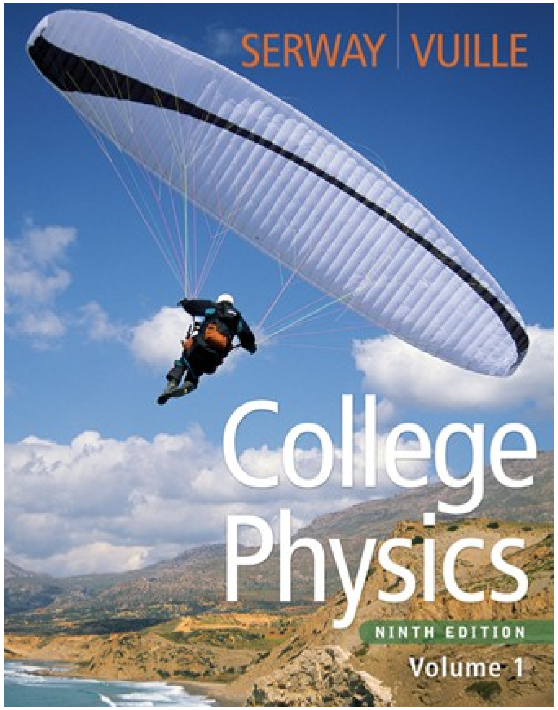

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Chapter 19

Magnetism

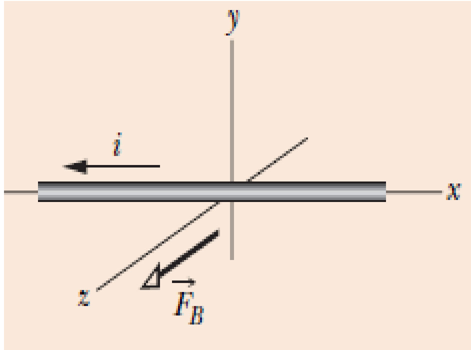
Quiz 6.

1. The north-pole end of a bar magnet is held near a stationary positively charged piece of plastic. Is the plastic (a) attracted, (b) repelled, or (c) unaffected by the magnet?

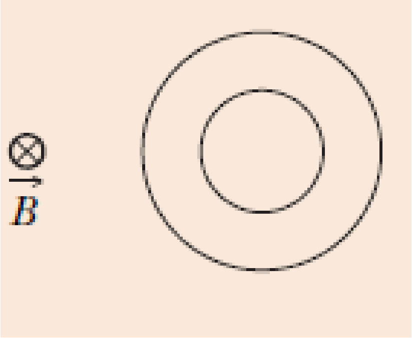
2. Can a constant electric field change the ***speed*** of a moving charged particle? Can a constant magnetic field change the speed of a moving charged particle? **Explain with necessary equations.**.

Quiz 7. 1. A square and a circular loop with the same area lie in the *xy*-plane, where there is a uniform magnetic field **B** pointing at some angle ≥ with respect to the positive *z*-direction. Each loop carries the same current, in the same direction. Which magnetic torque is larger? (a) the torque on the square loop (b) on the circular loop (c) the torques are the same (d) more info. is needed

2. The figure shows a current *i* through a wire in a uniform magnetic field , as well as the magnetic force acting on the wire. The field is oriented so that the force is maximum. In what direction is the field?



3. The figure here shows the circular paths of two particles that travel at the same speed in a uniform magnetic field , which is directed into the page. One particle is a proton; the other is an electron (which is less massive). (a) Which particle follows the smaller circle,and (b) does that particle travel clockwise or counterclockwise?



Magnetism

- Magnetism is one of the most important fields in physics in terms of applications.
- Magnetism is closely linked with electricity.
  - Magnetic fields affect moving charges.
  - Moving charges produce magnetic fields.
  - Changing magnetic fields can create electric fields.
- James Clerk Maxwell first described the underlying unity of electricity and magnetism in the 19th century.

