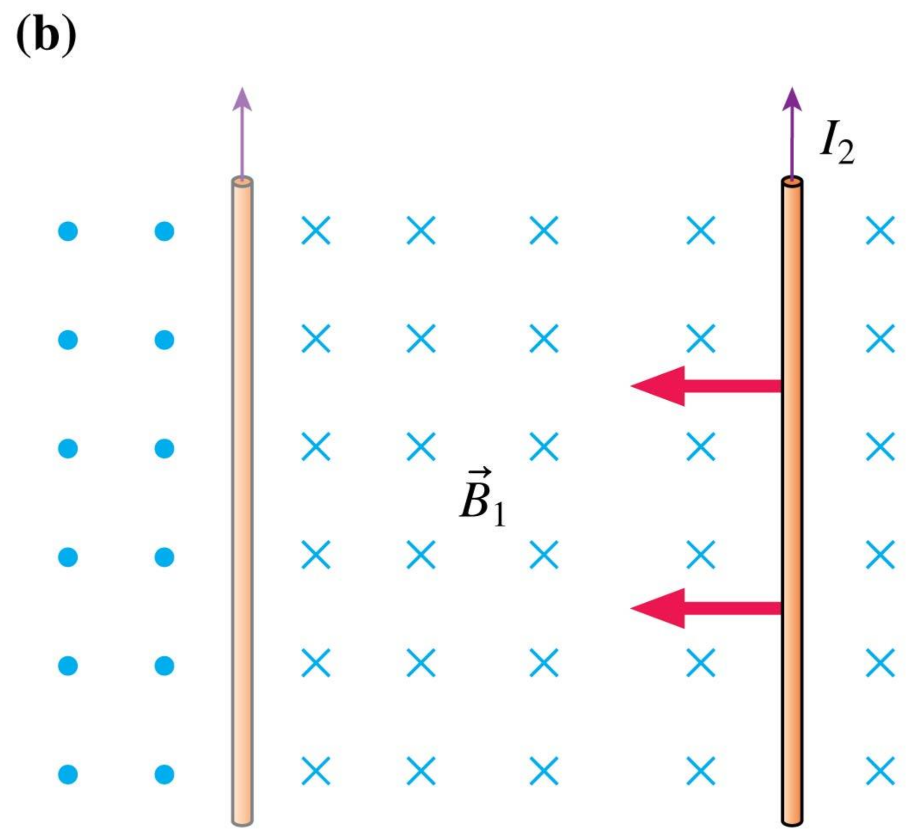
Forces Between Currents

- A second wire with current I_2 will experience the magnetic force due to the wire with current I_1.
- Using the right-hand rule for forces, we can see that when I_2 is in the same direction as I_1, the second wire is *attracted* to the first wire.
- If they were in opposite directions, the second wire would be repelled.

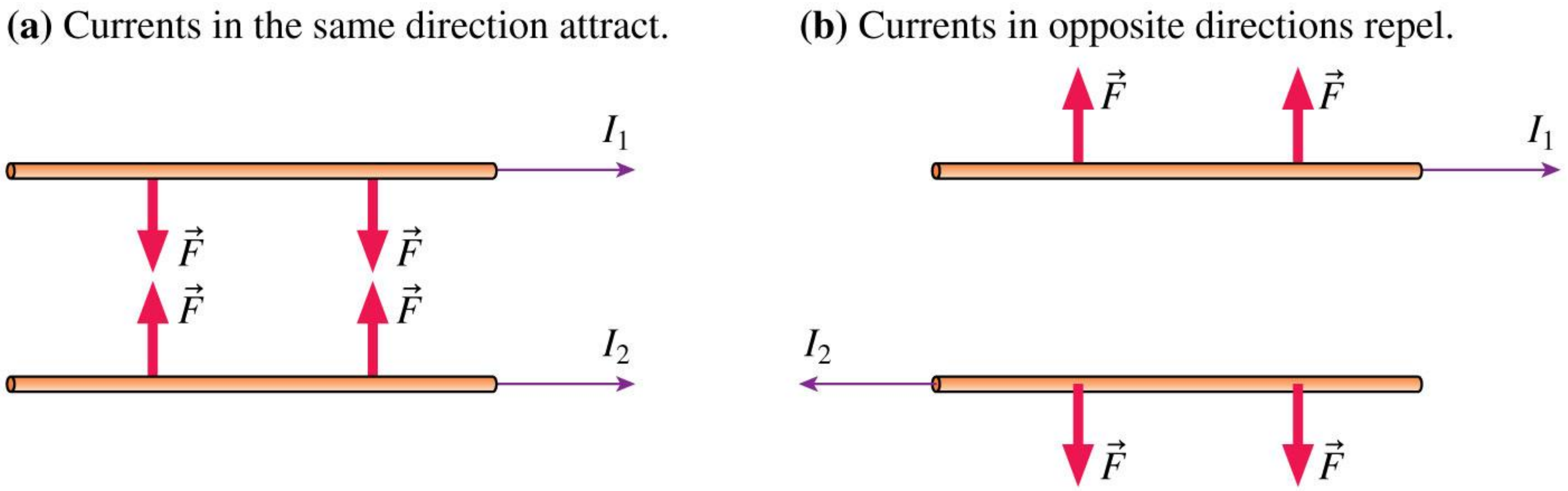


Forces Between Currents

- The magnetic field created by the wire with current I_2 will also exert an attractive force on the wire with current I_1.
- The forces on the two wires form a Newton's third law action/reaction pair.
- The forces due to the magnetic fields of the wires are directed in opposite directions and must have the *same* magnitude.



Forces Between Currents

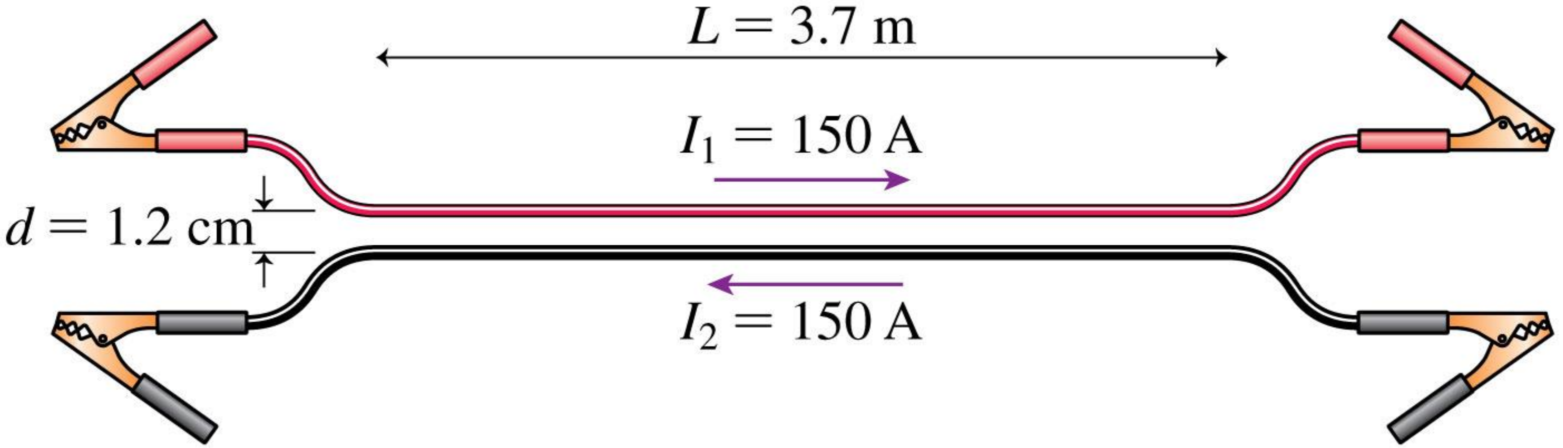


Example 24.12 Finding the force between wires in jumper cables

You may have used a set of jumper cables connected to a running vehicle to start a car with a dead battery. Jumper cables are a matched pair of wires, red and black, joined together along their length. Suppose we have a set of jumper cables in which the two wires are separated by 1.2 cm along their 3.7 m (12 ft) length. While starting a car, the wires each carry a current of 150 A, in opposite directions. What is the force between the two wires?

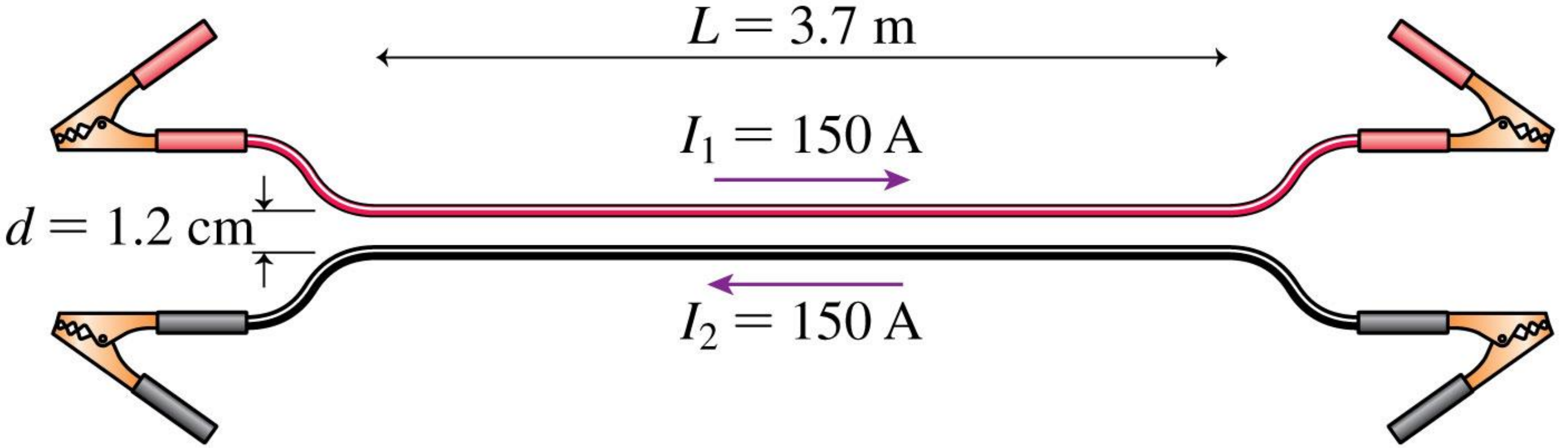
Example 24.12 Finding the force between wires in jumper cables (cont.)

PREPARE Our first step is to sketch the situation, noting distances and currents, as shown in **FIGURE 24.41**. Let's find the force on the red wire; from the discussion above, the force on the black wire has the same magnitude but is in the opposite direction.



Example 24.12 Finding the force between wires in jumper cables (cont.)

The force on the red wire is found using a two-step process. First, we find the magnetic field due to the current in the black wire at the position of the red wire. Then, we find the force on the current in the red wire due to this magnetic field.



Example 24.12 Finding the force between wires in jumper cables (cont.)

SOLVE The magnetic field at the position of the red wire, due to the current in the black wire, is

$$B = \frac{\mu_0 I}{2\pi d} = \frac{(1.26 \times 10^{-6}\ \mathrm{T \cdot m/A})(150\ \mathrm{A})}{2\pi(0.012\ \mathrm{m})} = 2.51 \times 10^{-3}\ \mathrm{T}$$

According to the right-hand rule for fields, this magnetic field is directed into the page. The magnitude of the force on the red wire is then

$$F_{\mathrm{wire}} = ILB = (150\ \mathrm{A})(3.7\ \mathrm{m})(2.51 \times 10^{-3}\ \mathrm{T}) = 1.4\ \mathrm{N}$$

Example 24.12 Finding the force between wires in jumper cables (cont.)

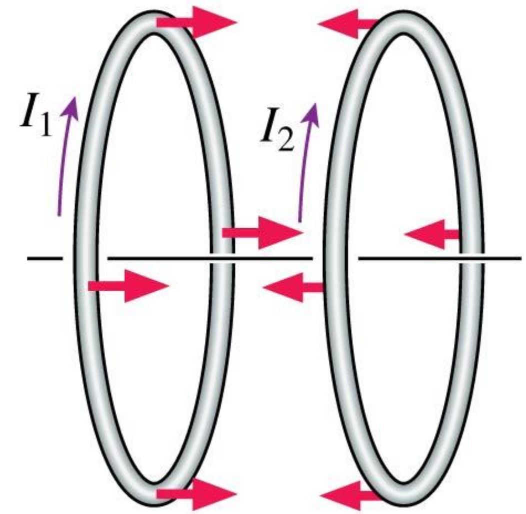
The direction of the force can be found using the right-hand rule for forces. The magnetic field at the position of the red wire is into the page, while the current is to the right. This means that the force on the red wire is in the plane of the page, directed *away* from the black wire. Thus the force between the two wires is repulsive, as we expect when their currents are directed oppositely.

