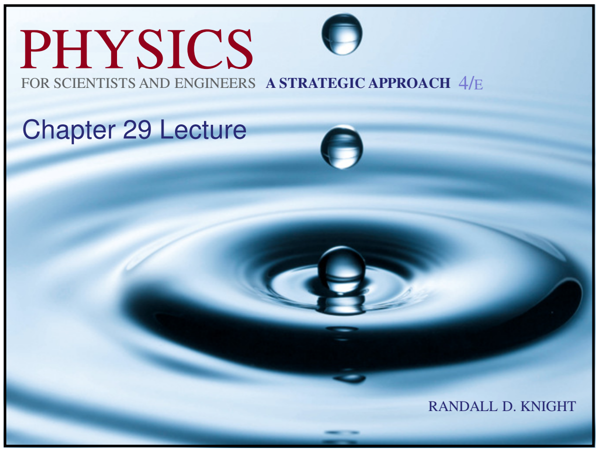


Chapter 29 The Magnetic Field

IN THIS CHAPTER, you will learn about magnetism and the magnetic field.

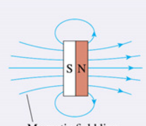
Slide 29-2

Chapter 29 Preview

What is magnetism?

Magnetism is an interaction between *moving* charges.

- Magnetic forces, similar to electric forces, are due to the action of magnetic fields.
- A magnetic field $\vec{B}$ is created by a moving charge.
- Magnetic interactions are understood in terms of magnetic poles: north and south.
- Magnetic poles never occur in isolation. All magnets are dipoles, with two poles.
- Practical magnetic fields are created by currents—collections of moving charges.
- Magnetic materials, such as iron, occur because electrons have an inherent magnetic dipole called electron spin.

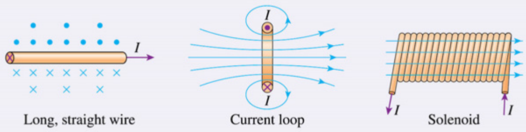


Slide 29-3

Chapter 29 Preview

What fields are especially important?

We will develop and use three important magnetic field models.

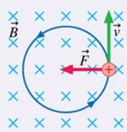


Slide 29-4

Chapter 29 Preview

How do charges respond to magnetic fields?

A charged particle *moving* in a magnetic field experiences a force perpendicular to both $\vec{B}$ and $\vec{v}$. The perpendicular force causes charged particles to move in circular orbits in a uniform magnetic field. This cyclotron motion has many important applications.



« LOOKING BACK Sections 8.2–8.3 Circular motion

« LOOKING BACK Section 12.10 The cross product

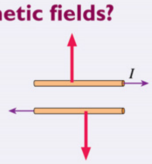
Slide 29-5

Chapter 29 Preview

How do currents respond to magnetic fields?

Currents are moving charged particles, so:

- There's a force on a current-carrying wire in a magnetic field.
- Two parallel current-carrying wires attract or repel each other.
- There's a torque on a current loop in a magnetic field. This is how motors work.



Slide 29-6

Chapter 29 Preview

Why is magnetism important?

Magnetism is much more important than a way to hold a shopping list on the refrigerator door. Motors and generators are based on magnetic forces. Many forms of data storage, from hard disks to the stripe on your credit card, are magnetic. Magnetic resonance imaging (MRI) is essential to modern medicine. Magnetic levitation trains are being built around the world. And the earth's magnetic field keeps the solar wind from sterilizing the surface. There would be no life and no modern technology without magnetism.

Chapter 29 Reading Questions

Reading Question 29.1

What is the SI unit for the strength of the magnetic field?

A. Gauss
B. Henry
C. Tesla
D. Becquerel
E. Bohr magneton

Reading Question 29.1

What is the SI unit for the strength of the magnetic field?

A. Gauss
B. Henry
✔ **C. Tesla**
D. Becquerel
E. Bohr magneton

Slide 29-10

Reading Question 29.2

What is the *shape* of the trajectory that a charged particle follows in a uniform magnetic field?

A. Helix
B. Parabola
C. Circle
D. Ellipse
E. Hyperbola

Slide 29-11

Reading Question 29.2

What is the *shape* of the trajectory that a charged particle follows in a uniform magnetic field?

✔ **A. Helix**
B. Parabola
C. Circle
D. Ellipse
E. Hyperbola

Slide 29-12

Reading Question 29.3

The magnetic field of a point charge is given by

A. Biot-Savart's law.
B. Faraday's law.
C. Gauss's law.
D. Ampère's law.
E. Einstein's law.

Reading Question 29.3

The magnetic field of a point charge is given by

✔**A. Biot-Savart's law.**
B. Faraday's law.
C. Gauss's law.
D. Ampère's law.
E. Einstein's law.

Reading Question 29.4

The magnetic field of a straight, current-carrying wire is

A. Parallel to the wire.
B. Inside the wire.
C. Perpendicular to the wire.
D. Around the wire.
E. Zero.

Reading Question 29.4

The magnetic field of a straight, current-carrying wire is

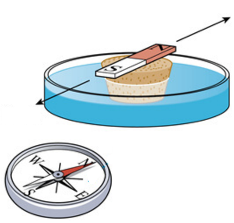
A. Parallel to the wire.
B. Inside the wire.
C. Perpendicular to the wire.
✔**D. Around the wire.**
E. Zero.

Slide 29-16

Chapter 29 Content, Examples, and QuickCheck Questions

Slide 29-17

Discovering Magnetism: Experiment 1



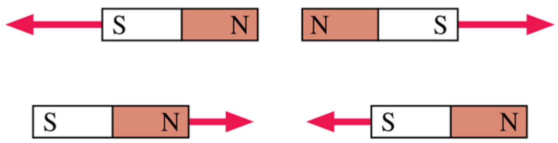
- Tape a bar magnet to a piece of cork and allow it to float in a dish of water.
- It always turns to align itself in an approximate north-south direction.

- The end of a magnet that points north is called the *north-seeking pole*, or simply the **north pole**.
- The end of a magnet that points south is called the **south pole**.

Slide 29-18

Discovering Magnetism: Experiment 2

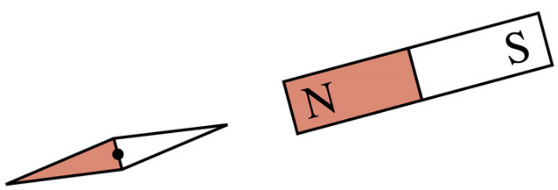
- If the north pole of one magnet is brought near the north pole of another magnet, they repel each other.
- Two south poles also repel each other, but the north pole of one magnet exerts an attractive force on the south pole of another magnet.



Slide 29-19

Discovering Magnetism: Experiment 3

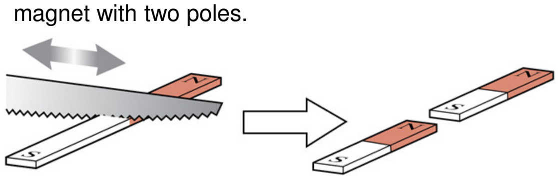
- The north pole of a bar magnet attracts one end of a compass needle and repels the other.
- Apparently the compass needle itself is a little bar magnet with a north pole and a south pole.



Slide 29-20

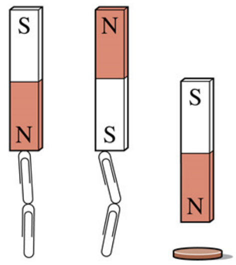
Discovering Magnetism: Experiment 4

- Cutting a bar magnet in half produces two weaker but still complete magnets, each with a north pole and a south pole.
- No matter how small the magnets are cut, even down to microscopic sizes, each piece remains a complete magnet with two poles.



Slide 29-21

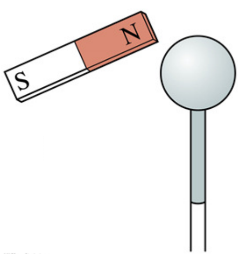
Discovering Magnetism: Experiment 5



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

Slide 29-22

Discovering Magnetism: Experiment 6



- A magnet does not affect an electroscope.
- A charged rod exerts a weak *attractive* force on *both* ends of a magnet.
- However, the force is the same as the force on a metal bar that isn't a magnet, so it is simply a polarization force like the ones we studied in Chapter 22.
- Other than polarization forces, charges have *no effects* on magnets.

Slide 29-23

What Do These Experiments Tell Us?

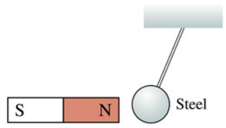
1. Magnetism is *not* the same as electricity.
2. Magnetism is a long range force.
3. All magnets have two poles, called north and south poles. Two like poles exert repulsive forces on each other; two opposite poles attract.
4. The poles of a bar magnet can be identified by using it as a compass. The north pole tends to rotate to point approximately north.
5. Materials that are attracted to a magnet are called **magnetic materials**. The most common magnetic material is iron.

Slide 29-24

QuickCheck 29.1

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.

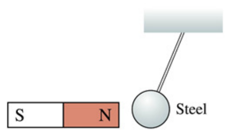


Slide 29-25

QuickCheck 29.1

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.

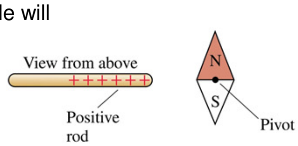


Slide 29-26

QuickCheck 29.2

The compass needle can rotate on a pivot in a horizontal plane. If a positively charged rod is brought near, as shown, the compass needle will

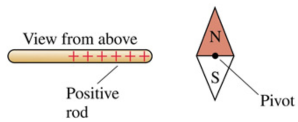
A. Rotate clockwise.
B. Rotate counterclockwise.
C. Do nothing.
D. I'm not sure.



Slide 29-27

QuickCheck 29.2

The compass needle can rotate on a pivot in a horizontal plane. If a positively charged rod is brought near, as shown, the compass needle will

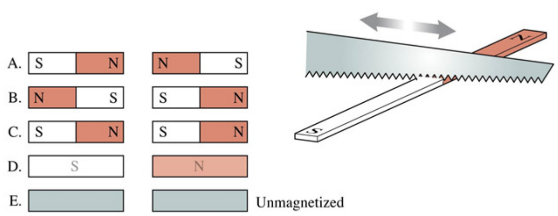


A. Rotate clockwise.
B. Rotate counterclockwise.
✔**C. Do nothing.**
D. I'm not sure.

Magnetic poles are ***not*** the same as electric charges.