Magnets

- *Poles* of a magnet are the ends where objects are most strongly attracted.
  - Two poles, called *north* and *south*
- Like poles repel each other and unlike poles attract each other.
  - Similar to electric charges
- Magnetic poles cannot be isolated.
  - If a permanent magnetic is cut in half repeatedly, you will still have a north and a south pole.
  - This differs from electric charges
  - There is some theoretical basis for monopoles, but none have been detected.

More About Magnetism

- An unmagnetized piece of iron can be magnetized by stroking it with a magnet.
  - Somewhat like stroking an object to charge it
- Magnetism can be induced.
  - If a piece of iron, for example, is placed near a strong permanent magnet, it will become magnetized.

Types of Magnetic Materials

- *Soft magnetic* materials, such as iron, are easily magnetized.
  - They also tend to lose their magnetism easily.
- *Hard magnetic* materials are difficult to magnetize.
  - They tend to retain their magnetism.

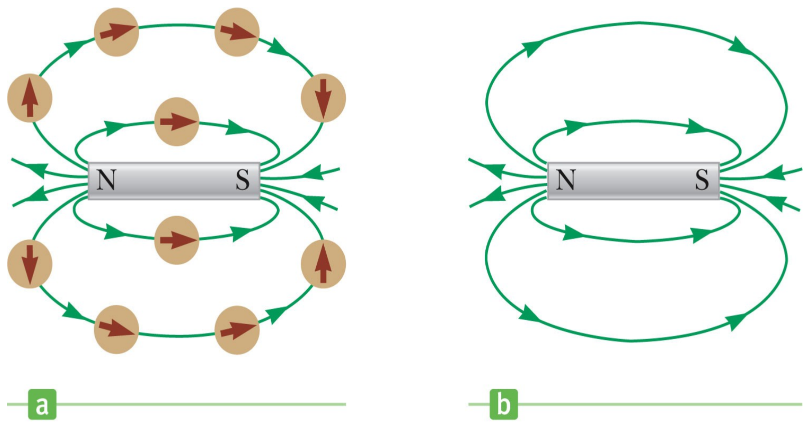
Sources of Magnetic Fields

- The region of space surrounding a *moving* charge includes a magnetic field.
  - The charge will also be surrounded by an electric field.
- A magnetic field surrounds a properly magnetized magnetic material.

Magnetic Fields

- A vector quantity
- Symbolized by $\vec{\mathbf{B}}$
- Direction is given by the direction a *north pole* of a compass needle points in that location.
- *Magnetic field lines* can be used to show how the field lines, as traced out by a compass, would look.

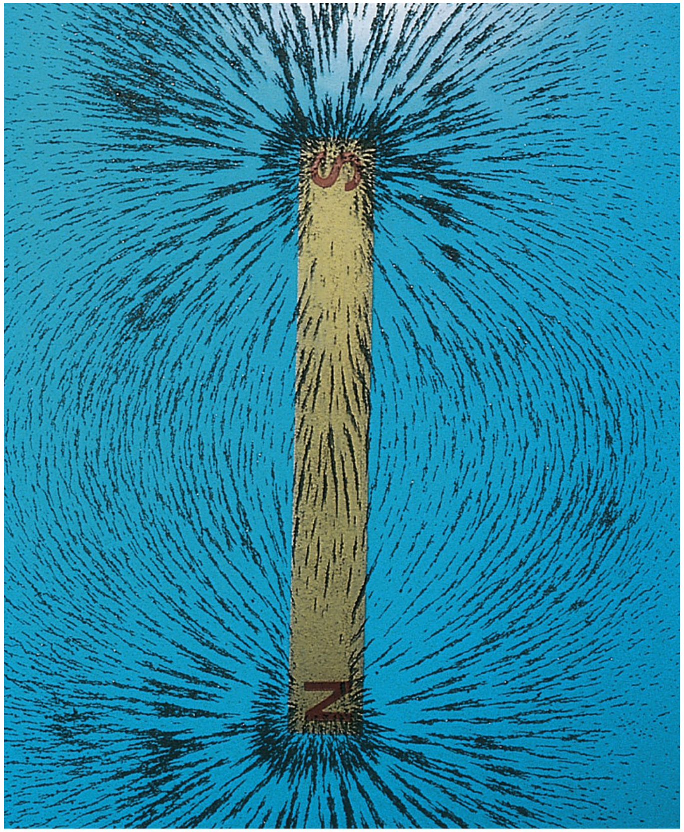
Magnetic Field Lines, Sketch



- A compass can be used to show the direction of the magnetic field lines (a).
- A sketch of the magnetic field lines (b)