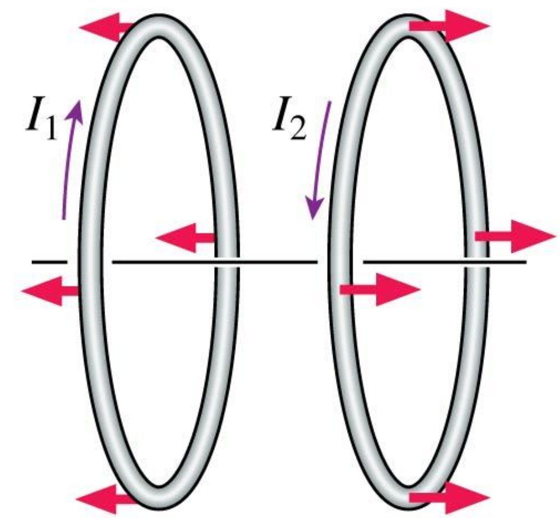
Example 24.12 Finding the force between wires in jumper cables (cont.)

ASSESS These wires are long, close together, and carry very large currents. But the force between them is quite small—much less than the weight of the wires. In practice, the forces between currents are not an important consideration unless there are many coils of wire, leading to a large total force. This is the case in an MRI solenoid.

Forces Between Current Loops

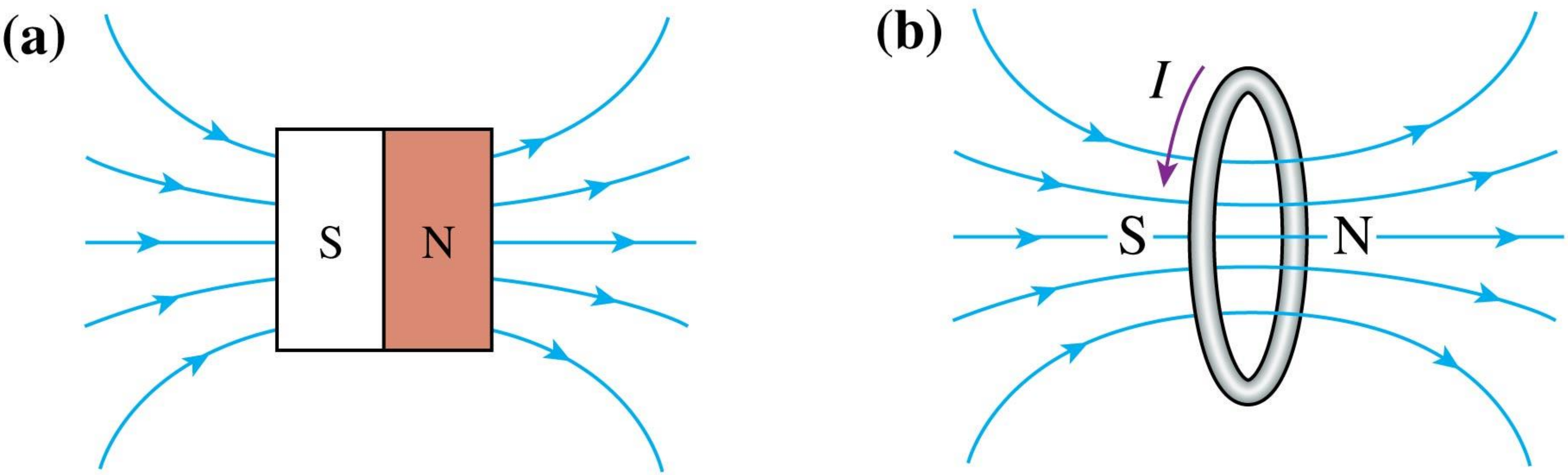
- Just as there is an attractive force between parallel wires that have currents in the same direction, there is an attractive force between parallel loops with currents in the same direction.
- There is a repulsive force between parallel loops with currents in opposite directions.



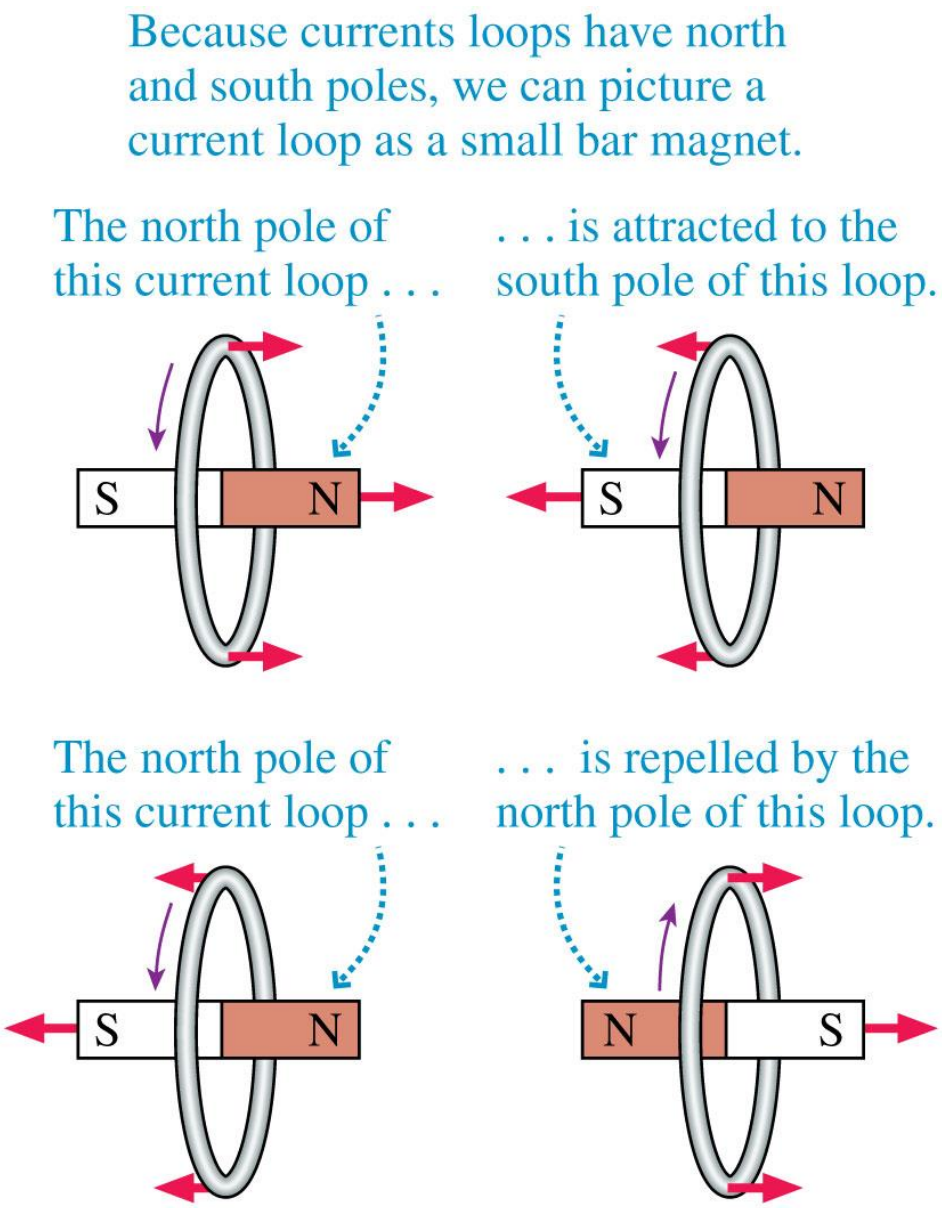


Forces Between Current Loops

- The field of a current loop is very similar to that of a bar magnet.
- **A current loop, like a bar magnet, is a magnetic dipole** with a north and a south pole.

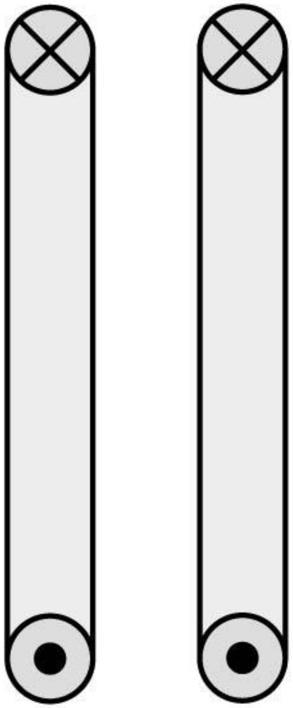


Forces Between Current Loops



QuickCheck 24.24

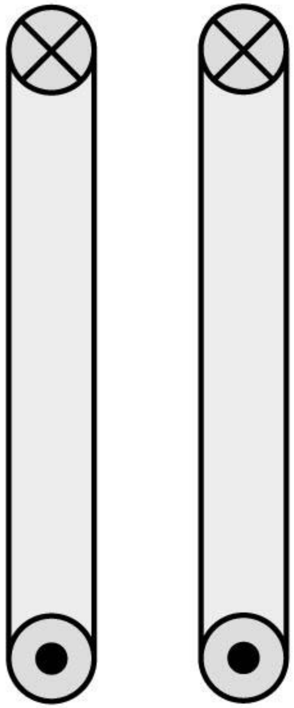
The diagram below shows slices through two adjacent current loops. Think about the force exerted on the loop on the right due to the loop on the left. The force on the right loop is directed



A. To the left.
B. Up.
C. To the right.
D. Down.

QuickCheck 24.24

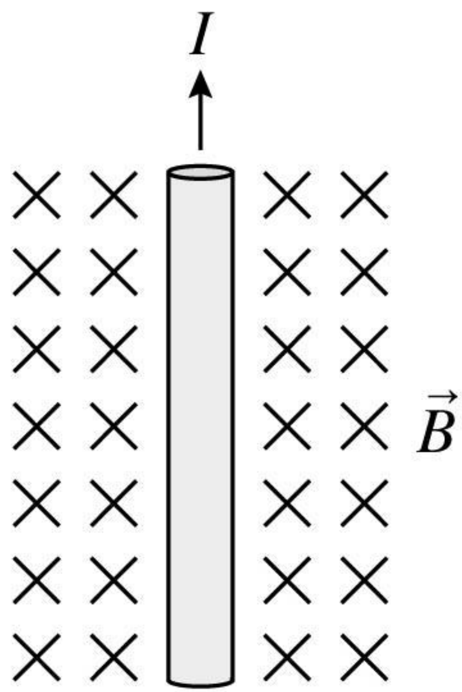
The diagram below shows slices through two adjacent current loops. Think about the force exerted on the loop on the right due to the loop on the left. The force on the right loop is directed



✔ A. To the left.
B. Up.
C. To the right.
D. Down.

Example Problem

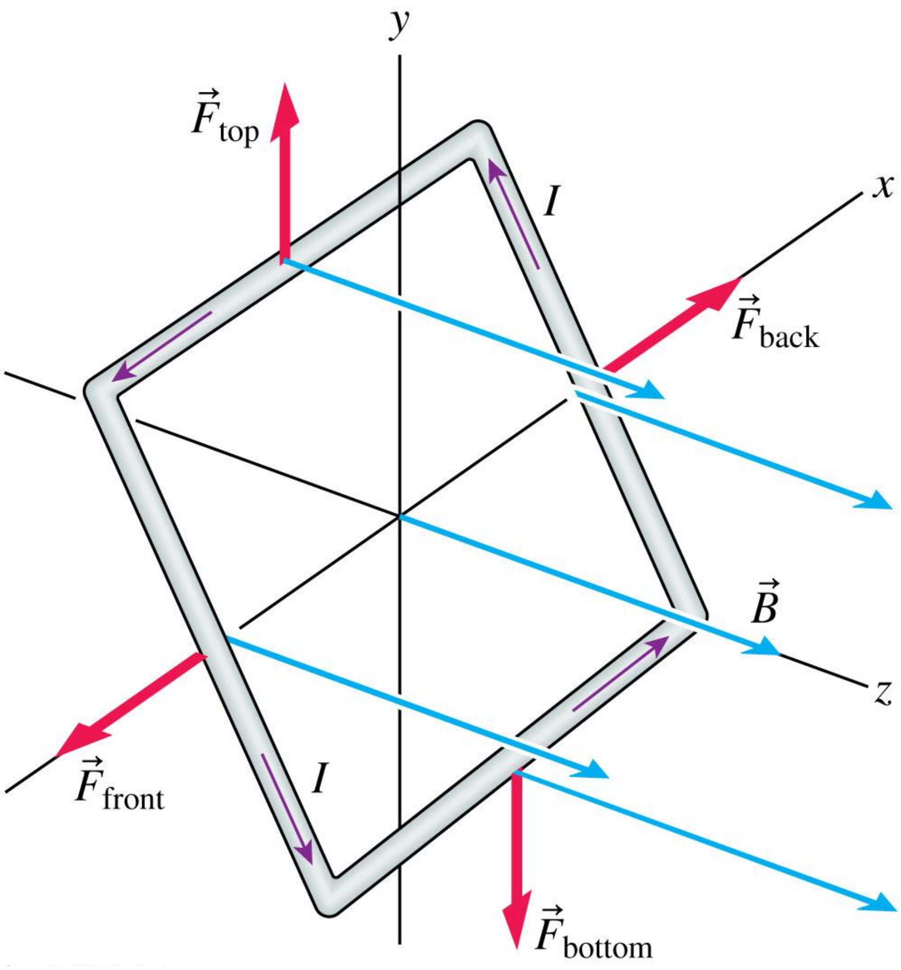
A 10 cm length of wire carries a current of 3.0 A. The wire is in a uniform field with a strength of 5E-3 Tesla as in the following diagram. What are the magnitude and direction of the force on this segment of wire?