QuickCheck 29.3

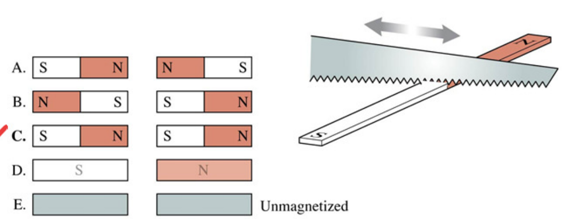
If a bar magnet is cut in half, you end up with



QuickCheck 29.3

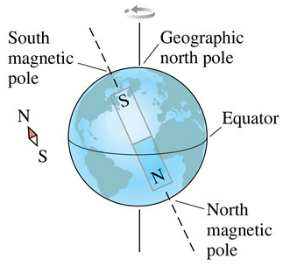
If a bar magnet is cut in half, you end up with

✔



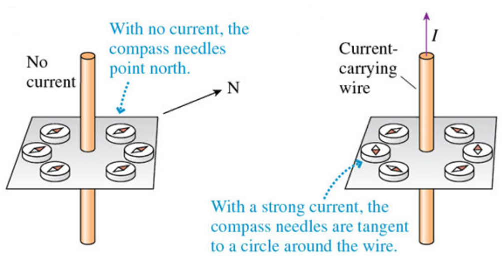
Compasses and Geomagnetism

- Due to currents in the molten iron core, the earth itself acts as a large magnet.
- The poles are slightly offset from the poles of the rotation axis.
- The geographic north pole is actually a *south* magnetic pole!



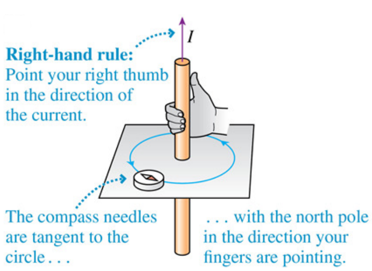
Electric Current Causes a Magnetic Field

- In 1819 Hans Christian Oersted discovered that an electric current in a wire causes a compass to turn.

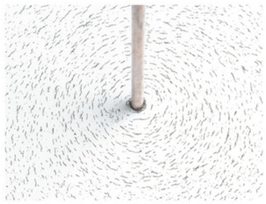


Electric Current Causes a Magnetic Field

- The **right-hand rule** determines the orientation of the compass needles to the direction of the current.



Electric Current Causes a Magnetic Field

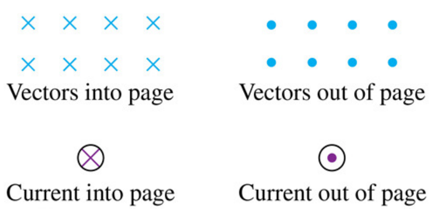


- The magnetic field is revealed by the pattern of iron filings around a current-carrying wire.

Slide 29-34

Notation for Vectors and Currents Perpendicular to the Page

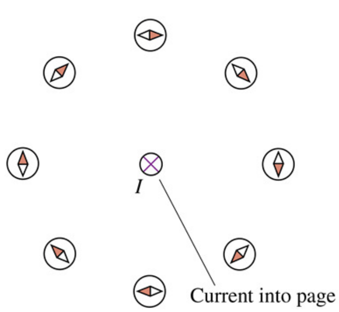
- Magnetism requires a three-dimensional perspective, but two-dimensional figures are easier to draw.
- We will use the following notation:



Slide 29-35

Electric Current Causes a Magnetic Field

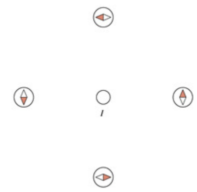
- The **right-hand rule** determines the orientation of the compass needles to the direction of the current.



Slide 29-36

QuickCheck 29.4

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

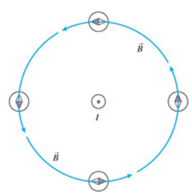


A. Into the screen.
B. Out of the screen.
C. There is no current in the wire.
D. Not enough info to tell the direction.

Slide 29-37

QuickCheck 29.4

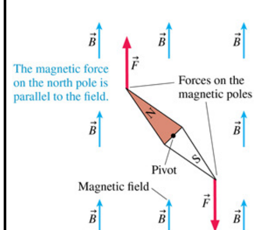
A long, straight wire extends into and out of the screen. The current in the wire is



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

Slide 29-38

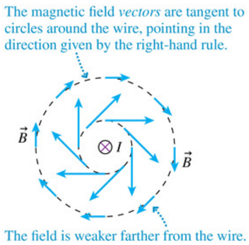
Magnetic Force on a Compass



- The figure shows a compass needle in a magnetic field.
- A magnetic force is exerted on each of the two poles of the compass, parallel to $\vec{B}$ for the north pole and opposite $\vec{B}$ for the south pole.
- This pair of opposite forces exerts a torque on the needle, rotating the needle until it is parallel to the magnetic field at that point.

Slide 29-39

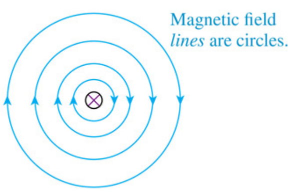
Electric Current Causes a Magnetic Field



- Because compass needles align with the magnetic field, the magnetic field at each point must be tangent to a circle around the wire.
- The figure shows the magnetic field by drawing field vectors.
- Notice that the field is weaker (shorter vectors) at greater distances from the wire.

Slide 29-40

Electric Current Causes a Magnetic Field



- Magnetic field lines are imaginary lines drawn through a region of space so that:
  - A tangent to a field line is in the direction of the magnetic field.
  - The field lines are closer together where the magnetic field strength is larger.

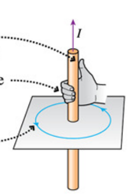
Slide 29-41

Tactics: Right-Hand Rule for Fields

TACTICS BOX 29.1 MP

Right-hand rule for fields

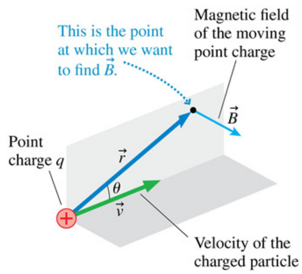
1. Point your *right* thumb in the direction of the current.
2. Curl your fingers around the wire to indicate a circle.
3. Your fingers point in the direction of the magnetic field lines around the wire.



Exercises 6–8

Slide 29-42

The Source of the Magnetic Field: Moving Charges



- The magnetic field of a charged particle q moving with velocity v is given by the **Biot-Savart law**:

$$\vec{B}_{\text{point charge}} = \left(\frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}, \text{direction given by the right-hand rule}\right)$$

 Slide 29-43

The Magnetic Field

$$\vec{B}_{\text{point charge}} = \left(\frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}, \text{direction given by the right-hand rule}\right)$$

- The constant μ_0 in the Biot-Savart law is called the **permeability constant**:

$$\mu_0 = 4\pi \times 10^{-7}\ \text{T m/A} = 1.257 \times 10^{-6}\ \text{T m/A}$$

- The SI unit of magnetic field strength is the tesla, abbreviated as T:

$$1\ \text{tesla} = 1\ \text{T} = 1\ \text{N/A m}$$

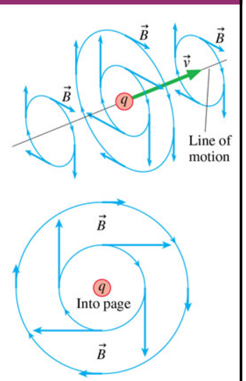
TABLE 29.1 Typical magnetic field strengths

Field source	Field strength (T)
Surface of the earth	5×10^{-5}
Refrigerator magnet	5×10^{-3}
Laboratory magnet	0.1 to 1
Superconducting magnet	10

 Slide 29-44

Magnetic Field of a Moving Positive Charge

- The right-hand rule for finding the direction of $\vec{B}$ due to a moving positive charge is similar to the rule used for a current carrying wire.
- Note that the component of $\vec{B}$ parallel to the line of motion is zero.



 Slide 29-45

Example 29.1 The Magnetic Field of a Proton

EXAMPLE 29.1 **The magnetic field of a proton**

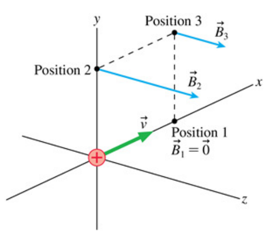
A proton moves with velocity $\vec{v} = 1.0 \times 10^7\,\hat{\imath}$ m/s. As it passes the origin, what is the magnetic field at the (x, y, z) positions (1 mm, 0 mm, 0 mm), (0 mm, 1 mm, 0 mm), and (1 mm, 1 mm, 0 mm)?

MODEL The magnetic field is that of a moving charged particle.

Example 29.1 The Magnetic Field of a Proton

EXAMPLE 29.1 **The magnetic field of a proton**

VISUALIZE FIGURE 29.9 shows the geometry. The first point is on the x-axis, directly in front of the proton, with $\theta_1 = 0°$. The second point is on the y-axis, with $\theta_2 = 90°$, and the third is in the xy-plane.