Magnetic Field Lines, Bar Magnet

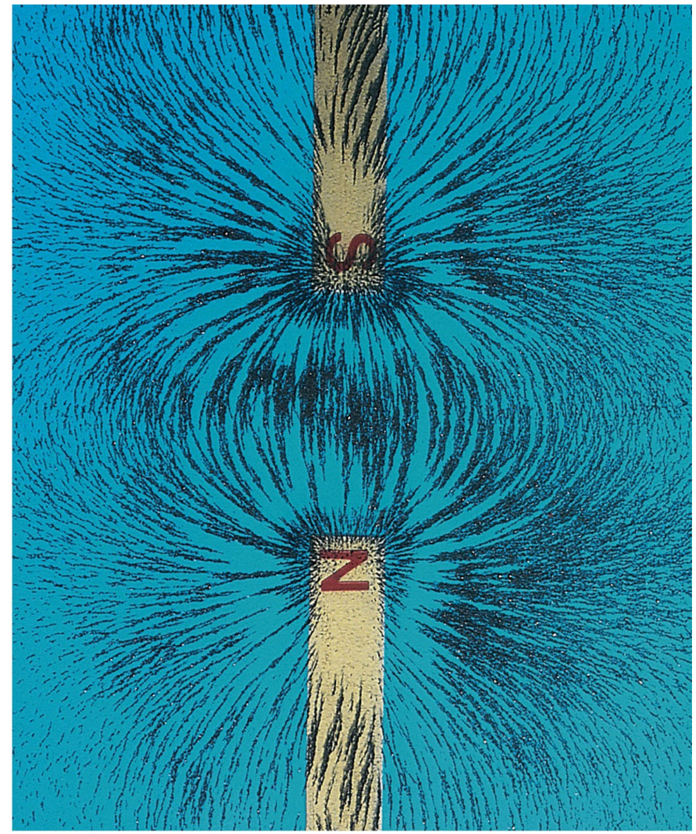
- Iron filings are used to show the pattern of the magnetic field lines.
- The direction of the field is the direction a north pole would point.



a

Magnetic Field Lines, Unlike Poles

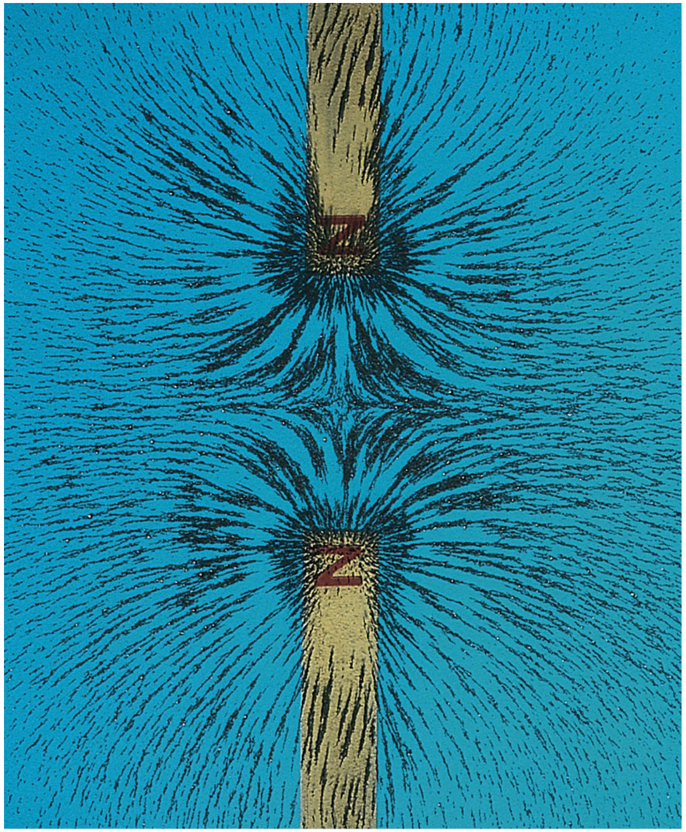
- Iron filings are used to show the pattern of the magnetic field lines.
- The direction of the field is the direction a north pole would point.
  - Compare to the electric field produced by an electric dipole