Section 24.7 Magnetic Fields Exert Torques on Dipoles

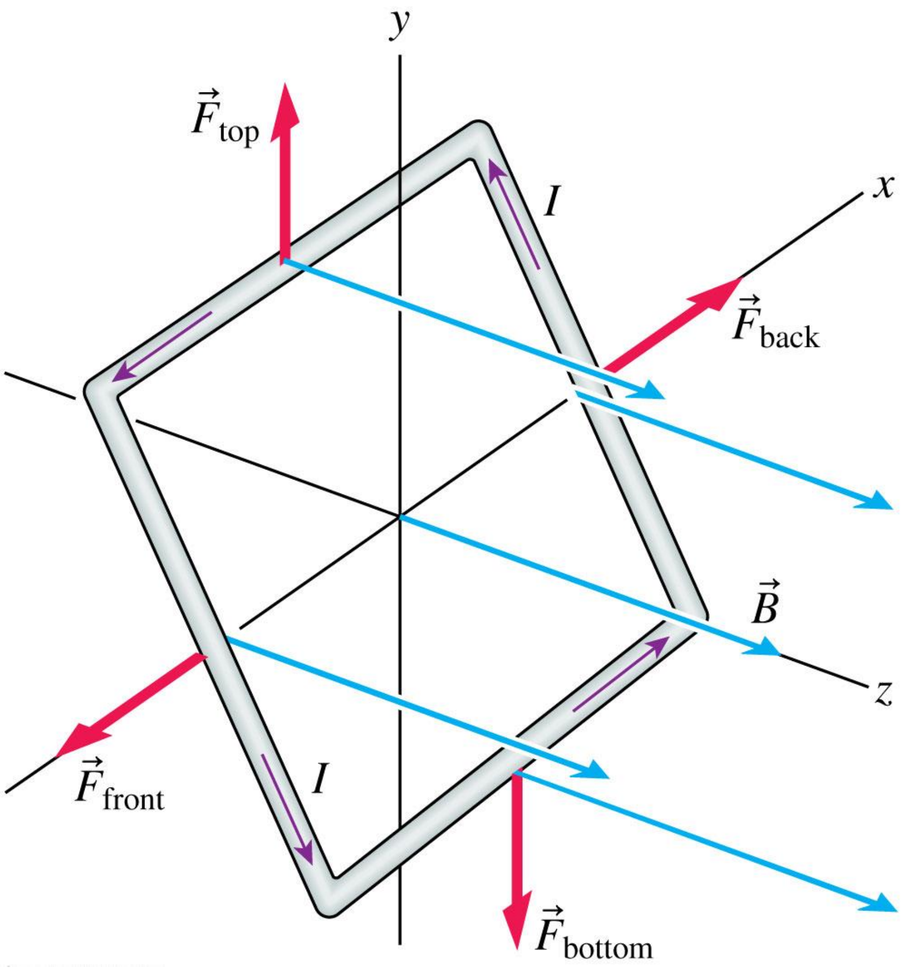
A Current Loop in a Uniform Field

- A current loop, which is a magnetic dipole, experiences a magnetic force due to a uniform magnetic field.
- Because the field is uniform, the forces on opposite sides of the loop are of equal magnitude and therefore produce no net force.



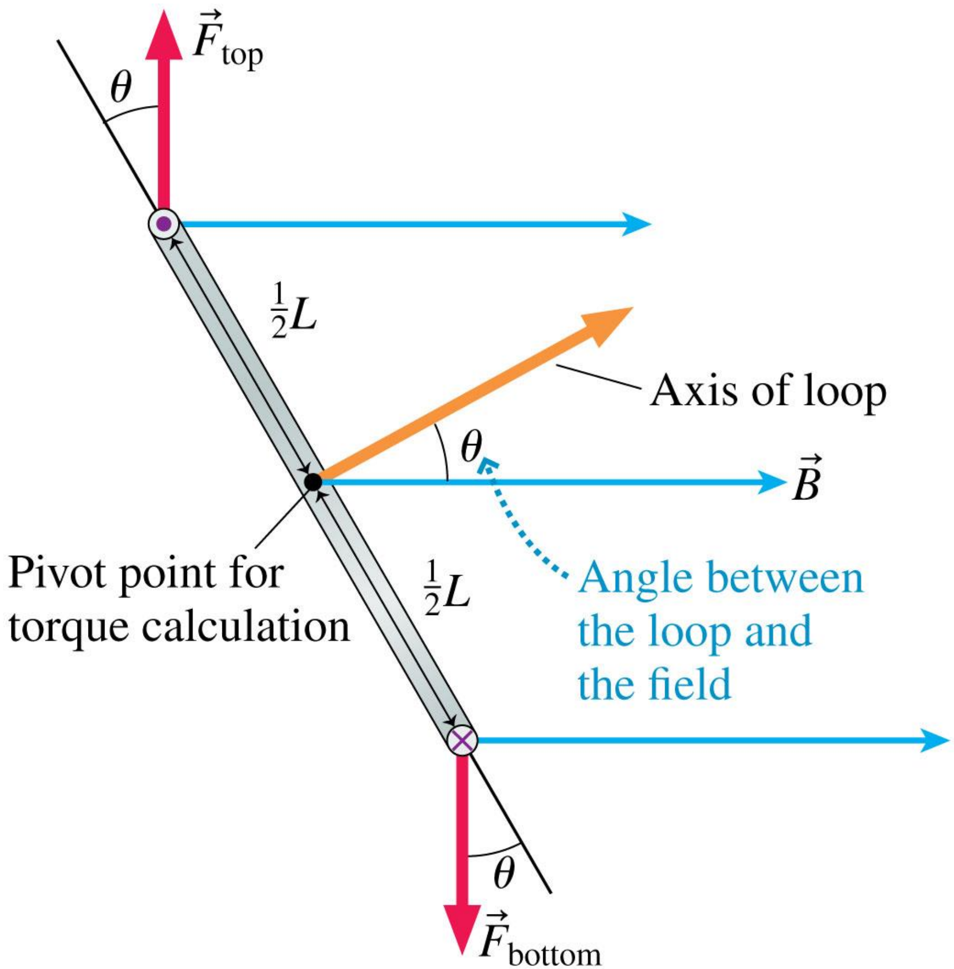
A Current Loop in a Uniform Field

- The forces on the top and bottom of the loop will rotate the loop by exerting a torque on it.
- **In a uniform field, a dipole experiences a torque but no net force.**



A Current Loop in a Uniform Field

- Looking at a current loop from the side, the forces F_{top} and F_{bottom} act to rotate the loop clockwise.



A Current Loop in a Uniform Field

- The net torque is

$$\tau = \tau_{\text{top}} + \tau_{\text{bottom}} = \left(\tfrac{1}{2}L\right)F_{\text{top}}\sin\theta + \left(\tfrac{1}{2}L\right)F_{\text{bottom}}\sin\theta$$
$$= \left(\tfrac{1}{2}L\right)(ILB)\sin\theta + \left(\tfrac{1}{2}L\right)(IL\text{B})\sin\theta$$
$$= (IL^2)B\sin\theta$$

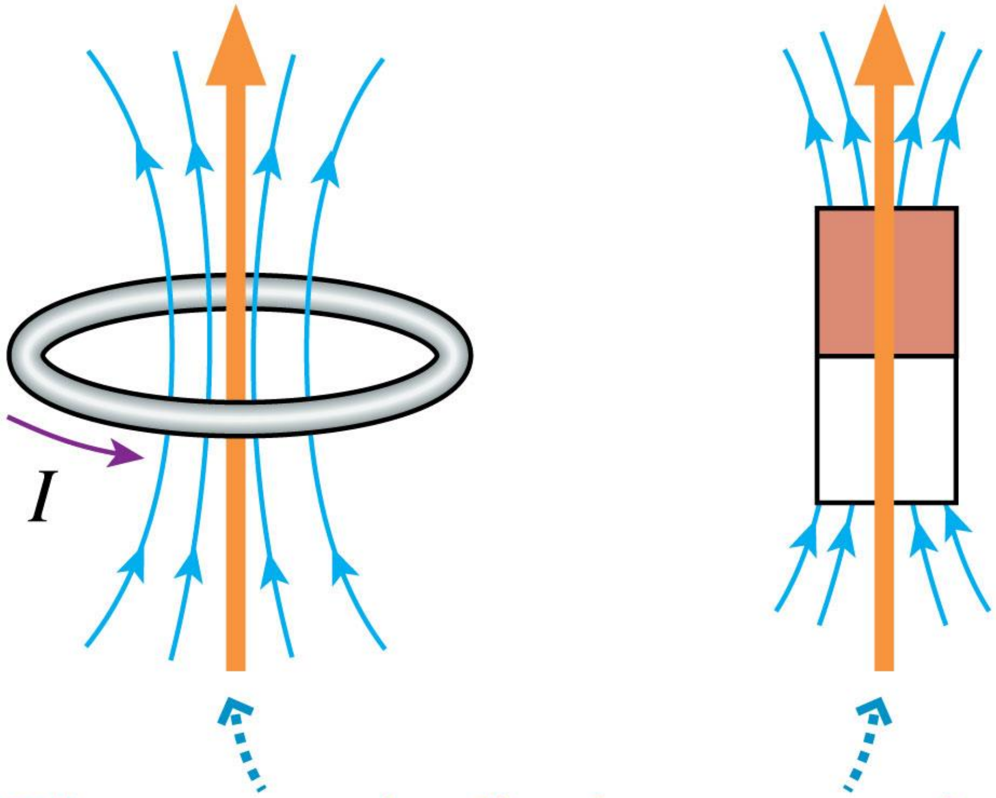
- L^2 is the area A of the square loop. The general result of the torque on any loop of area A:

$$\tau = (IA)B\sin\theta$$

A Current Loop in a Uniform Field

- **The torque depends on properties of the current loop**: its area A and the current I.
- The quantity IA is the **magnetic dipole moment**, and is a measure of how much torque the dipole will feel in a magnetic field.

A Current Loop in a Uniform Field

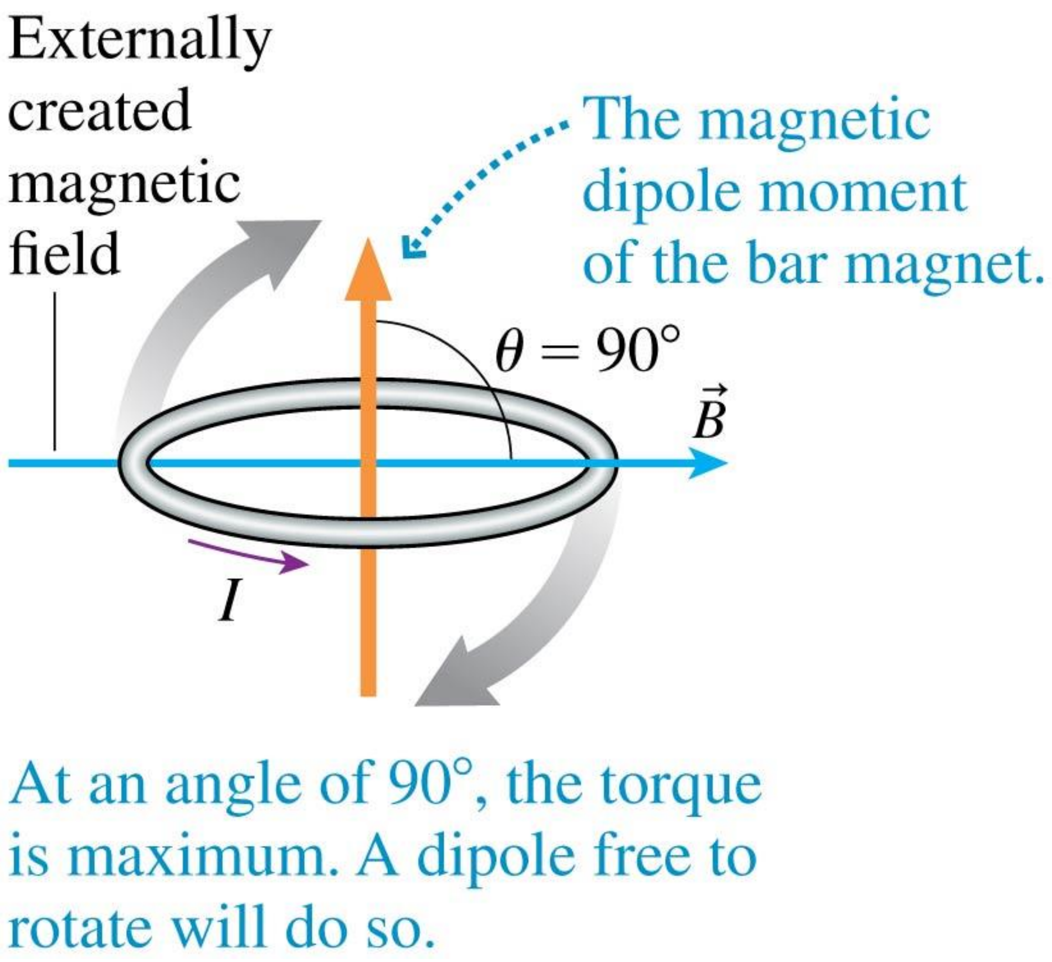


The magnetic dipole moment is represented as a vector that points in the direction of the dipole's field. A longer vector means a stronger field.