Example 29.1 The Magnetic Field of a Proton

EXAMPLE 29.1 **The magnetic field of a proton**

SOLVE Position 1, which is along the line of motion, has $\theta_1 = 0°$. Thus $\vec{B}_1 = \vec{0}$. Position 2 (at 0 mm, 1 mm, 0 mm) is at distance $r_2 = 1$ mm $= 0.001$ m. Equation 29.1, the Biot-Savart law, gives us the magnetic field strength at this point as

$$B = \frac{\mu_0}{4\pi}\frac{qv\sin\theta_2}{r_2^2}$$

$$= \frac{4\pi \times 10^{-7}\ \mathrm{T\,m/A}}{4\pi}\frac{(1.60 \times 10^{-19}\,\mathrm{C})(1.0 \times 10^7\ \mathrm{m/s})\sin 90°}{(0.0010\ \mathrm{m})^2}$$

$$= 1.60 \times 10^{-13}\ \mathrm{T}$$

Example 29.1 The Magnetic Field of a Proton

EXAMPLE 29.1 **The magnetic field of a proton**

SOLVE According to the right-hand rule, the field points in the positive z-direction. Thus

$$\vec{B}_2 = 1.60 \times 10^{-13}\,\hat{k}\text{ T}$$

where $\hat{k}$ is the unit vector in the positive z-direction. The field at position 3, at (1 mm, 1 mm, 0 mm), also points in the z-direction, but it is weaker than at position 2 both because r is larger *and* because θ is smaller. From geometry we know $r_3 = \sqrt{2}$ mm $= 0.00141$ m and $\theta_3 = 45°$. Another calculation using Equation 29.1 gives

$$\vec{B}_3 = 0.57 \times 10^{-13}\,\hat{k}\text{ T}$$

ASSESS The magnetic field of a single moving charge is *very* small.

Slide 29-49

Superposition of Magnetic Fields

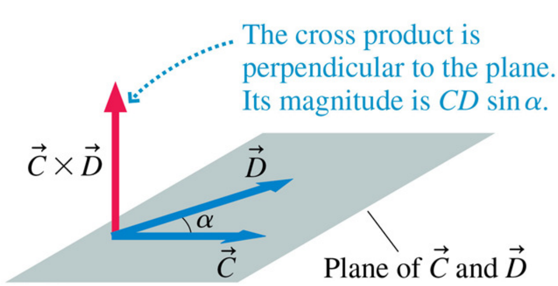
- Magnetic fields, like electric fields, have been found experimentally to obey the principle of superposition.
- If there are n moving point charges, the net magnetic field is given by the vector sum:

$$\vec{B}_{\text{total}} = \vec{B}_1 + \vec{B}_2 + \cdots + \vec{B}_n$$

- The principle of superposition will be the basis for calculating the magnetic fields of several important current distributions.

Slide 29-50

The Cross Product



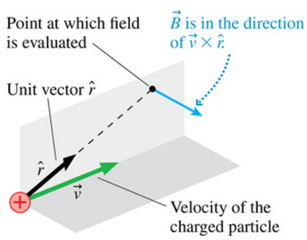
$\vec{C}\times\vec{D}$ = ($CD\sin\alpha$, direction given by the right-hand rule)

Slide 29-51

Magnetic Field of a Moving Charge

- The magnetic field of a charged particle q moving with velocity $\vec{v}$ is given by the **Biot-Savart law**:

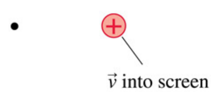
$$\vec{B}_{\text{point charge}} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \quad \text{(magnetic field of a point charge)}$$



QuickCheck 29.5

What is the direction of the magnetic field at the position of the dot?

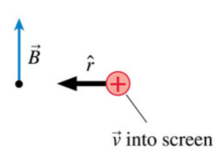
A. Into the screen
B. Out of the screen
C. Up
D. Down
E. Left



QuickCheck 29.5

What is the direction of the magnetic field at the position of the dot?

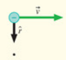
A. Into the screen
B. Out of the screen
✔C. **Up** Direction of $\vec{v}\times\hat{r}$
D. Down
E. Left



Example 29.2 The Magnetic Field Direction of a Moving Electron

EXAMPLE 29.2 **The magnetic field direction of a moving electron**

The electron in FIGURE 29.12 is moving to the right. What is the direction of the electron's magnetic field at the dot?

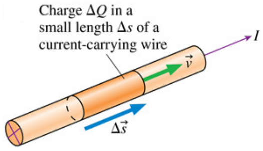


► FIGURE 29.12 A moving electron.

VISUALIZE Because the charge is negative, the magnetic field points *opposite* the direction of $\vec{v} \times \hat{r}$. Unit vector $\hat{r}$ points from the charge toward the dot. We can use the right-hand rule to find that $\vec{v} \times \hat{r}$ points *into* the page. Thus the electron's magnetic field at the dot points *out* of the page.

 Slide 29-55

The Magnetic Field of a Current



- The figure shows a current-carrying wire.
- The wire as a whole is electrically neutral, but current I represents the motion of positive charge carriers through the wire:

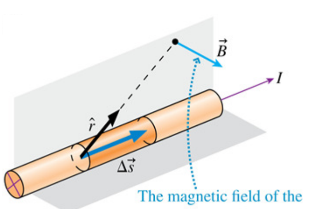
$$(\Delta Q)\vec{v} = \Delta Q\frac{\Delta\vec{s}}{\Delta t} = \frac{\Delta Q}{\Delta t}\Delta\vec{s} = I\,\Delta\vec{s}$$

 Slide 29-56

The Magnetic Field of a Current

$$\vec{B}_{\text{current segment}} = \frac{\mu_0}{4\pi}\frac{I\,\Delta\vec{s} \times \hat{r}}{r^2}$$

(magnetic field of a very short segment of current)



 Slide 29-57

The Magnetic Field of a Current

- The magnetic field of a long, straight wire carrying current I at a distance r from the wire is

$$B_{\text{wire}} = \frac{\mu_0}{2\pi}\frac{I}{r} \quad \text{(long, straight wire)}$$

- The magnetic field at the center of a coil of N turns and radius R, carrying a current I is

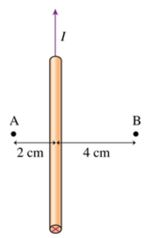
$$B_{\text{coil center}} = \frac{\mu_0}{2}\frac{NI}{R} \quad \text{(}N\text{-turn current loop)}$$

Slide 29-58

QuickCheck 29.6

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.

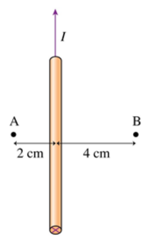


Slide 29-59

QuickCheck 29.6

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.



Slide 29-60

Problem-Solving Strategy: The Magnetic Field of a Current

PROBLEM-SOLVING STRATEGY 29.1

The magnetic field of a current

MODEL Model the wire as a simple shape.

VISUALIZE For the pictorial representation:

- Draw a picture, establish a coordinate system, and identify the point P at which you want to calculate the magnetic field.
- Divide the current-carrying wire into small segments for which you *already know* how to determine $\vec{B}$. This is usually, though not always, a division into very short segments of length Δs.
- Draw the magnetic field vector for one or two segments. This will help you identify distances and angles that need to be calculated.

Problem-Solving Strategy: The Magnetic Field of a Current

PROBLEM-SOLVING STRATEGY 29.1

The magnetic field of a current

SOLVE The mathematical representation is $\vec{B}_{net} = \Sigma \vec{B}_i$.

- Write an algebraic expression for *each* of the three components of $\vec{B}$ (unless you are sure one or more is zero) at point P. Let the (x, y, z)-coordinates of the point remain as variables.
- Express all angles and distances in terms of the coordinates.
- Let $\Delta s \rightarrow ds$ and the sum become an integral. Think carefully about the integration limits for this variable; they will depend on the boundaries of the wire and on the coordinate system you have chosen to use.

ASSESS Check that your result is consistent with any limits for which you know what the field should be.

Example 29.4 The Magnetic Field Strength Near a Heater Wire

EXAMPLE 29.4 **The magnetic field strength near a heater wire**

A 1.0-m-long, 1.0-mm-diameter nichrome heater wire is connected to a 12 V battery. What is the magnetic field strength 1.0 cm away from the wire?

MODEL 1 cm is much less than the 1 m length of the wire, so model the wire as infinitely long.

Example 29.4 The Magnetic Field Strength Near a Heater Wire

EXAMPLE 29.4 **The magnetic field strength near a heater wire**

SOLVE The current through the wire is $I = \Delta V_{bat}/R$, where the wire's resistance R is

$$R = \frac{\rho L}{A} = \frac{\rho L}{\pi r^2} = 1.91\ \Omega$$

The nichrome resistivity $\rho = 1.50 \times 10^{-6}\ \Omega\,\text{m}$ was taken from Table 27.2. Thus the current is $I = (12\ \text{V})/(1.91\ \Omega) = 6.28\ \text{A}$. The magnetic field strength at distance $d = 1.0\ \text{cm} = 0.010\ \text{m}$ from the wire is

$$B_{wire} = \frac{\mu_0}{2\pi}\frac{I}{d} = (2.0 \times 10^{-7}\ \text{T m/A})\frac{6.28\ \text{A}}{0.010\ \text{m}} = 1.3 \times 10^{-4}\ \text{T}$$

ASSESS The magnetic field of the wire is slightly more than twice the strength of the earth's magnetic field.

 Slide 29-64

Example 29.6 Matching the Earth's Magnetic Field

EXAMPLE 29.6 **Matching the earth's magnetic field**

What current is needed in a 5-turn, 10-cm-diameter coil to cancel the earth's magnetic field at the center of the coil?

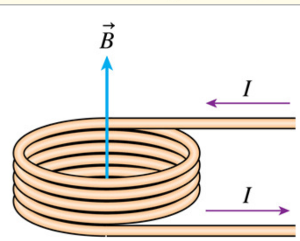
MODEL One way to create a zero-field region of space is to generate a magnetic field equal to the earth's field but pointing in the opposite direction. The vector sum of the two fields is zero.

 Slide 29-65

Example 29.6 Matching the Earth's Magnetic Field

EXAMPLE 29.6 **Matching the earth's magnetic field**

VISUALIZE FIGURE 29.18 shows a five-turn coil of wire. The magnetic field is five times that of a single current loop.