b

Magnetic Field Lines, Like Poles

- Iron filings are used to show the pattern of the electric field lines.
- The direction of the field is the direction a north pole would point.
  - Compare to the electric field produced by like charges



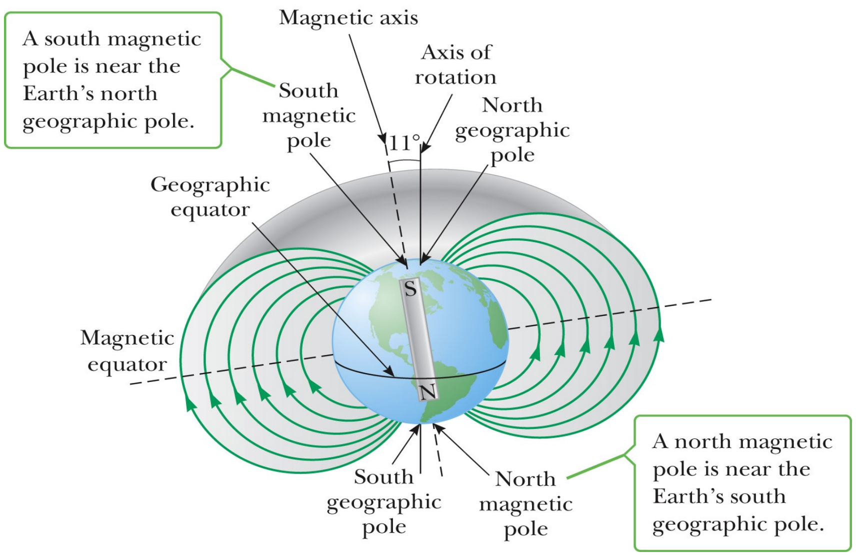
c

Earth's Magnetic Field

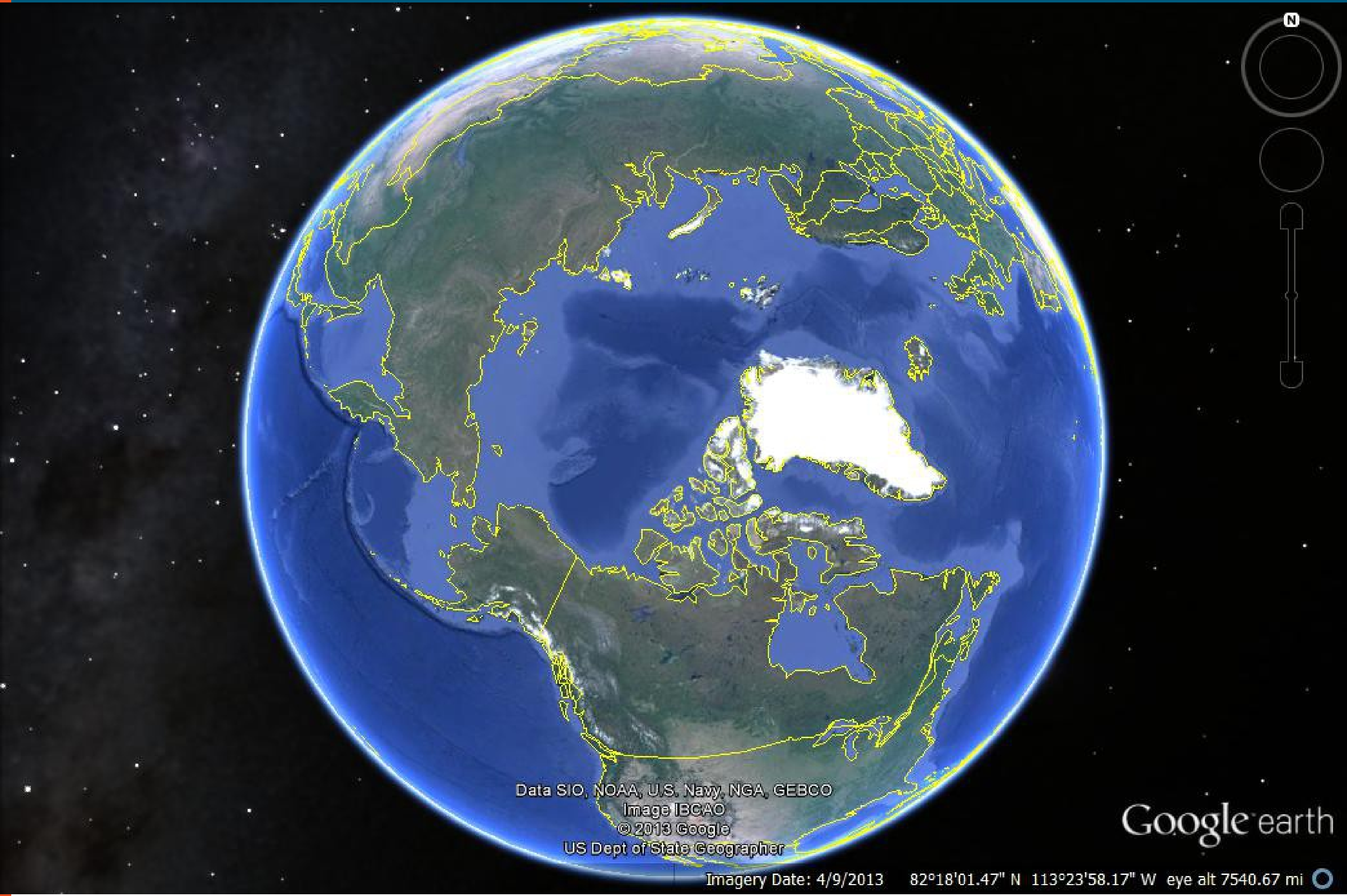
- The Earth's geographic north pole corresponds to a magnetic south pole.
- The Earth's geographic south pole corresponds to a magnetic north pole.
  - Strictly speaking, a north pole should be a "north-seeking" pole and a south pole a "south-seeking" pole.
  -

Earth's Magnetic Field

- The Earth's magnetic field resembles that achieved by burying a huge bar magnet deep in the Earth's interior.



The Geographic North Pole Is the magnetic South Pole The north pole of a magnet in a compass points north because it's attracted to Earth's *magnetic* south pole, located near Earth's *geographic* north pole.


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
© 2013 Google
US Dept of State Geographer
Google earth
Imagery Date: 4/9/2013
82°18'01.47" N 113°23'58.17" W eye alt 7540.67 mi
N

Dip Angle of Earth's Magnetic Field

- If a compass is free to rotate vertically as well as horizontally, it points to the earth's surface.
- The angle between the horizontal and the direction of the magnetic field is called the *dip angle.*