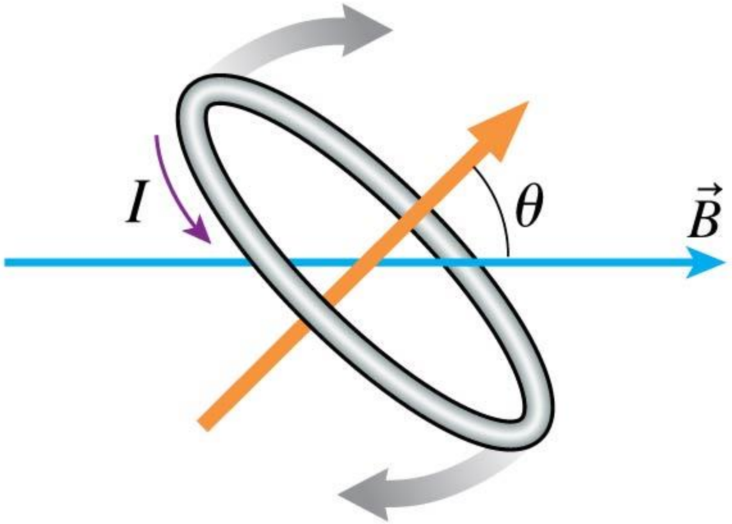
A Current Loop in a Uniform Field

- **The torque depends on the angle between the magnetic dipole moment and the magnetic field.**
- The torque is maximum when $\theta = 90°$, when the magnetic moment is perpendicular to the field. The torque is zero when $\theta = 90°$, when the magnetic moment is parallel to the field.
- **A magnetic dipole will rotate to line up with a magnetic field** just as an electric dipole will rotate to line up with an electric field.

A Current Loop in a Uniform Field

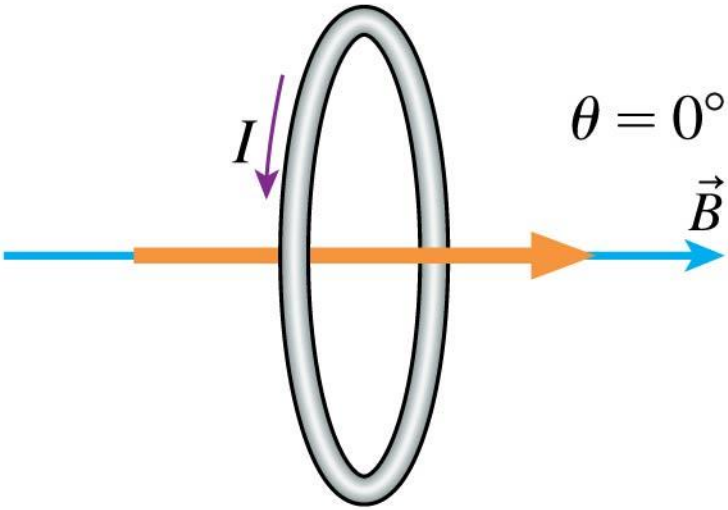


A Current Loop in a Uniform Field



The dipole will continue to rotate; as the angle θ decreases, the torque decreases.

A Current Loop in a Uniform Field

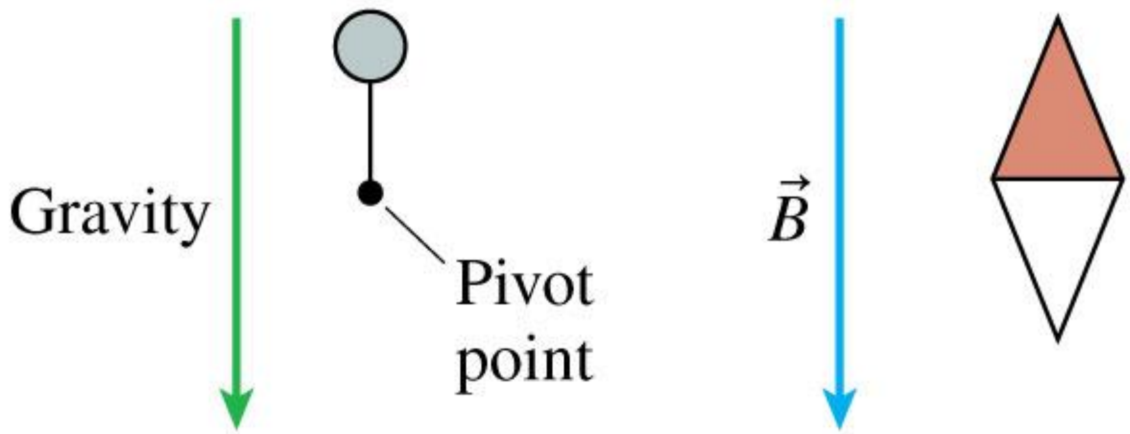


The torque is zero once the dipole is lined up so that the angle θ is zero.

A Current Loop in a Uniform Field

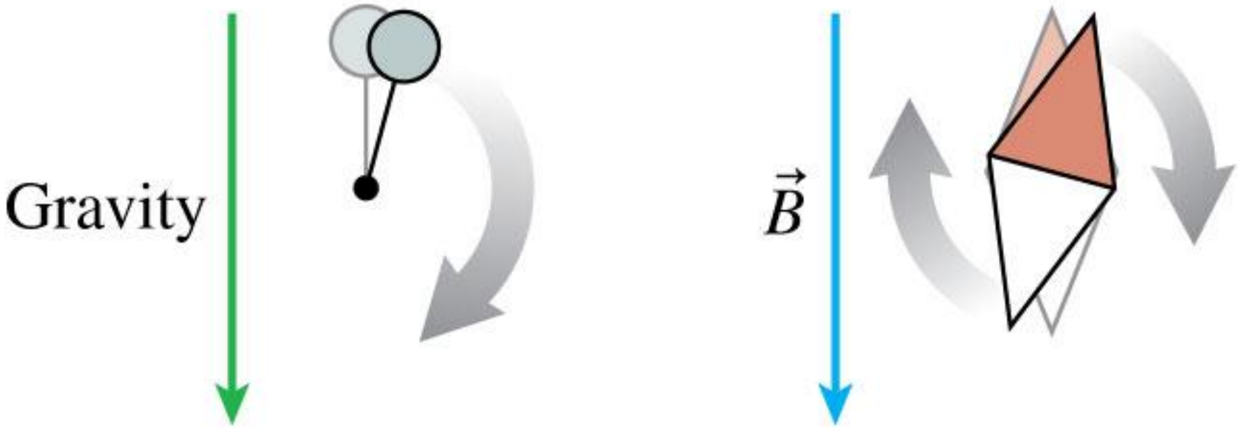
- For any dipole in a field, there are two angles for which the torque is zero, $\theta = 0°$ and $\theta = 180°$.
- $\theta = 0°$ is *stable*: The dipole will stay in this configuration.
- $\theta = 180°$ is *unstable*. The slightest rotation will result in a torque and rotate the dipole until it reaches $\theta = 0°$.
- This situation has a gravitational analogy: an upside-down pendulum.
- The unstable alignment of the dipole has a higher energy and will rotate "downhill" to the stable equilibrium of lower energy.

A Current Loop in a Uniform Field



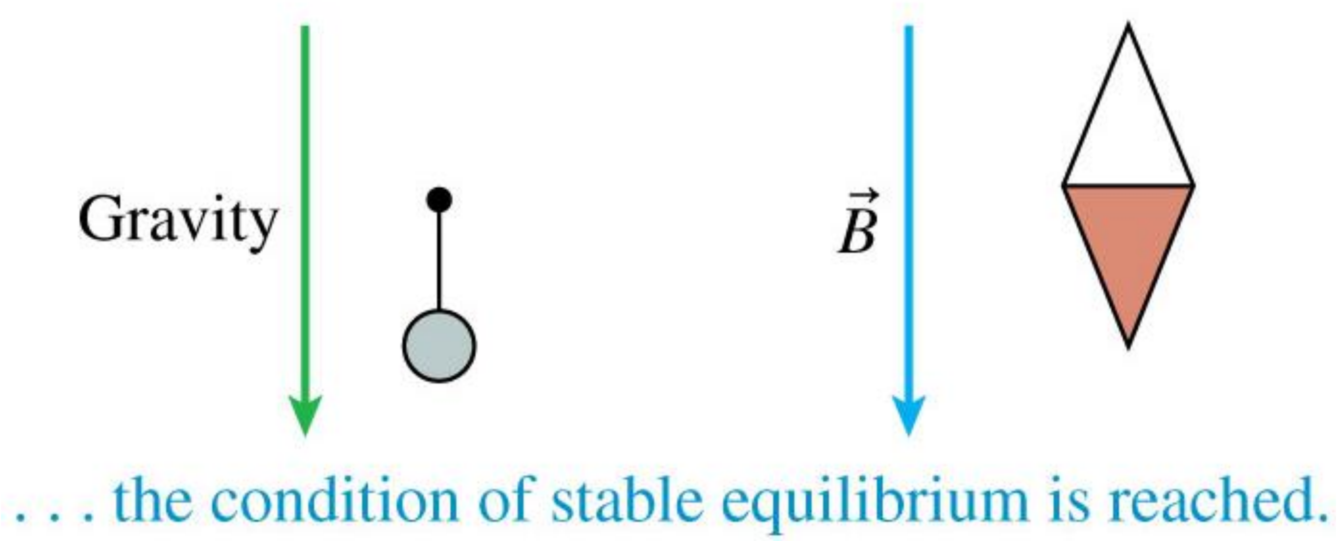
The pendulum balancing upside down and the magnet aligned opposite the field are in unstable equilibrium. A small nudge . . .

A Current Loop in a Uniform Field



. . . will lead to a torque that will cause a rotation that will continue until . . .

A Current Loop in a Uniform Field



QuickCheck 24.25

If released from rest, the current loop will

A. Move upward.
B. Move downward.
C. Rotate clockwise.
D. Rotate counterclockwise.
E. Do something not listed here.

QuickCheck 24.25

If released from rest, the current loop will

A. Move upward.
B. Move downward.
C. Rotate clockwise.
✔ D. Rotate counterclockwise.
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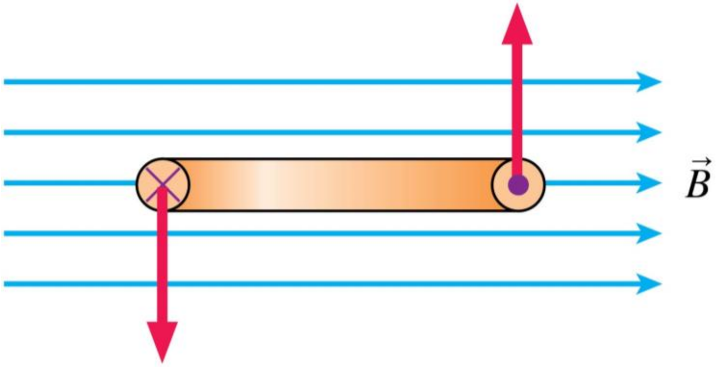
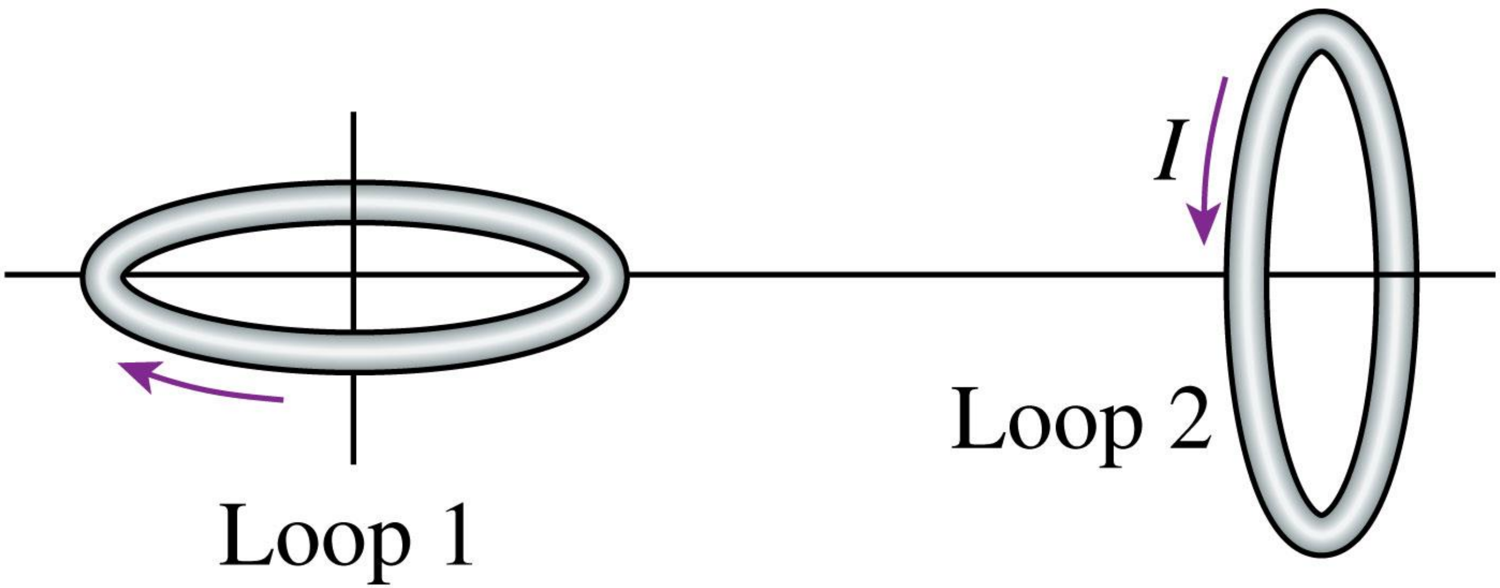