 Slide 29-66

Example 29.6 Matching the Earth's Magnetic Field

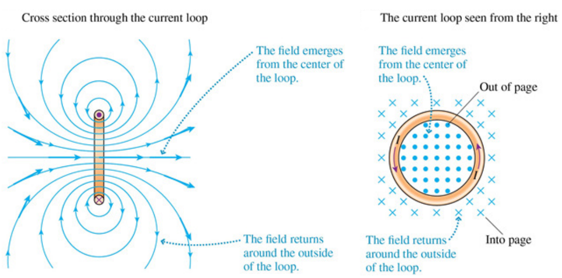
EXAMPLE 29.6 Matching the earth's magnetic field

SOLVE The earth's magnetic field, from Table 29.1, is 5×10^{-5} T. We can use Equation 29.8 to find that the current needed to generate a 5×10^{-5} T field is

$$I = \frac{2RB}{\mu_0 N} = \frac{2(0.050\text{ m})(5.0 \times 10^{-5}\text{ T})}{5(4\pi \times 10^{-7}\text{ T m/A})} = 0.80\text{ A}$$

ASSESS A 0.80 A current is easily produced. Although there are better ways to cancel the earth's field than using a simple coil, this illustrates the idea.

The Magnetic Field of a Current Loop



The Magnetic Field of a Current Loop

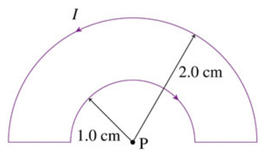
A photo of iron filings

- The magnetic field is revealed by the pattern of iron filings around a current-carrying loop of wire.

QuickCheck 29.7

The magnet field at point P is

A. Into the screen.
B. Out of the screen.
C. Zero.

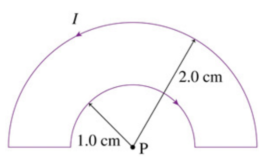


Slide 29-70

QuickCheck 29.7

The magnet field at point P is

✔ **A. Into the screen.**
B. Out of the screen.
C. Zero.



Slide 29-71

Tactics: Finding the Magnetic Field Direction of a Current Loop

TACTICS BOX 29.2 MP

Finding the magnetic field direction of a current loop

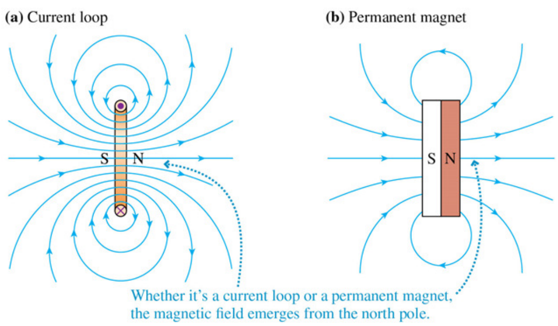
Use either of the following methods to find the magnetic field direction:

1. Point your right thumb in the direction of the current at any point on the loop and let your fingers curl through the center of the loop. Your fingers are then pointing in the direction in which $\vec{B}$ leaves the loop.
2. Curl the fingers of your right hand around the loop in the direction of the current. Your thumb is then pointing in the direction in which $\vec{B}$ leaves the loop.

Exercises 18–20

Slide 29-72

A Current Loop Is a Magnetic Dipole



 Slide 29-73

QuickCheck 29.8

Where is the north magnetic pole of this current loop?

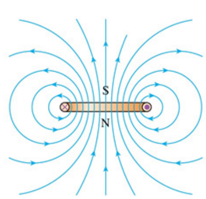
A. Top side.
B. Bottom side.
C. Right side.
D. Left side.
E. Current loops don't have north poles.

 Slide 29-74

QuickCheck 29.8

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.

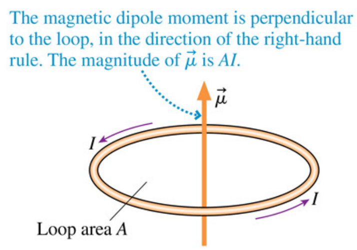


 Slide 29-75

The Magnetic Dipole Moment

- The **magnetic dipole moment** of a current loop enclosing an area A is defined as

$$\vec{\mu} = (AI, \text{ from the south pole to the north pole})$$

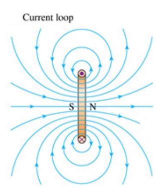


The Magnetic Dipole Moment

$$\vec{\mu} = (AI, \text{ from the south pole to the north pole})$$

- The SI units of the magnetic dipole moment are A m^2.
- The on-axis field of a magnetic dipole is

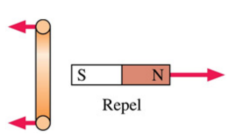
$$\vec{B}_{\text{dipole}} = \frac{\mu_0}{4\pi}\frac{2\vec{\mu}}{z^3} \quad \text{(on the axis of a magnetic dipole)}$$



QuickCheck 29.9

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.



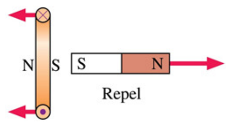
QuickCheck 29.9

What is the current direction in the loop?

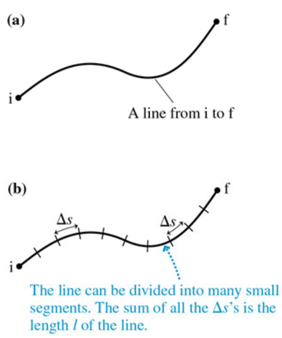
A. Out at the top, in at the bottom.

✔**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.



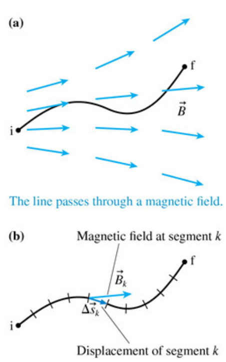
Line Integrals



- Figure (a) shows a curved line from i to f.
- The length l of this line can be found by doing a line integral:

$$l = \sum_k \Delta s_k \rightarrow \int_i^f ds$$

Line Integrals



- Figure (a) shows a curved line which passes through a magnetic field $\vec{B}$.
- We can find the line integral of $\vec{B}$ from i to f as measured along this line, in this direction:

$$\sum_k \vec{B}_k \cdot \Delta\vec{s}_k \rightarrow \int_i^f \vec{B} \cdot d\vec{s}$$

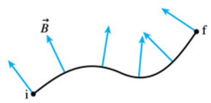
Tactics: Evaluating Line Integrals

TACTICS BOX 29.3

Evaluating line integrals

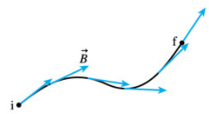
1. If $\vec{B}$ is everywhere perpendicular to a line, the line integral of $\vec{B}$ is

$$\int_{i}^{f} \vec{B} \cdot d\vec{s} = 0$$



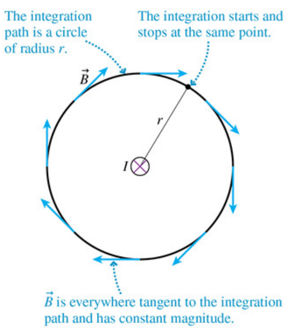
2. If $\vec{B}$ is everywhere tangent to a line of length l *and* has the same magnitude B at every point, then

$$\int_{i}^{f} \vec{B} \cdot d\vec{s} = Bl$$



Exercises 23–24

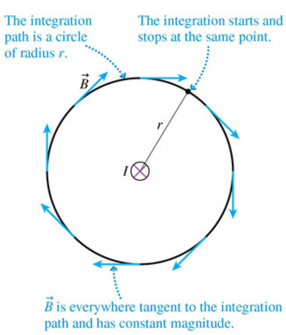
Ampère's Law



- Consider a line integral of $\vec{B}$ evaluated along a circular path all the way around a wire carrying current I.
- This is the line integral around a *closed curve*, which is denoted

$$\oint \vec{B} \cdot d\vec{s}$$

Ampère's Law



- Because $\vec{B}$ is tangent to the circle and of constant magnitude at every point on the circle, we can write

$$\oint \vec{B} \cdot d\vec{s} = Bl = B(2\pi r)$$

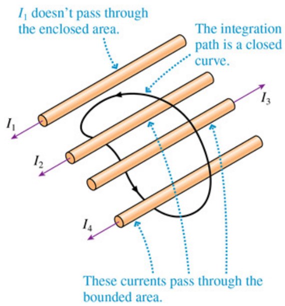
- Here $B = \mu_0 I/2\pi r$ where I is the current *through* this loop, hence

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I$$

Ampère's Law

- Whenever total current I_{through} passes through an area bounded by a *closed curve*, the line integral of the magnetic field around the curve is given by Ampère's law:

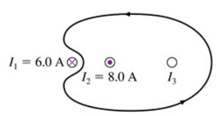
$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$



QuickCheck 29.10

The line integral of B around the loop is $\mu_0 \cdot 7.0$ A. Current I_3 is

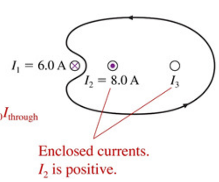
A. 0 A.
B. 1 A out of the screen.
C. 1 A into the screen.
D. 5 A out of the screen.
E. 5 A into the screen.



QuickCheck 29.10

The line integral of B around the loop is $\mu_0 \cdot 7.0$ A. Current I_3 is

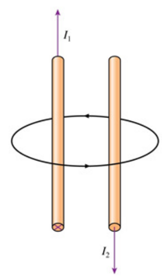
A. 0 A.
B. 1 A out of the screen.
✔**C. 1 A into the screen.** $\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$
D. 5 A out of the screen.
E. 5 A into the screen.



QuickCheck 29.11

For the path shown, $\oint \vec{B} \cdot d\vec{s} =$

A. 0
B. $\mu_0(I_1 - I_2)$
C. $\mu_0(I_2 - I_1)$
D. $\mu_0(I_1 + I_2)$

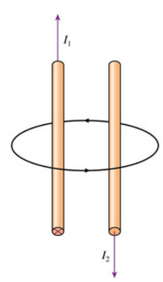


Slide 29-88

QuickCheck 29.11

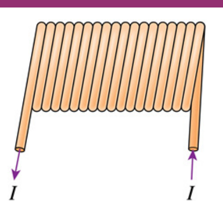
For the path shown, $\oint \vec{B} \cdot d\vec{s} =$

A. 0
✔ **B. $\mu_0(I_1 - I_2)$**
C. $\mu_0(I_2 - I_1)$
D. $\mu_0(I_1 + I_2)$

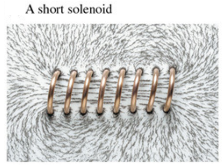


Slide 29-89

Solenoids



A short solenoid

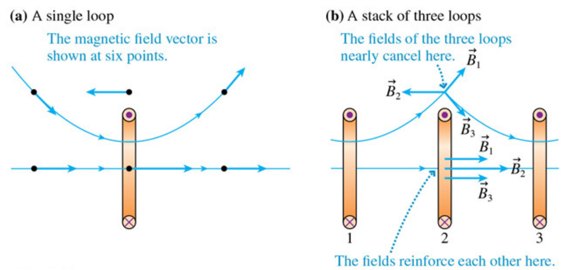


- A **uniform magnetic field** can be generated with a **solenoid**.
- A solenoid is a helical coil of wire with the same current I passing through each loop in the coil.
- Solenoids may have hundreds or thousands of coils, often called *turns*, sometimes wrapped in several layers.
- The magnetic field is strongest and most uniform *inside* the solenoid.

Slide 29-90

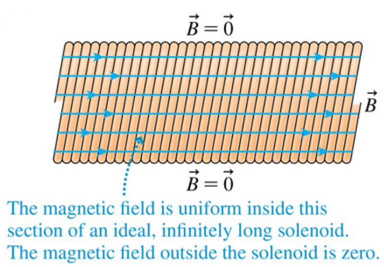
The Magnetic Field of a Solenoid

- With many current loops along the same axis, the field in the center is strong and roughly parallel to the axis, whereas the field outside the loops is very close to zero.



Slide 29-91

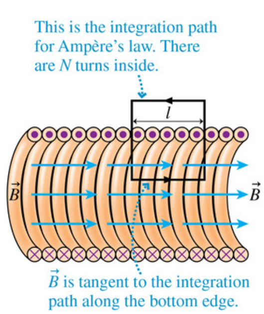
The Magnetic Field of a Solenoid



- No real solenoid is ideal, but a very uniform magnetic field can be produced near the center of a tightly wound solenoid whose length is much larger than its diameter.

Slide 29-92

The Magnetic Field of a Solenoid

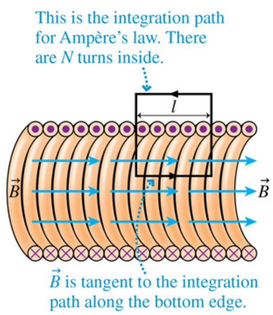


- The figure shows a cross section through an infinitely long solenoid.
- The integration path that we'll use is a rectangle.
- The current passing through this rectangle is $I_{\text{through}} = NI$.
- Ampère's Law is thus

$$\oint \vec{B} \cdot d\vec{s} = Bl = \mu_0 NI$$

Slide 29-93

The Magnetic Field of a Solenoid



- Along the top, the line integral is zero since $B = 0$ outside the solenoid.
- Along the sides, the line integral is zero since the field is perpendicular to the path.
- Along the bottom, the line integral is simply Bl.
- Solving for B inside the solenoid:

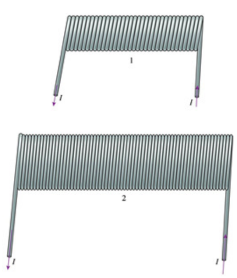
$$B_{\text{solenoid}} = \frac{\mu_0 NI}{l} = \mu_0 nI \qquad \text{(solenoid)}$$

where $n = N/l$ is the number of turns per unit length.

QuickCheck 29.12

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?

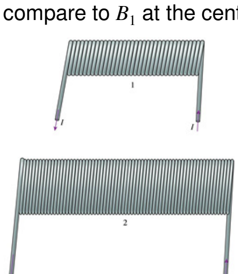
A. $B_2 = B_1/4$
B. $B_2 = B_1/2$
C. $B_2 = B_1$
D. $B_2 = 2B_1$
E. $B_2 = 4B_1$



QuickCheck 29.12

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. $B_2 = 4B_1$

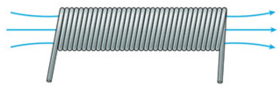


Same turns-per-length

QuickCheck 29.13

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.

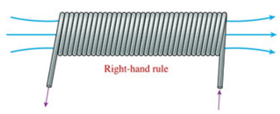


Slide 29-97

QuickCheck 29.13

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.



Slide 29-98

Example 29.9 Generating an MRI Magnetic Field

EXAMPLE 29.9 **Generating an MRI magnetic field**

A 1.0-m-long MRI solenoid generates a 1.2 T magnetic field. To produce such a large field, the solenoid is wrapped with superconducting wire that can carry a 100 A current. How many turns of wire does the solenoid need?

MODEL Assume that the solenoid is ideal.

Slide 29-99

Example 29.9 Generating an MRI Magnetic Field

EXAMPLE 29.9 **Generating an MRI magnetic field**

SOLVE Generating a magnetic field with a solenoid is a trade-off between current and turns of wire. A larger current requires fewer turns, but the resistance of ordinary wires causes them to overheat if the current is too large. For a superconducting wire that can carry 100 A with no resistance, we can use Equation 29.17 to find the required number of turns:

$$N = \frac{lB}{\mu_0 I} = \frac{(1.0\text{ m})(1.2\text{ T})}{(4\pi \times 10^{-7}\text{ T m/A})(100\text{ A})} = 9500\text{ turns}$$

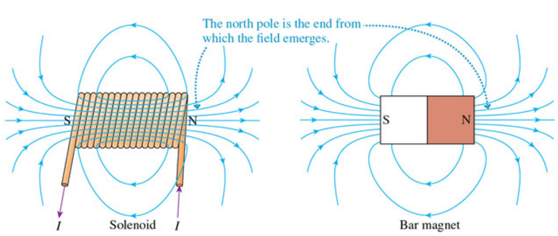
Example 29.9 Generating an MRI Magnetic Field

EXAMPLE 29.9 **Generating an MRI magnetic field**

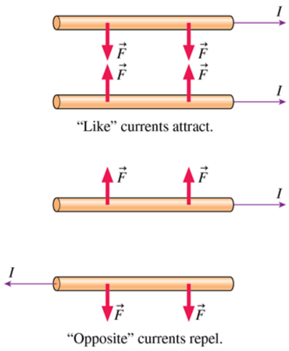
ASSESS The solenoid coil requires a large number of turns, but that's not surprising for generating a very strong field. If the wires are 1 mm in diameter, there would be 10 layers with approximately 1000 turns per layer.

The Magnetic Field Outside a Solenoid

- The magnetic field *outside* a solenoid looks like that of a bar magnet.
- Thus a solenoid is an electromagnet, and you can use the right-hand rule to identify the north-pole end.



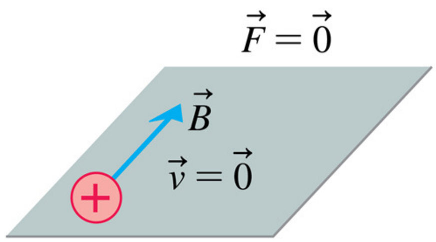
Ampère’s Experiment



- After the discovery that electric current produces a magnetic field, Ampère set up two parallel wires that could carry large currents either in the same direction or in opposite directions.
- Ampère’s experiment showed that a magnetic field exerts a force on a current.

Slide 29-103

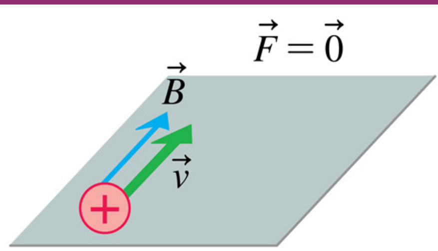
Magnetic Force on a Charged Particle



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

Slide 29-104

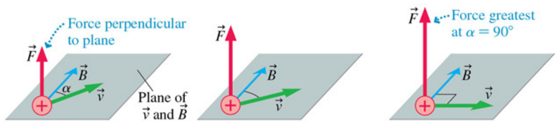
Magnetic Force on a Charged Particle



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

Slide 29-105

The Magnetic Force on a Moving Charge



- 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 90º.
- The magnetic force is always perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.

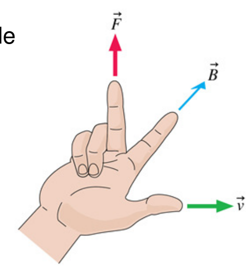
 Slide 29-106

The Magnetic Force on a Moving Charge

- The magnetic force on a charge q as it moves through a magnetic field $\vec{B}$ with velocity $\vec{v}$ is

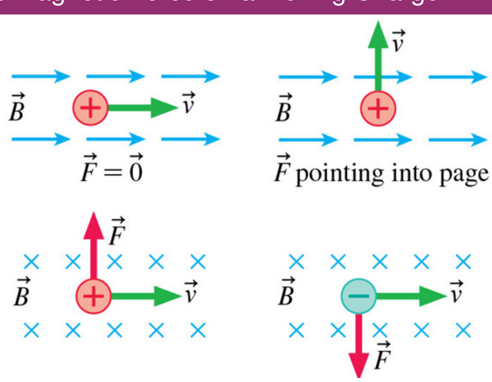
$$\vec{F}_{\text{on } q} = q\vec{v} \times \vec{B} = (qvB\sin\alpha, \text{ direction of right-hand rule})$$

where α is the angle between $\vec{v}$ and $\vec{B}$.



 Slide 29-107

The Magnetic Force on a Moving Charge

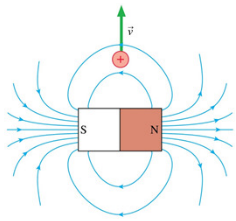


 Slide 29-108

QuickCheck 29.14

The direction of the magnetic force on the proton is

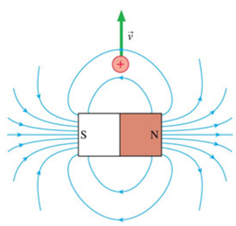
A. To the right.
B. To the left.
C. Into the screen.
D. Out of the screen.
E. The magnetic force is zero.