Net torque but no net force

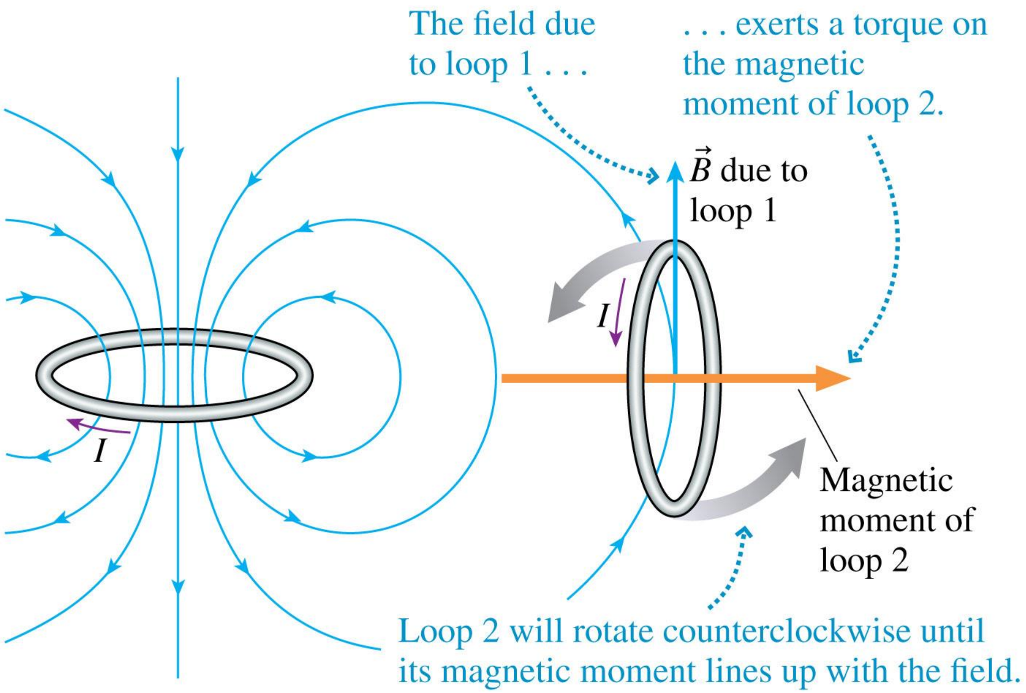
Conceptual Example 24.13 Does the loop rotate?

Two nearby current loops are oriented as shown in **FIGURE 24.49**. Loop 1 is fixed in place; loop 2 is free to rotate. Will it do so?



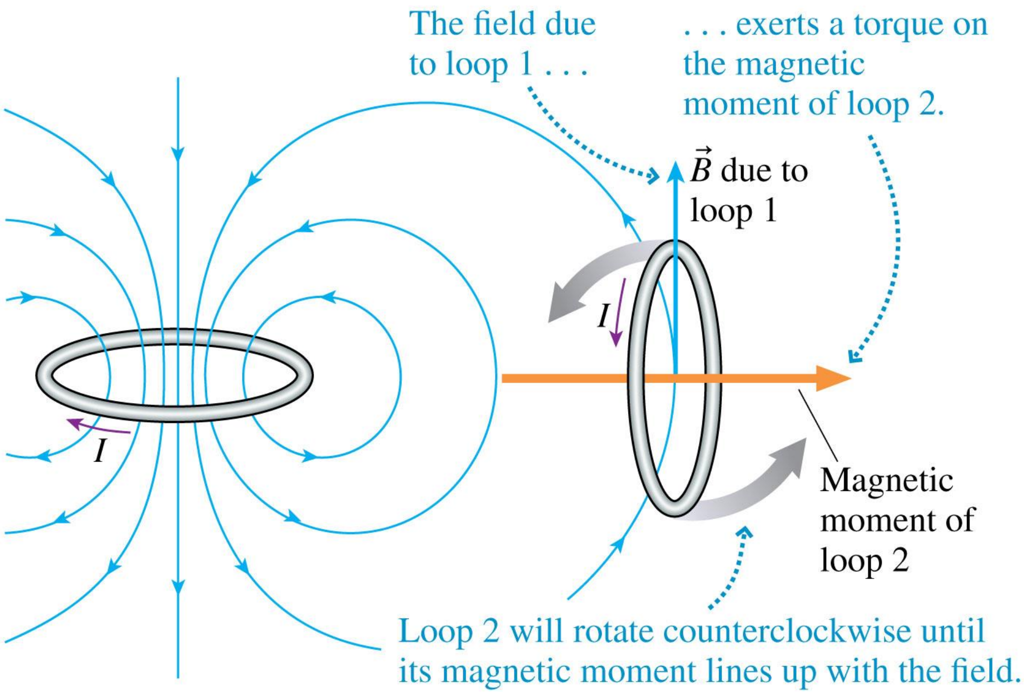
Conceptual Example 24.13 Does the loop rotate? (cont.)

REASON The current in loop 1 generates a magnetic field. As **FIGURE 24.50** shows, the field of loop 1 is upward as it passes loop 2. Because the field is perpendicular to the magnetic moment of loop 2, the field exerts a torque on loop 2 and causes loop 2 to rotate until its magnetic moment lines up with the field from loop 1.



Conceptual Example 24.13 Does the loop rotate? (cont.)

ASSESS These two loops align so that their magnetic moments point in opposite directions. We can think of this in terms of their poles: When aligned this way, the north pole of loop 1 is closest to the south pole of loop 2. This makes sense because these opposite poles attract each other.



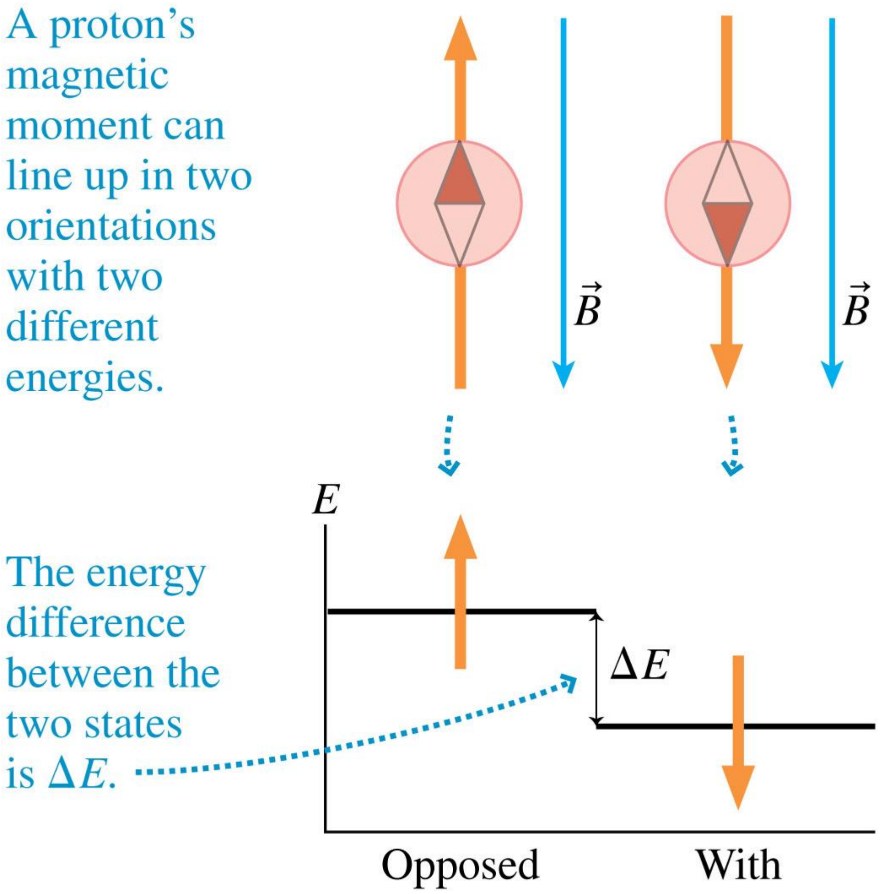
Magnetic Resonance Imaging (MRI)

- Magnetic resonance imaging is a modern diagnostic tool that provides detailed images of tissues and structures in the body with no radiation exposure.
- The key to the imaging technique is the magnetic nature of atoms.
- **The nuclei of individual atoms have magnetic moments and behave like magnetic dipoles.**
- Atoms of different elements have different magnetic moments. A magnetic field exerts different torques on different kinds of atoms.

Magnetic Resonance Imaging (MRI)

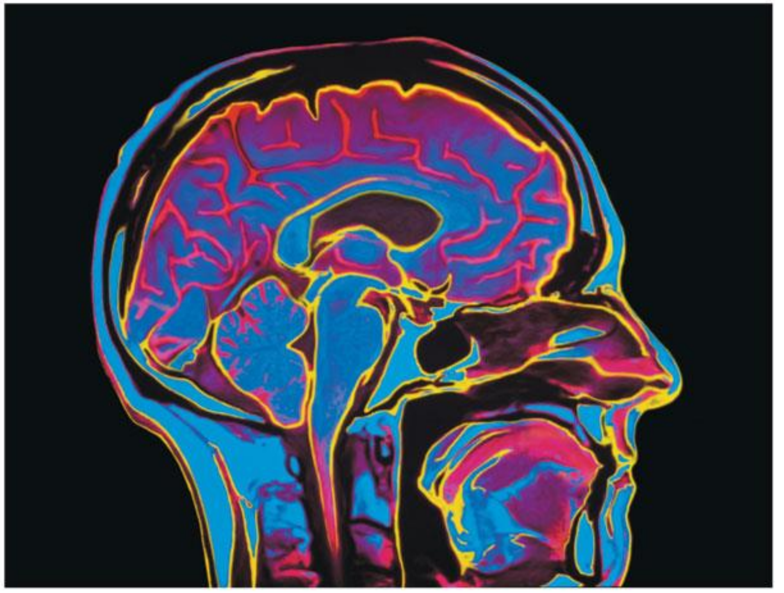
- If we consider only the hydrogen atoms in a person's body, the single proton of each hydrogen atom will align either *with the field* (the low-energy state) or *opposed to the field* (the high-energy state).

Magnetic Resonance Imaging (MRI)



- The energy difference depends on the magnetic moment of the proton and the strength of the magnetic field.