QuickCheck 29.14

The direction of the magnetic force on the proton is

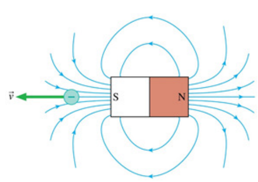
A. To the right.
B. To the left.
C. Into the screen.
✔**D. Out of the screen.**
E. The magnetic force is zero.



QuickCheck 29.15

The direction of the magnetic force on the electron is

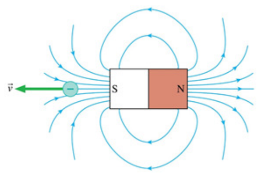
A. Upward.
B. Downward.
C. Into the screen.
D. Out of the screen.
E. The magnetic force is zero.



QuickCheck 29.15

The direction of the magnetic force on the electron is

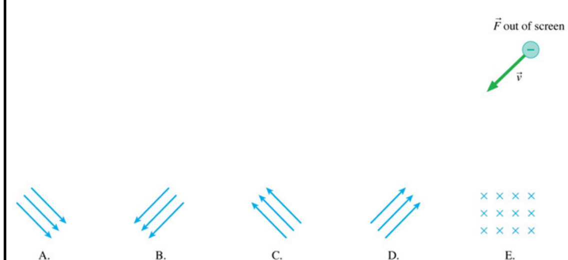
A. Upward.
B. Downward.
C. Into the screen.
D. Out of the screen.
✔ **E. The magnetic force is zero.**



Slide 29-112

QuickCheck 29.16

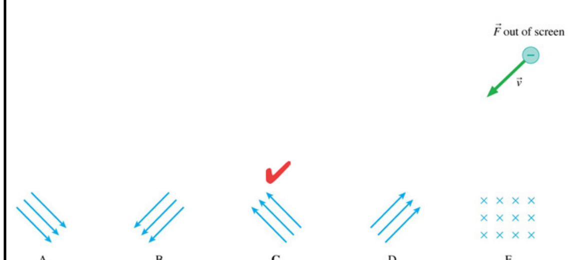
Which magnetic field causes the observed force?



Slide 29-113

QuickCheck 29.16

Which magnetic field causes the observed force?



Slide 29-114

Example 29.10 The Magnetic Force on an Electron

EXAMPLE 29.10 The magnetic force on an electron

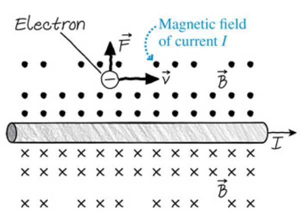
A long wire carries a 10 A current from left to right. An electron 1.0 cm above the wire is traveling to the right at a speed of 1.0×10^7 m/s. What are the magnitude and the direction of the magnetic force on the electron?

MODEL The magnetic field is that of a long, straight wire.

Example 29.10 The Magnetic Force on an Electron

EXAMPLE 29.10 The magnetic force on an electron

VISUALIZE FIGURE 29.36 shows the current and an electron moving to the right. The right-hand rule tells us that the wire's magnetic field above the wire is out of the page, so the electron is moving perpendicular to the field.

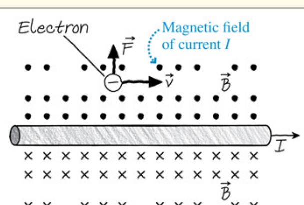


Example 29.10 The Magnetic Force on an Electron

EXAMPLE 29.10 The magnetic force on an electron

SOLVE The electron charge is negative, thus the direction of the force is opposite the direction of $\vec{v} \times \vec{B}$. The right-hand rule shows that $\vec{v} \times \vec{B}$ points down, toward the wire, so $\vec{F}$ points up, away from the wire. The magnitude of the force is $|q|vB = evB$. The field is that of a long, straight wire:

$$B = \frac{\mu_0 I}{2\pi r} = 2.0 \times 10^{-4}\ \text{T}$$



Example 29.10 The Magnetic Force on an Electron

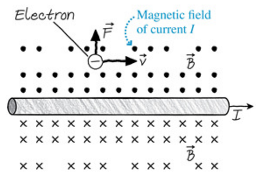
EXAMPLE 29.10 The magnetic force on an electron

SOLVE Thus the magnitude of the force on the electron is

$$F = evB = (1.60 \times 10^{-19}\,\text{C})(1.0 \times 10^{7}\,\text{m/s})(2.0 \times 10^{-4}\,\text{T})$$
$$= 3.2 \times 10^{-16}\,\text{N}$$

The force on the electron is $\vec{F} = (3.2 \times 10^{-16}\,\text{N, up})$.

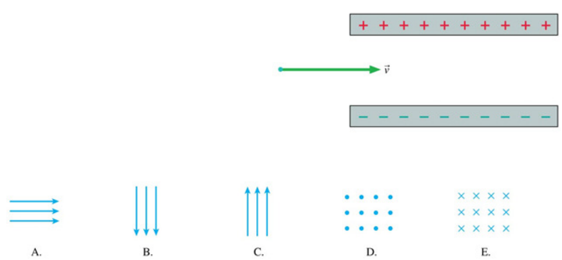
ASSESS This force will cause the electron to curve away from the wire.



Slide 29-118

QuickCheck 29.17

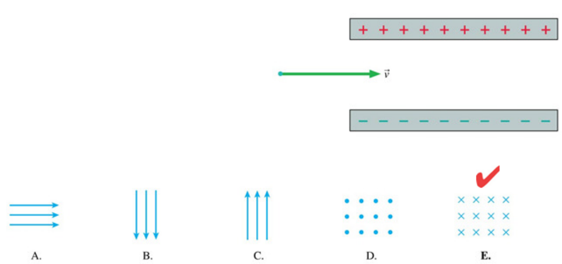
Which magnetic field (if it's the correct strength) allows the electron to pass through the charged electrodes without being deflected?



Slide 29-119

QuickCheck 29.17

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

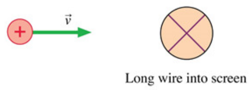


Slide 29-120

QuickCheck 29.18

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

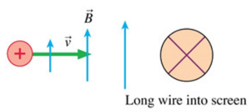
A. Go straight into the wire.
B. Hit the wire in front of the screen.
C. Hit the wire behind the screen.
D. Be deflected over the wire.
E. Be deflected under the wire.



QuickCheck 29.18

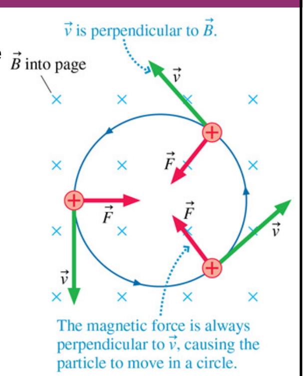
A proton is shot straight at the center of a long, straight wire carrying current into the screen. The proton will

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.

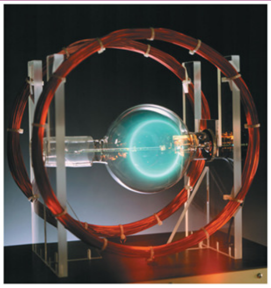


Cyclotron Motion

- The figure shows a positive charge moving in a plane that is perpendicular to a *uniform* magnetic field.
- Since $\vec{F}$ is always perpendicular to $\vec{v}$, the charge undergoes **uniform circular motion**.
- This motion is called the **cyclotron motion** of a charged particle in a magnetic field.



Cyclotron Motion



- Electrons undergoing circular **cyclotron motion** in a magnetic field. You can see the electrons' path because they collide with a low density gas that then emits light.

Slide 29-124

Cyclotron Motion

- Consider a particle with mass m and charge q moving with a speed v in a plane that is perpendicular to a uniform magnetic field of strength B.
- Newton's second law for circular motion, which you learned in Chapter 8, is

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

- The radius of the cyclotron orbit is

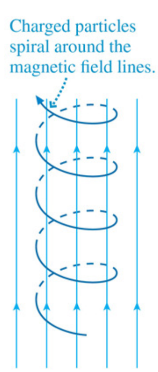
$$r_{\text{cyc}} = \frac{mv}{qB}$$

- Recall that the frequency of revolution of circular motion is $f = v/2\pi r$, so the cyclotron frequency is

$$f_{\text{cyc}} = \frac{qB}{2\pi m}$$

Slide 29-125

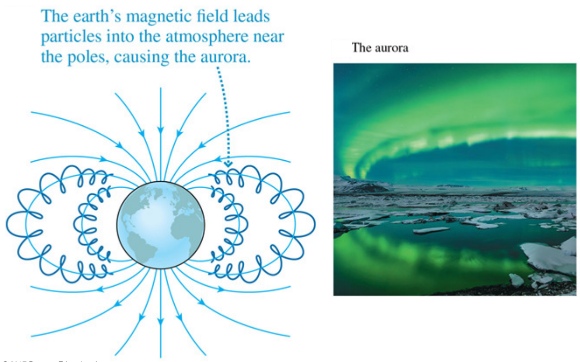
Cyclotron Motion



- The figure shows a more general situation in which the charged particle's velocity is not exactly perpendicular to $\vec{B}$.
- The component of $\vec{v}$ parallel to $\vec{B}$ is not affected by the field, so the charged particle spirals around the magnetic field lines in a helical trajectory.
- The radius of the helix is determined by $v_{\perp}$, the component of $\vec{v}$ perpendicular to $\vec{B}$.

Slide 29-126

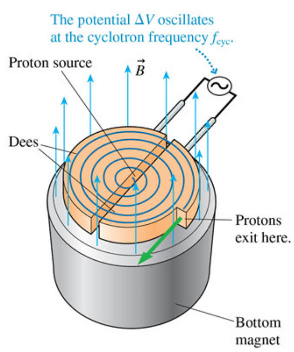
Aurora



 Slide 29-127

The Cyclotron

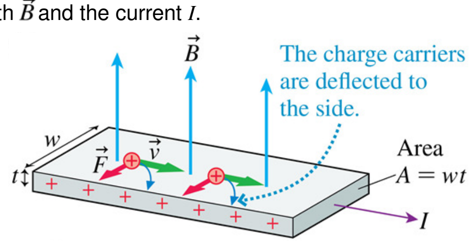
- The first practical particle accelerator, invented in the 1930s, was the **cyclotron**.
- Cyclotrons remain important for many applications of nuclear physics, such as the creation of radioisotopes for medicine.