Magnetic Resonance Imaging (MRI)

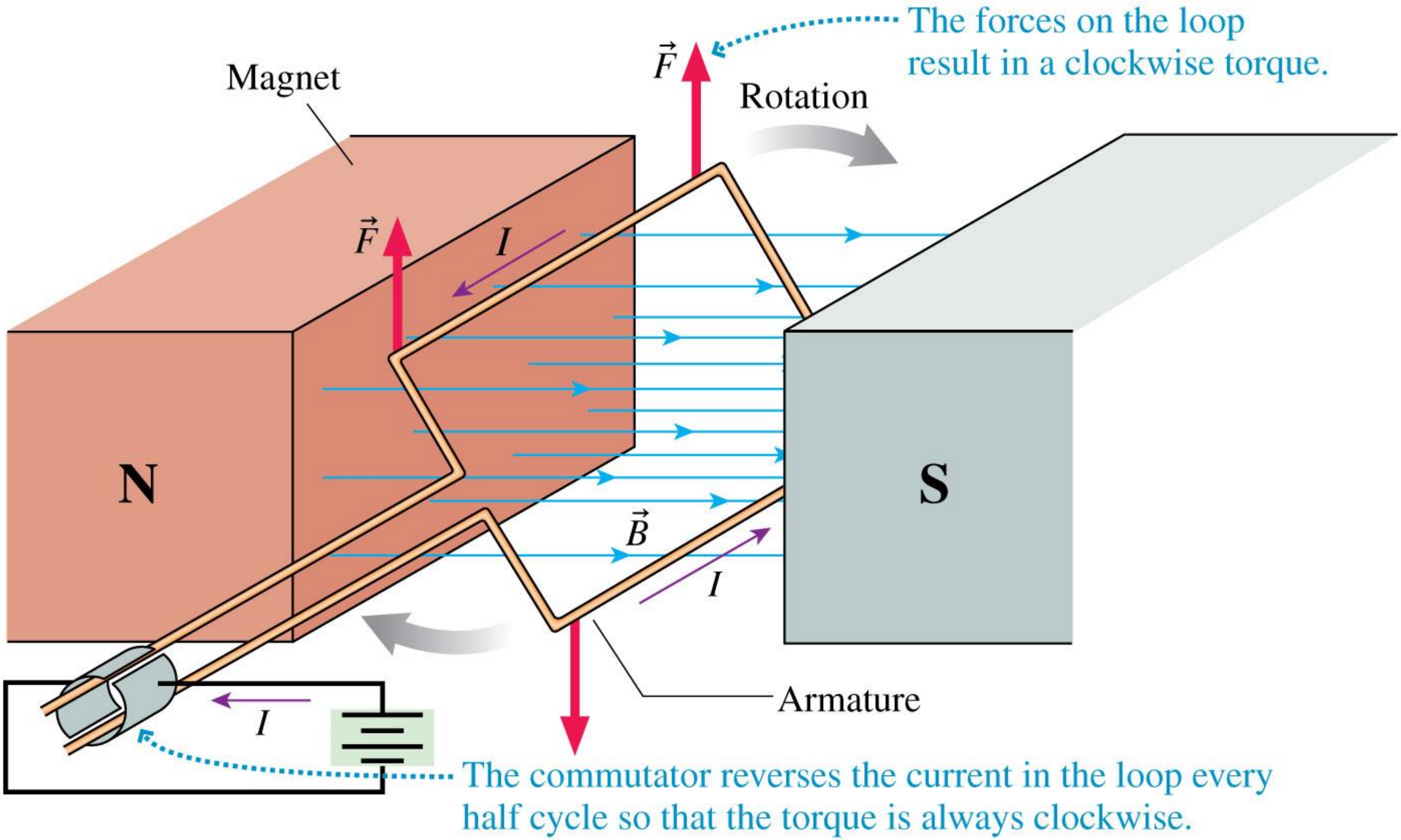


- A *probe field*, precisely tuned to the proper energy, "flips" the atom dipoles from the low energy state to the high energy state in an MRI.
- A strong signal indicates that many of the atoms of interest are present.
- Different tissues have different concentrations of atoms.
- A record of the intensity versus position of measurement gives an image of the structure of the interior of the body.

Electric Motors

- In an electric motor, a loop of wire called the *armature* is free to rotate in a strong magnetic field.
- A current in the loop causes it to feel a torque.
- The loops rotates to align itself with the external field, but the *commutator* reverses the current direction in the loop every 180°.
- When the loop is close to a stable configuration, the current switches, so the loop continues to rotate.

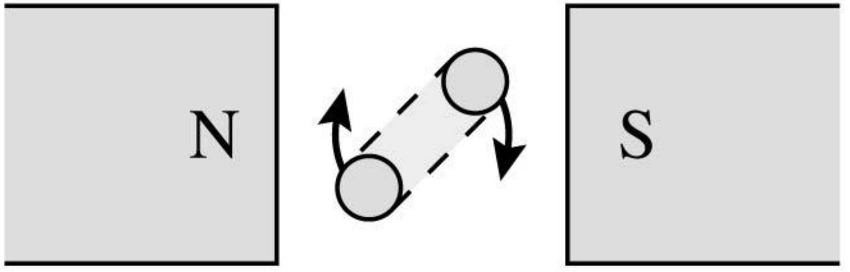
Electric Motors



QuickCheck 24.26

A current-carrying loop sits between the poles of a magnet. Magnetic forces rotate the loop as shown in the figure. From the point of view of the north pole of the magnet, the current in the loop is

A. Clockwise
B. Counterclockwise.



QuickCheck 24.26

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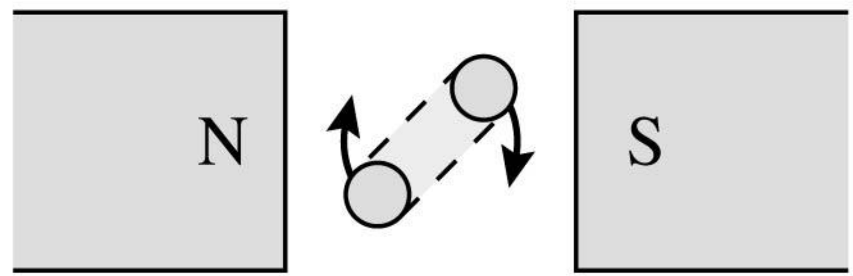
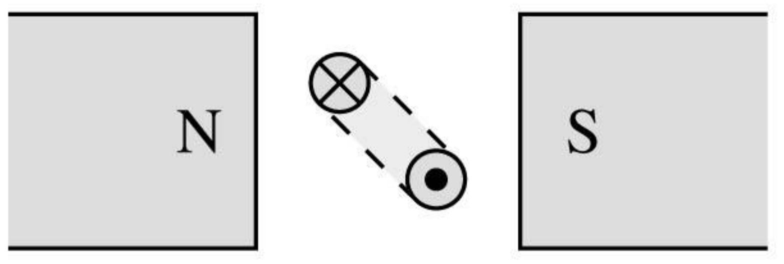


Example Problem

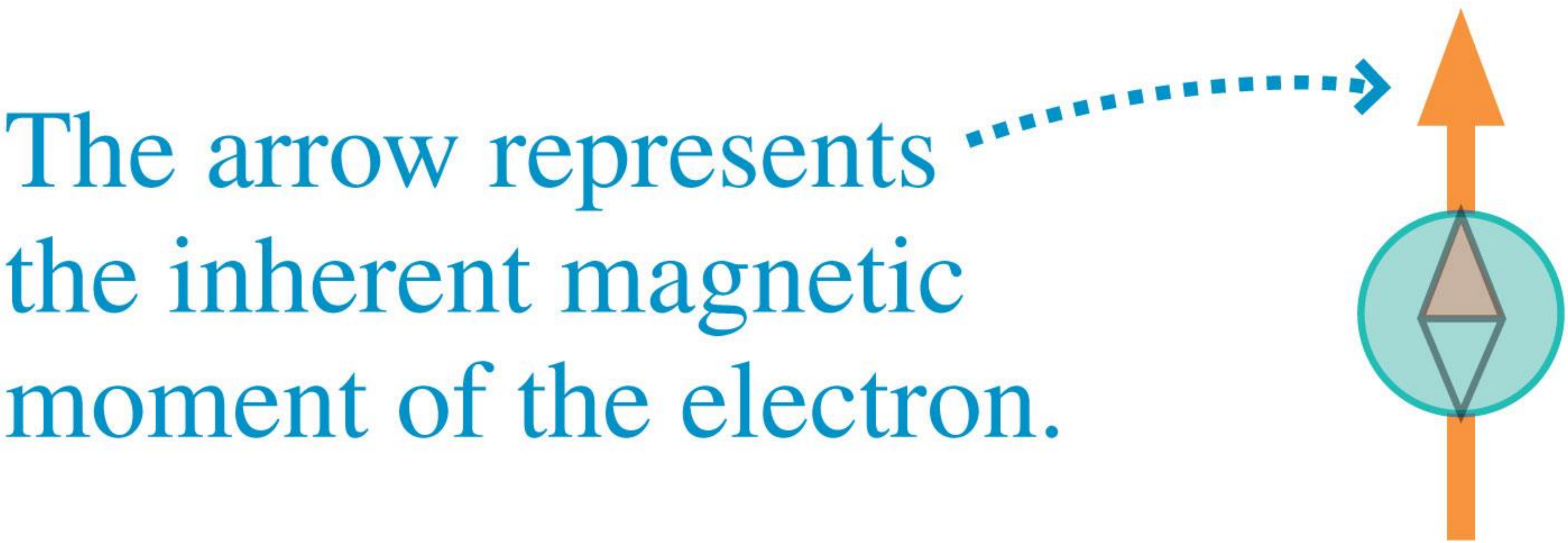
A current-carrying loop sits between the poles of a magnet. Which way will the loop rotate? Make this determination by considering the forces on different parts of the loop, then by considering the pole structure of the loop. What will be the loop's equilibrium position?



Section 24.8 Magnets and Magnetic Materials

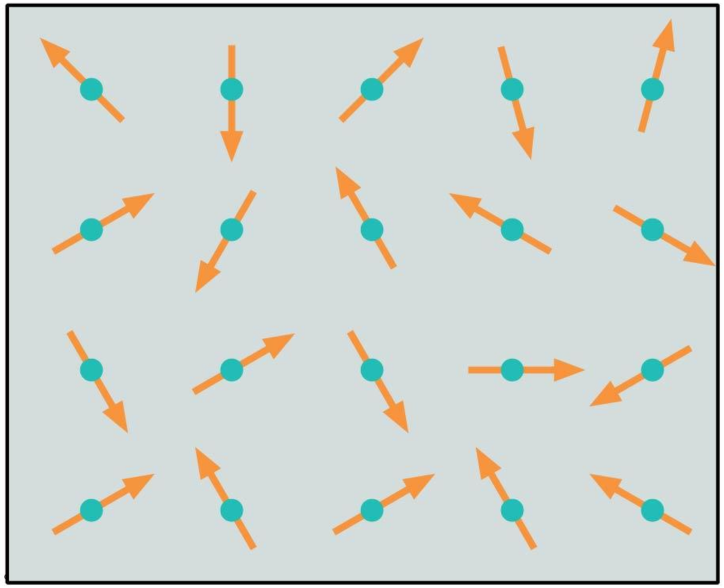
Ferromagnetism

- Materials that are strongly attracted to a magnet and that can be magnetized are called **ferromagnetic**.
- Magnetism, at an atomic level, is due to the *inherent magnetic moment* of electrons.



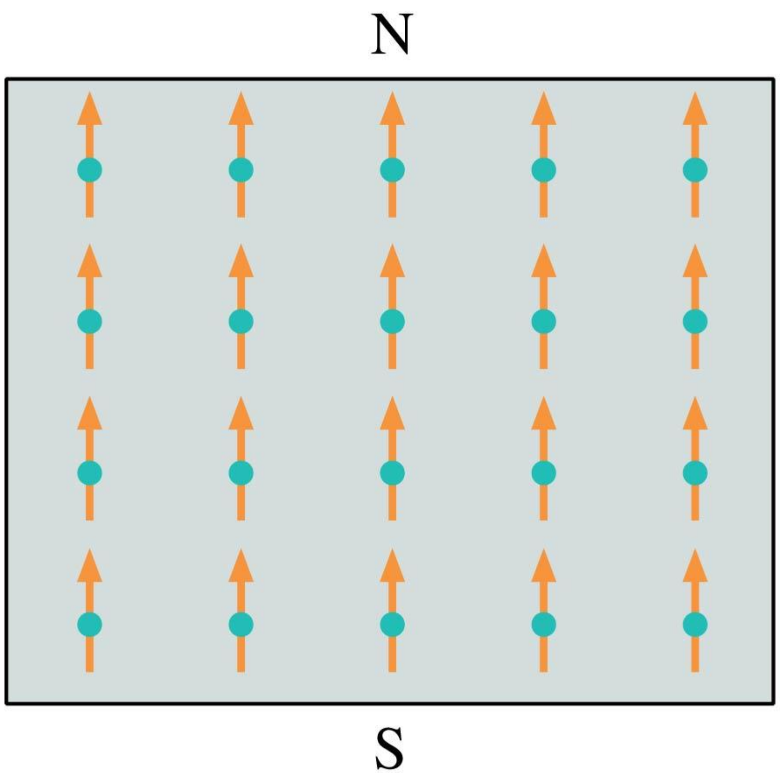
Ferromagnetism

- In most atoms with many electrons, the electrons occur in pairs with magnetic moments in opposite directions.
- Unpaired electrons are able to give an atom a net magnetic moment.
- For most elements whose atoms have magnetic moments, the moments are randomly arranged when the atoms join together to form a solid, so there is no net magnetism.



Ferromagnetism

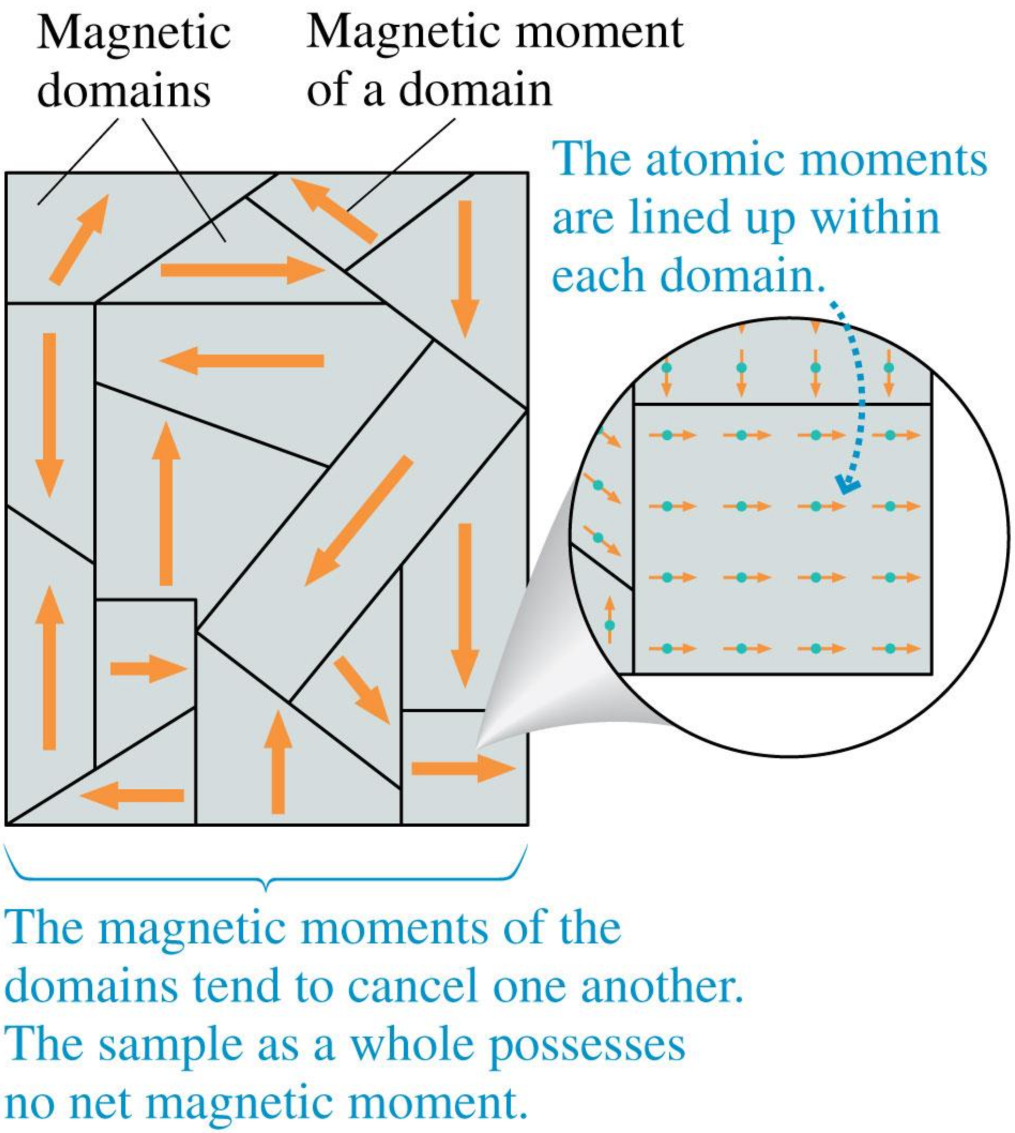
- Ferromagnetic materials have atoms with net magnetic moments that tend to line up and reinforce each other.
- This alignment of moments occurs in only a few elements and alloys.
- A piece of such a material has a north and a south magnetic pole, generates a magnetic field, and aligns parallel to an external magnetic field—it is a magnet.



Ferromagnetism

- In a large sample of a ferromagnetic material, the magnetic moments will be lined up in local regions called **domains**, but there will be no long-range ordering.
- Although the atomic magnetic moments are aligned within a domain, the magnetic moments of the individual domains will be randomly oriented, so there is no overall magnetic moment.

Ferromagnetism

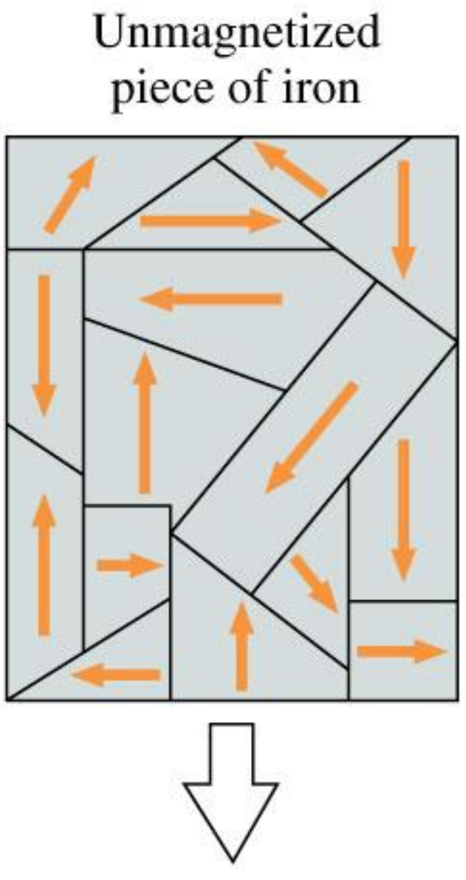


Induced Magnetic Moments

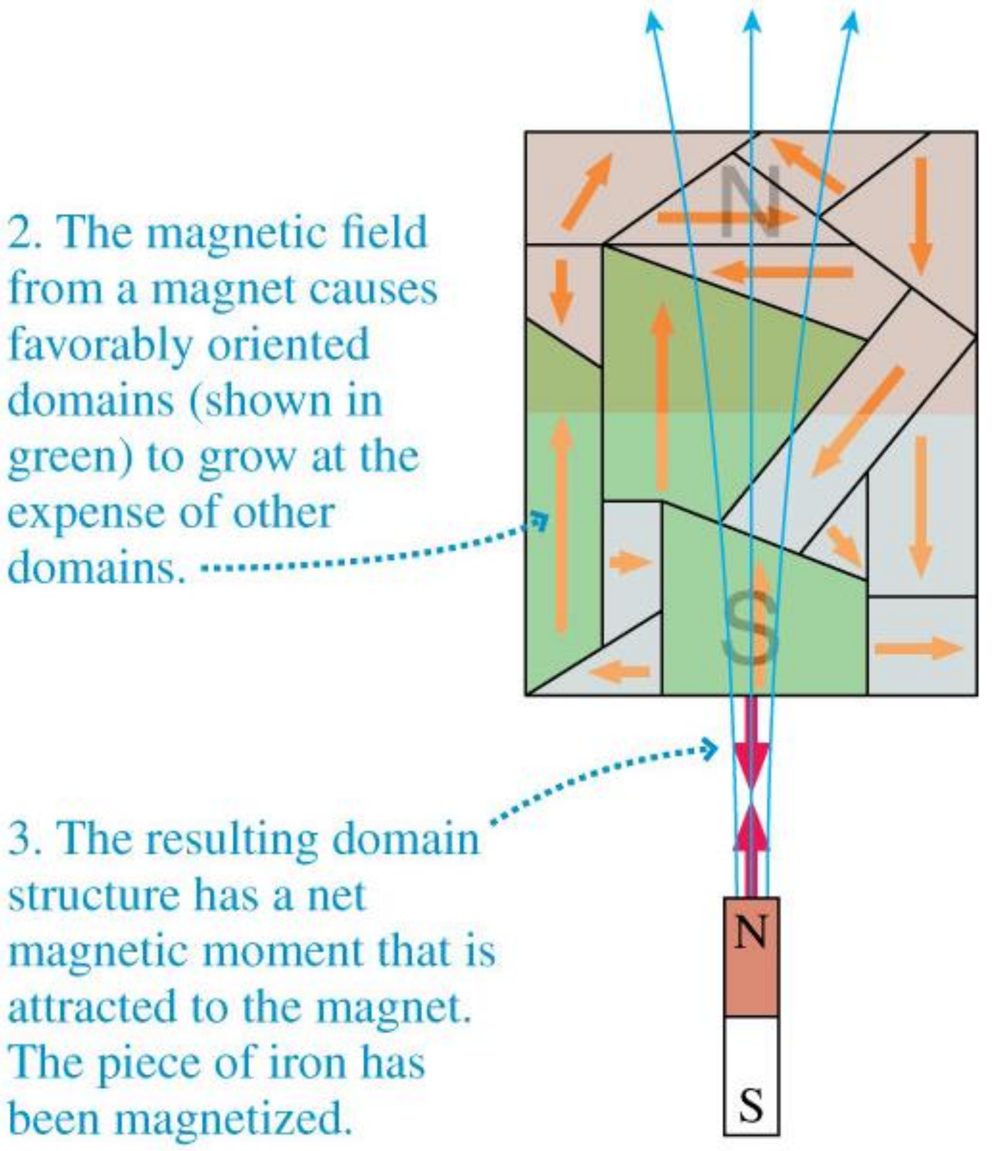
- A ferromagnetic material can develop an *induced magnetic moment* when a magnet is nearby.

Induced Magnetic Moments

1. Initially, the magnetic moments of the domains cancel each other; there is no net magnetic moment.



Induced Magnetic Moments



Induced Magnetic Moments

- We now understand why a ferromagnetic material, like iron, will be attracted to the magnet:
  1. Electrons are microscopic magnets due to their inherent magnetic moment.
  2. In a ferromagnetic material, these atomic magnetic moments are aligned. Regions of aligned moments form magnetic domains.
  3. The individual domains shift in response to an external magnetic field to produce an induced magnetic moment for the entire object, which will be attracted by the magnet that produced the orientation.

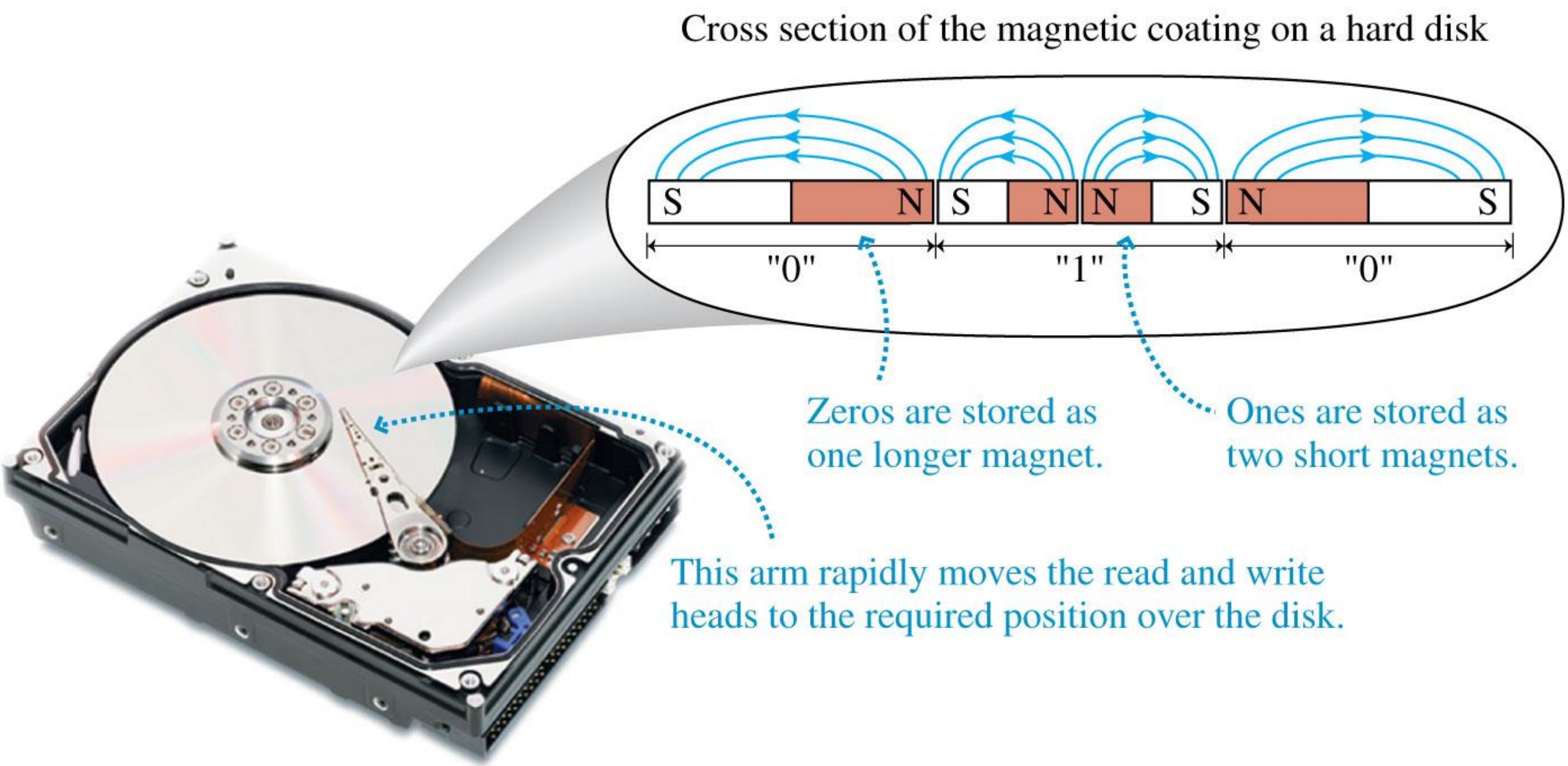
Induced Magnetic Moments

- When ferromagnetic material is near a magnet, it becomes a magnet as well.
- Once the magnetic field is taken away, the domain structure will (generally) return to where is began: The induced magnetic moment will disappear.
- *Very* strong fields can cause permanent orientation changes to some domains, which will permanently magnetize the material.