 Slide 29-128

The Hall Effect

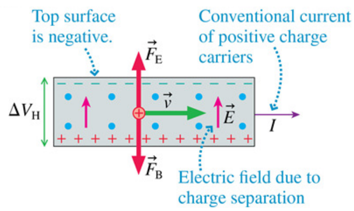
- Consider a magnetic field perpendicular to a flat, current-carrying conductor.
- As the charge carriers move at the drift speed v_d, they will experience a magnetic force $F_B = ev_dB$ perpendicular to both $\vec{B}$ and the current I.



 Slide 29-129

The Hall Effect

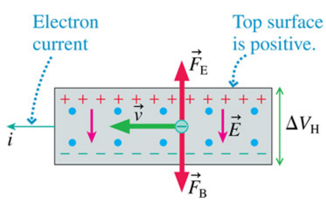
- If the charge carriers are *positive*, the magnetic force pushes these positive charges *down*, creating an excess positive charge on the bottom surface, and leaving negative charge on the top.
- This creates a measureable Hall voltage ΔV_H which is higher on the *bottom* surface.



Slide 29-130

The Hall Effect

- If the charge carriers are *negative*, the magnetic force pushes these positive charges *down*, creating an excess negative charge on the bottom surface, and leaving positive charge on the top.
- This creates a measureable Hall voltage ΔV_H which is higher on the *top* surface.



Slide 29-131

The Hall Effect

- When charges are separated by a magnetic field in a rectangular conductor of thickness t and width w, it creates an electric field $E = \Delta V_H/w$ inside the conductor.
- The steady-state condition is when the electric force balances the magnetic force, $F_B = F_E$:

$$F_B = ev_d B = F_E = eE = e\frac{\Delta V}{w}$$

where v_d is the drift speed, which is $v_d = I/(wtne)$.
- From this we can find the Hall voltage:

$$\Delta V_H = \frac{IB}{tne}$$

where n is the charge-carrier density (charge carriers per m^3).

Slide 29-132

Example 29.12 Measuring the Magnetic Field

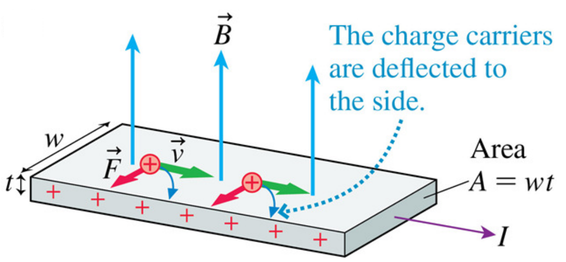
EXAMPLE 29.12 **Measuring the magnetic field**

A Hall probe consists of a strip of the metal bismuth that is 0.15 mm thick and 5.0 mm wide. Bismuth is a poor conductor with charge-carrier density $1.35 \times 10^{25}\ \mathrm{m^{-3}}$. The Hall voltage on the probe is 2.5 mV when the current through it is 1.5 A. What is the strength of the magnetic field, and what is the electric field strength inside the bismuth?

Example 29.12 Measuring the Magnetic Field

EXAMPLE 29.12 **Measuring the magnetic field**

VISUALIZE The bismuth strip looks like Figure 29.41a. The thickness is $t = 1.5 \times 10^{-4}$ m and the width is $w = 5.0 \times 10^{-3}$ m.



Example 29.12 Measuring the Magnetic Field

EXAMPLE 29.12 **Measuring the magnetic field**

SOLVE Equation 29.25 gives the Hall voltage. We can rearrange the equation to find that the magnetic field is

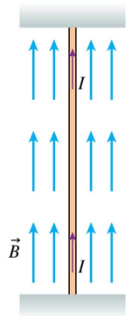
$$B = \frac{tne}{I}\Delta V_H$$
$$= \frac{(1.5 \times 10^{-4}\ \mathrm{m})(1.35 \times 10^{25}\ \mathrm{m^{-3}})(1.60 \times 10^{-19}\ \mathrm{C})}{1.5\ \mathrm{A}}\ 0.0025\ \mathrm{V}$$
$$= 0.54\ \mathrm{T}$$

The electric field created inside the bismuth by the excess charge on the surface is

$$E = \frac{\Delta V_H}{w} = \frac{0.0025\ \mathrm{V}}{5.0 \times 10^{-3}\ \mathrm{m}} = 0.50\ \mathrm{V/m}$$

ASSESS 0.54 T is a fairly typical strength for a laboratory magnet.

Magnetic Forces on Current-Carrying Wires



- There's *no* force on a current-carrying wire parallel to a magnetic field.

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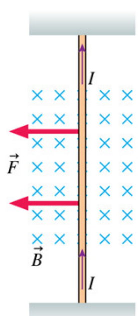
Magnetic Forces on Current-Carrying Wires



- A current perpendicular to the field experiences a force in the direction of the right-hand rule.
- If a wire of length l contains a current $I = q/\Delta t$, it means a charge q must move along its length in a time $\Delta t = l/v$.
- Thus we have $Il = qv$.
- Since $\vec{F} = q\vec{v} \times \vec{B}$, the magnetic force on a current-carrying wire is

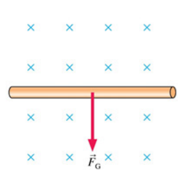
$$\vec{F}_{\text{wire}} = I\vec{l} \times \vec{B} = (IlB\sin\alpha, \text{ direction of right-hand rule})$$

Slide 29-137

QuickCheck 29.19

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.

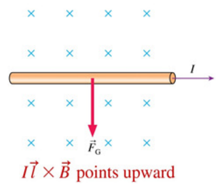


Slide 29-138

QuickCheck 29.19

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.

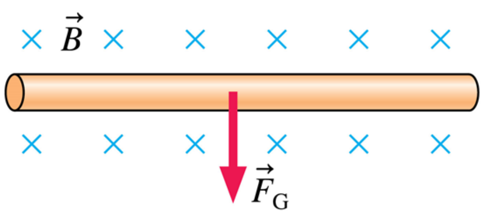


Slide 29-139

Example 29.13 Magnetic Levitation

EXAMPLE 29.13 Magnetic levitation

The 0.10 T uniform magnetic field of **FIGURE 29.44** is horizontal, parallel to the floor. A straight segment of 1.0-mm-diameter copper wire, also parallel to the floor, is perpendicular to the magnetic field. What current through the wire, and in which direction, will allow the wire to "float" in the magnetic field?

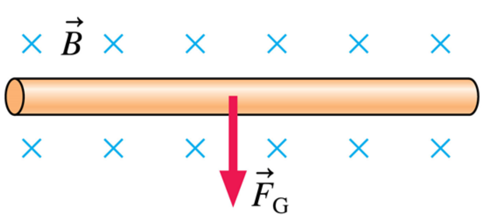


Slide 29-140

Example 29.13 Magnetic Levitation

EXAMPLE 29.13 Magnetic levitation

MODEL The wire will float in the magnetic field if the magnetic force on the wire points upward and has magnitude mg, allowing it to balance the downward gravitational force.



Slide 29-141

Example 29.13 Magnetic Levitation

EXAMPLE 29.13 **Magnetic levitation**

SOLVE We can use the right-hand rule to determine which current direction experiences an upward force. With $\vec{B}$ pointing away from us, the direction of the current needs to be from left to right. The forces will balance when

$$F = IlB = mg = \rho(\pi r^2 l)g$$

where $\rho = 8920\ \text{kg/m}^3$ is the density of copper. The length of the wire cancels, leading to

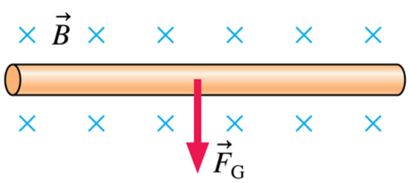
$$I = \frac{\rho \pi r^2 g}{B} = \frac{(8920\ \text{kg/m}^3)\pi(0.00050\ \text{m})^2(9.80\ \text{m/s}^2)}{0.10\ \text{T}}$$
$$= 0.69\ \text{A}$$

A 0.69 A current from left to right will levitate the wire in the magnetic field.

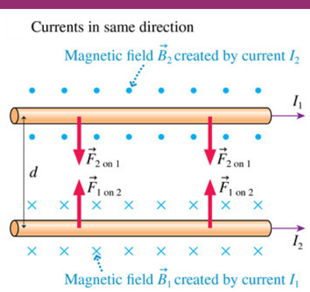
Example 29.13 Magnetic Levitation

EXAMPLE 29.13 **Magnetic levitation**

ASSESS A 0.69 A current is quite reasonable, but this idea is useful only if we can get the current into and out of this segment of wire. In practice, we could do so with wires that come in from below the page. These input and output wires would be parallel to $\vec{B}$ and not experience a magnetic force. Although this example is very simple, it is the basis for applications such as magnetic levitation trains.

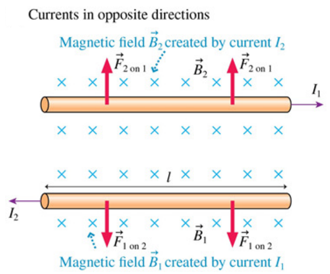


Magnetic Forces Between Parallel Current-Carrying Wires: Current in Same Direction



$$F_{\text{parallel wires}} = I_1 l B_2 = I_1 l \frac{\mu_0 I_2}{2\pi d} = \frac{\mu_0 l I_1 I_2}{2\pi d}$$

Magnetic Forces Between Parallel Current-Carrying Wires: Current in Opposite Directions

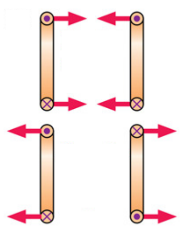


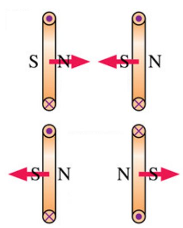
$$F_{\text{parallel wires}} = I_1 l B_2 = I_1 l \frac{\mu_0 I_2}{2\pi d} = \frac{\mu_0 l I_1 I_2}{2\pi d}$$

Slide 29-145

Forces on Current Loops

- The two figures show alternative but equivalent ways to view magnetic forces between two current loops.