Induced Magnetic Moments

- Induced magnetic moments are used to store information on computer hard disk drives.
- The magnetic field of a tiny switchable magnet (write head) changes the orientation of the domains of the magnetic coating on the surface of the hard drive.
- This encodes information, which can be read by a small probe sensitive to the magnetic fields of the tiny domains (read head).

Induced Magnetic Moments



Electromagnets

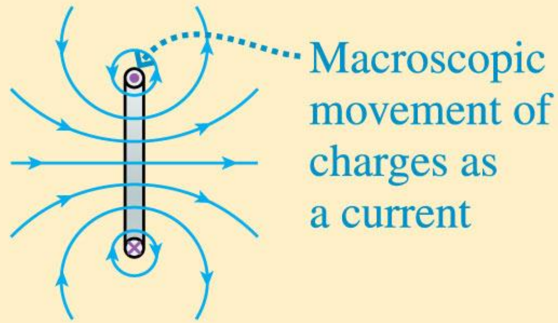
- The magnetic domains in a ferromagnetic material have a strong tendency to line up with an applied magnetic field.
- A ferromagnetic material can be used to increase the strength of the field from a current-carrying wire.
- A solenoid wound around a piece of iron will be magnetized when a current is passed through the wire, creating an **electromagnet**.
- An electromagnet can produce a field that is hundreds of times stronger than the field due to the solenoid itself.

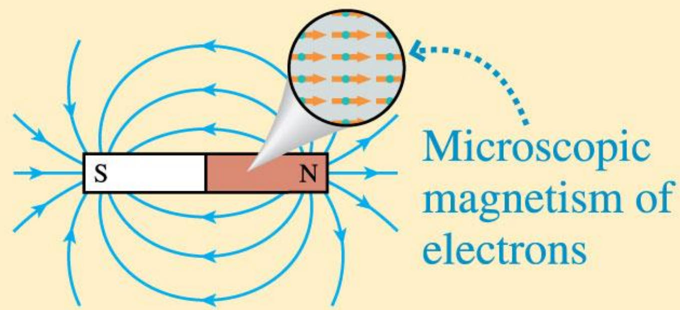
Summary: General Principles

Sources of Magnetism

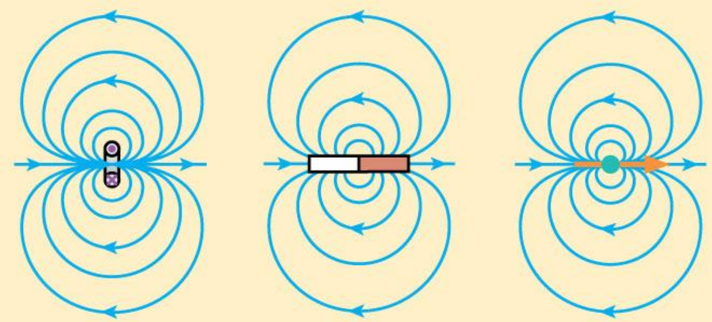
Magnetic fields can be created by either:

- Electric currents   or   • Permanent magnets





The most basic unit of magnetism is the **magnetic dipole,** which consists of a north and a south pole.



Three basic kinds of dipoles are: Current loop, Permanent magnet, Atomic magnet

Text: p. 794

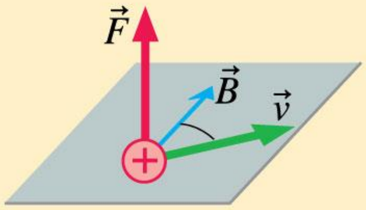
Summary: General Principles

Consequences of Magnetism

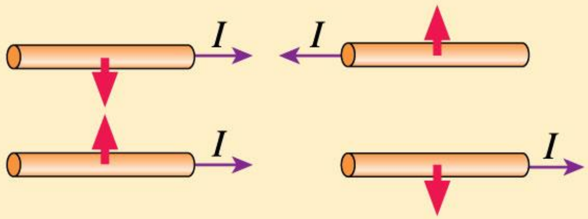
Magnetic fields exert long-range forces on magnetic materials and on moving charges or currents.

- Unlike poles of magnets attract each other; like poles repel each other.

- A magnetic field exerts a force on a moving charged particle.



- Parallel wires with currents in the same direction attract each other; when the currents are in opposite directions, the wires repel each other.



Magnetic fields exert torques on magnetic dipoles, aligning their axes with the field.

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Summary: Important Concepts

Magnetic Fields

The **direction of the magnetic field**

- is the direction in which the north pole of a compass needle points.
- due to a current can be found from the **right-hand rule for fields.**

The **strength of the magnetic field** is

- proportional to the torque on a compass needle when turned slightly from the field direction.
- measured in tesla (T).

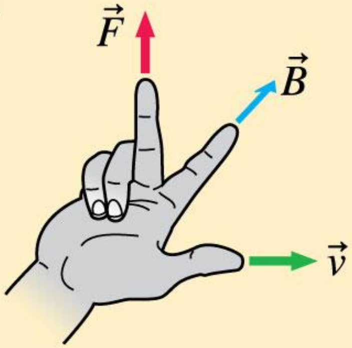
Text: p. 794

Summary: Important Concepts

Magnetic Forces and Torques

The magnitude of the magnetic force on a *moving* charge depends on its charge q, its speed v, and the angle α between the velocity and the field:

$$F = |q| vB \sin\alpha$$



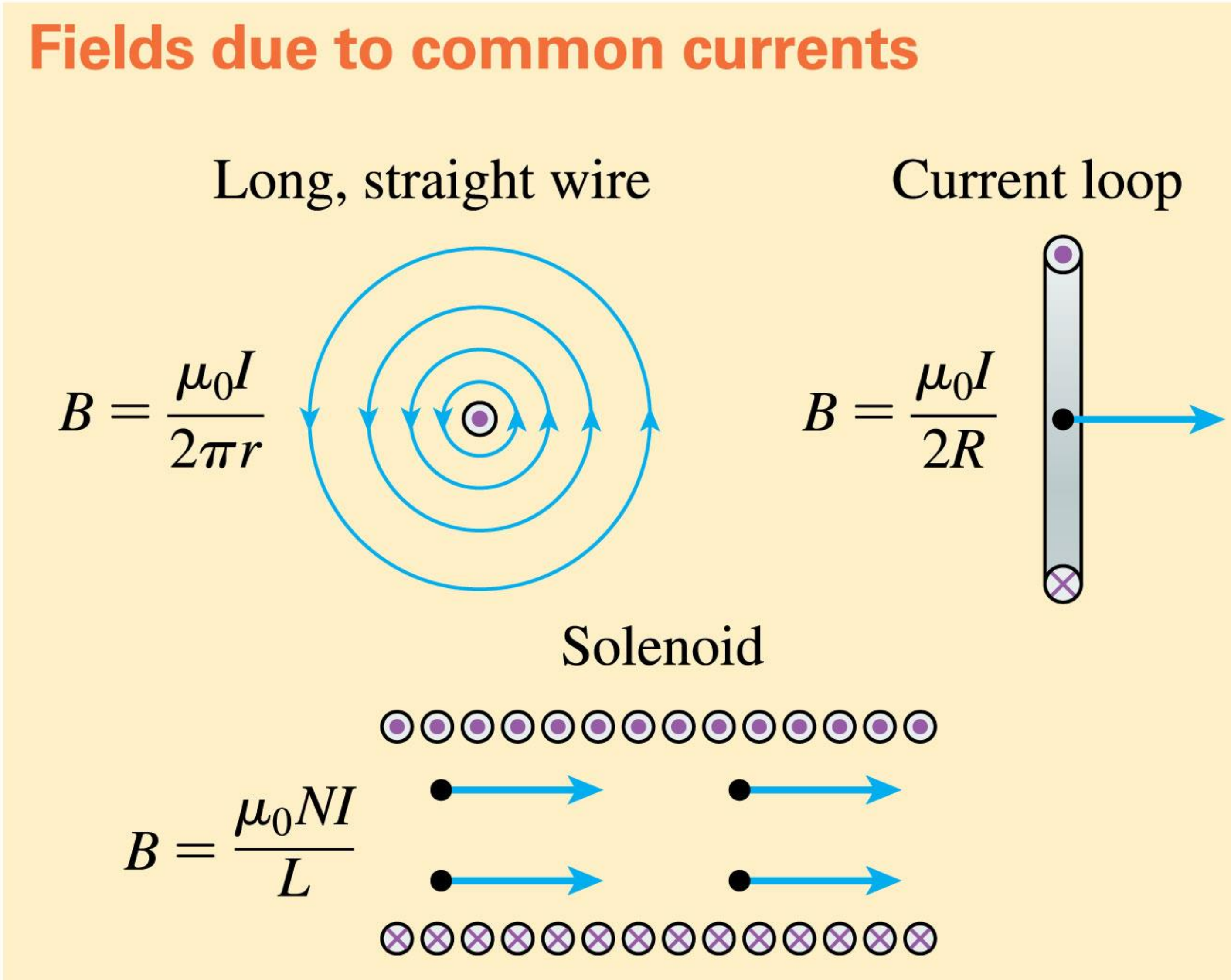
The direction of this force on a positive charge is given by the **right-hand rule for forces.**

The magnitude of the force on a *current-carrying wire* perpendicular to the magnetic field depends on the current and the length of the wire: $F = ILB$.

The torque on a *current loop* in a magnetic field depends on the current, the loop's area, and how the loop is oriented in the field: $\tau = (IA)B\sin\theta$.

Text: p. 794

Summary: Applications

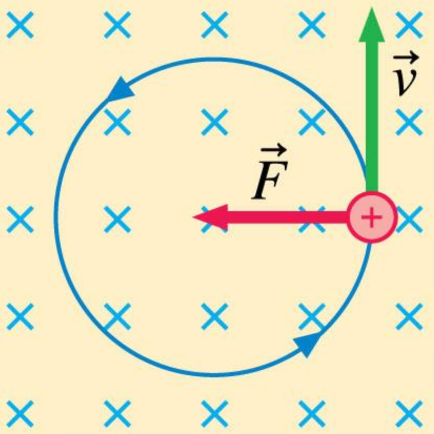


Text: p. 794

Summary: Applications

Charged-particle motion

There is no force if $\vec{v}$ is parallel to $\vec{B}$.



If $\vec{v}$ is perpendicular to $\vec{B}$, the particle undergoes uniform circular motion with radius $r = mv/|q|B$.

Text: p. 794

Summary: Applications

Stability of magnetic dipoles

A magnetic dipole is stable (in a lower energy state) when aligned with the external magnetic field. It is unstable (in a higher energy state) when aligned opposite to the field.

The probe field of an MRI scanner measures the flipping of magnetic dipoles between these two orientations.

Text: p. 794

Summary

GENERAL PRINCIPLES

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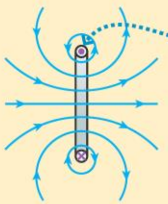

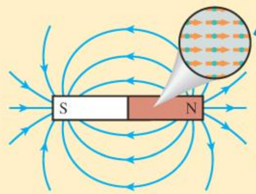

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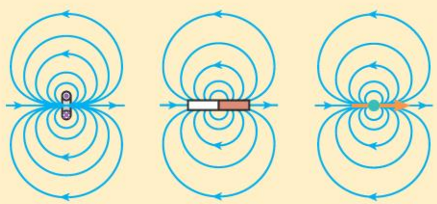

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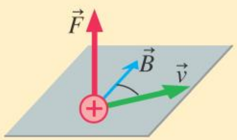
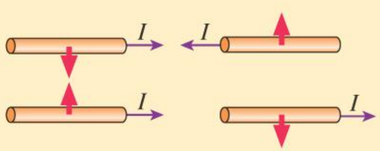


- Parallel wires with currents in the same direction attract each other; when the currents are in opposite directions, the wires repel each other.



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Text: p. 794

Summary

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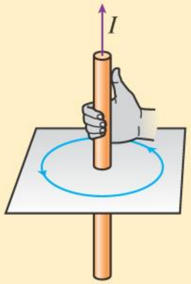

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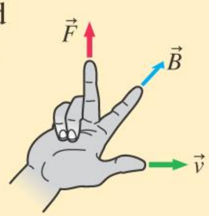

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Text: p. 794

Summary

APPLICATIONS

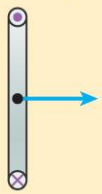
Fields due to common currents

Long, straight wire

$$B = \frac{\mu_0 I}{2\pi r}$$

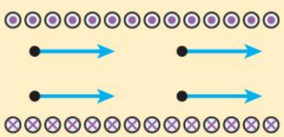
Current loop

$$B = \frac{\mu_0 I}{2R}$$



Solenoid

$$B = \frac{\mu_0 N I}{L}$$



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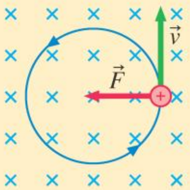

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