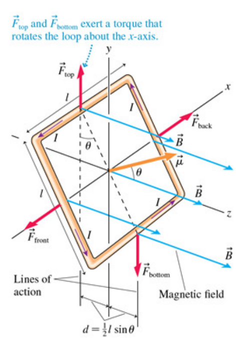


- Parallel currents attract, opposite currents repel.
- Opposite poles attract, like poles repel.

Slide 29-146

A Uniform Magnetic Field Exerts a Torque on a Square Current Loop

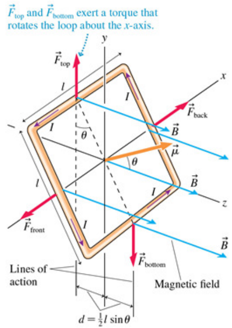
- $\vec{F}_{\text{front}}$ and $\vec{F}_{\text{back}}$ are opposite to each other and cancel.
- Both $\vec{F}_{\text{top}}$ and $\vec{F}_{\text{bottom}}$ exert a force of magnitude $F = IlB$ around a moment arm $d = ½l\sin\theta$.



Slide 29-147

A Uniform Magnetic Field Exerts a Torque on a Square Current Loop

- The total torque is
  $\tau = 2Fd = (Il^2)B\sin\theta = \mu B\sin\theta$
  where $\mu = Il^2 = IA$ is the loop's magnetic dipole moment.
- Although derived for a square loop, the result is valid for a loop of any shape:
  $$\vec{\tau} = \vec{\mu} \times \vec{B}$$



Slide 29-148

QuickCheck 29.20

If released from rest, the current loop will

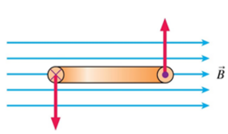
A. Move upward.
B. Move downward.
C. Rotate clockwise.
D. Rotate counterclockwise.
E. Do something not listed here.

Slide 29-149

QuickCheck 29.20

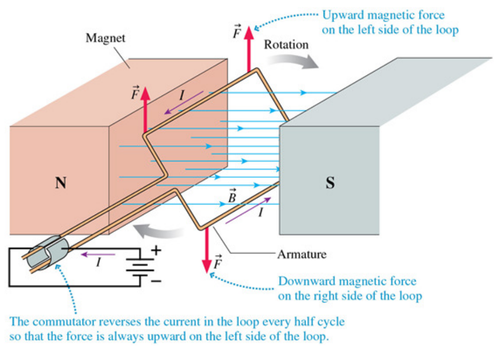
If released from rest, the current loop will

A. Move upward.
B. Move downward.
C. Rotate clockwise.
✔**D. Rotate counterclockwise.** Net torque but no net force
E. Do something not listed here.



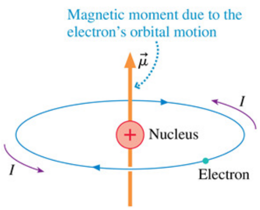
Slide 29-150

A Simple Electric Motor



 Slide 29-151

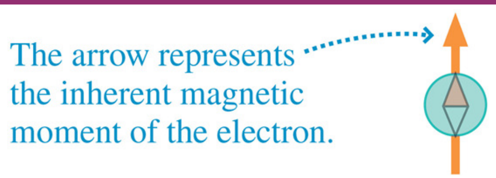
Atomic Magnets



- A plausible explanation for the magnetic properties of materials is the orbital motion of the atomic electrons.
- The figure shows a simple, classical model of an atom in which a negative electron orbits a positive nucleus.
- In this picture of the atom, the electron's motion is that of a current loop!
- An orbiting electron acts as a tiny magnetic dipole, with a north pole and a south pole.

 Slide 29-152

The Electron Spin

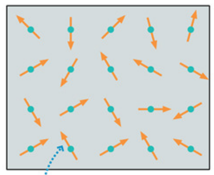


- An electron's inherent magnetic moment is often called the electron *spin* because, in a classical picture, a spinning ball of charge would have a magnetic moment.
- While it may not be spinning in a literal sense, an electron really is a microscopic magnet.

 Slide 29-153

Magnetic Properties of Matter

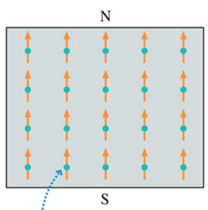
- For most elements, the magnetic moments of the atoms are randomly arranged when the atoms join together to form a solid.
- As the figure shows, this random arrangement produces a solid whose net magnetic moment is very close to zero.



The atomic magnetic moments due to unpaired electrons point in random directions. The sample has no net magnetic moment.

Ferromagnetism

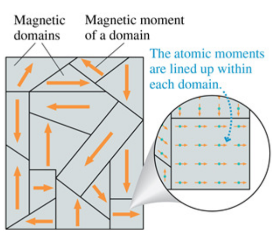
- In iron, and a few other substances, the atomic magnetic moments tend to all line up in the *same* direction, as shown in the figure.
- Materials that behave in this fashion are called **ferromagnetic**, with the prefix *ferro* meaning "iron-like."



The atomic magnetic moments are aligned. The sample has north and south magnetic poles.

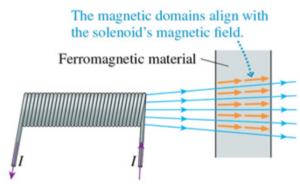
Ferromagnetism

- A typical piece of iron is divided into small regions, typically less than $100\ \mu m$ in size, called **magnetic domains**.
- The magnetic moments of all the iron atoms within each domain are perfectly aligned, so each individual domain is a strong magnet.
- However, the various magnetic domains that form a larger solid are randomly arranged.



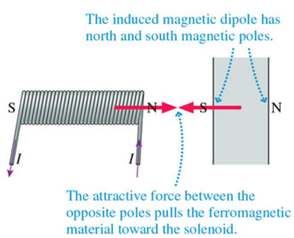
Induced Magnetic Dipoles

- If a ferromagnetic substance is subjected to an *external* magnetic field, the external field exerts a torque on the magnetic dipole of each domain.
- The torque causes many of the domains to rotate and become aligned with the external field.

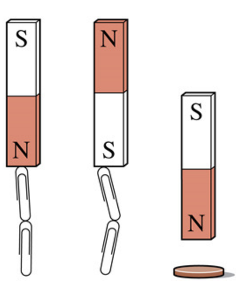


Induced Magnetic Dipoles

- The induced magnetic dipole always has an *opposite* pole facing the solenoid.
- Consequently the magnetic force between the poles *pulls* the ferromagnetic object to the electromagnet.

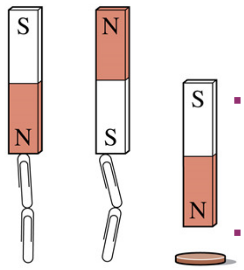


Induced Magnetism



- Now we can explain how a magnet attracts and picks up ferromagnetic objects:
  1. Electrons are microscopic magnets due to their spin.
  2. A ferromagnetic material in which the spins are aligned is organized into magnetic domains.
  3. The individual domains align with an external magnetic field to produce an induced magnetic dipole moment for the entire object.

Induced Magnetism



- An object's magnetic dipole may not return to zero when the external field is removed because some domains remain "frozen" in the alignment they had in the external field.
- Thus a ferromagnetic object that has been in an external field may be left with a net magnetic dipole moment after the field is removed.
- In other words, the object has become a **permanent magnet**.

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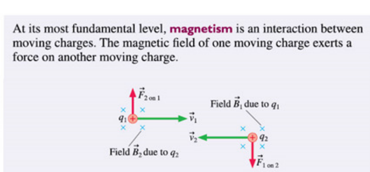
Chapter 29 Summary Slides

Slide 29-161

General Principles



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General Principles

Magnetic Fields

The **Biot-Savart law** for a moving point charge

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}$$

Magnetic field of a current

MODEL Model wires as simple shapes.

VISUALIZE Divide the wire into short segments.

SOLVE Use superposition:

- Find the field of each segment Δs.
- Find $\vec{B}$ by summing the fields of all Δs, usually as an integral.

An alternative method for fields with a high degree of symmetry is **Ampère's law**:

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$

where I_{through} is the current through the area bounded by the integration path.

General Principles

Magnetic Forces

The magnetic force on a moving charge is

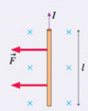
$$\vec{F} = q\vec{v} \times \vec{B}$$

The force is perpendicular to $\vec{v}$ and $\vec{B}$.

The magnetic force on a current-carrying wire is

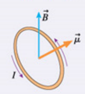
$$\vec{F} = I\vec{l} \times \vec{B}$$

$\vec{F} = \vec{0}$ for a charge or current moving parallel to $\vec{B}$.



The magnetic torque on a magnetic dipole is

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

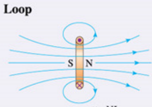


Applications

Wire

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

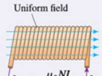
Loop



$B_{\text{center}} = \frac{\mu_0}{2}\frac{NI}{R}$

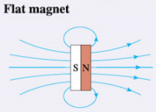
Solenoid

Uniform field



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

Flat magnet



Right-hand rule

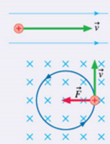
Point your right thumb in the direction of I. Your fingers curl in the direction of $\vec{B}$. For a dipole, $\vec{B}$ emerges from the side that is the north pole.

Applications

Charged-particle motion

No force if $\vec{v}$ is parallel to $\vec{B}$

Circular motion at the cyclotron frequency $f_{cyc} = qB/2\pi m$ if $\vec{v}$ is perpendicular to $\vec{B}$



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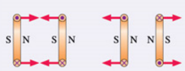
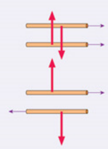
Applications

Parallel wires and current loops

Parallel currents attract.
Opposite currents repel.





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