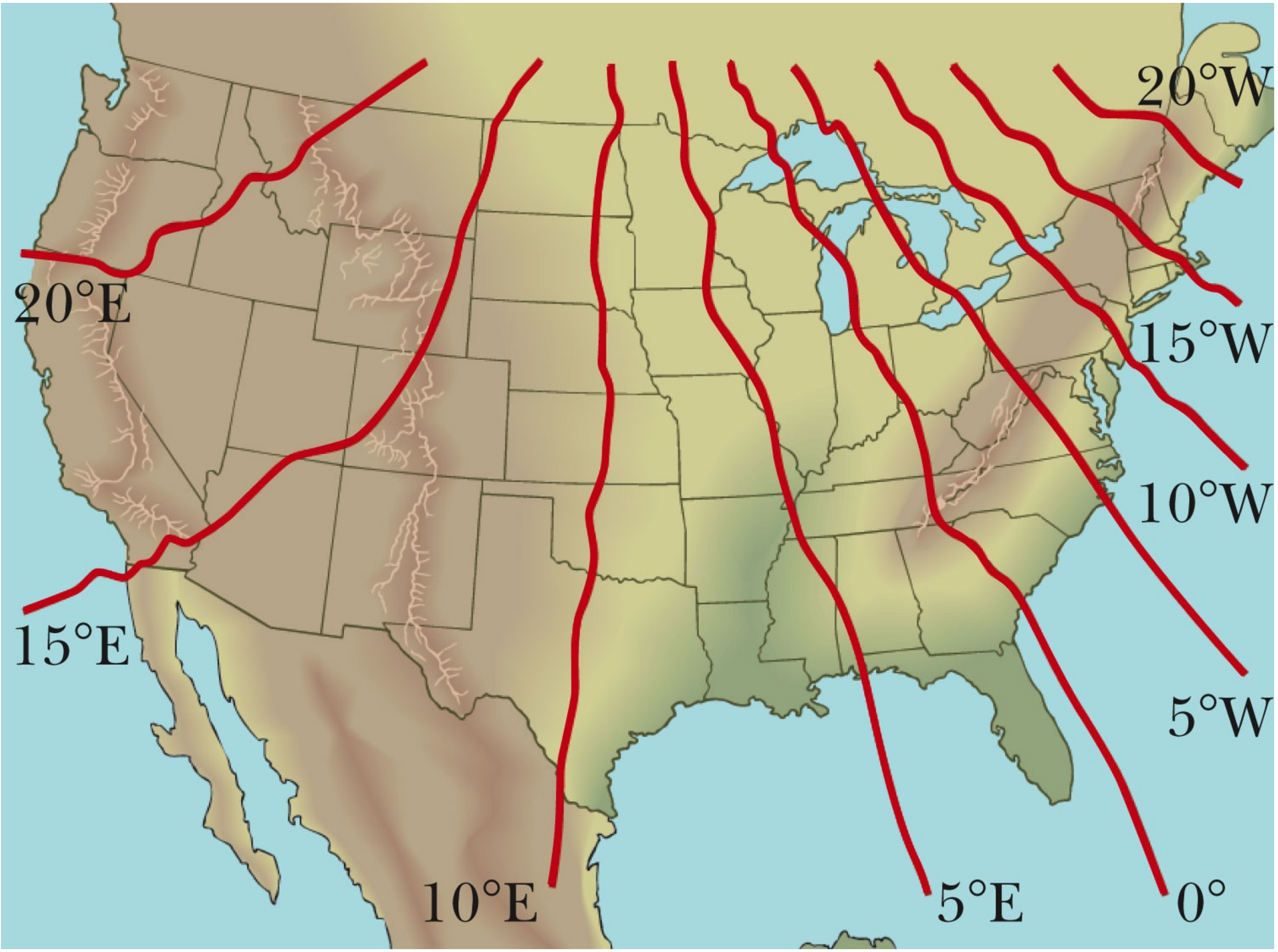
Dip Angle, Cont.

- The farther north the device is moved, the farther from horizontal the compass needle would be.
  - The compass needle would be horizontal at the equator and the dip angle would be 0°
  - The compass needle would point straight down at the south magnetic pole and the dip angle would be 90°

More About the Earth's Magnetic Poles

- The dip angle of 90° is found at a point just north of Hudson Bay in Canada.
  - This is considered to be the location of the south magnetic pole.
- The magnetic and geographic poles are not in the same exact location.
  - The difference between true north, at the geographic north pole, and magnetic north is called the *magnetic declination.*
- The amount of declination varies by location on the earth's surface.
-

Earth's Magnetic Declination



Source of the Earth's Magnetic Field

- There cannot be large masses of permanently magnetized materials since the high temperatures of the core prevent materials from retaining permanent magnetization.
- The most likely source of the Earth's magnetic field is believed to be electric currents in the liquid part of the core.

Reversals of the Earth's Magnetic Field

- The direction of the Earth's magnetic field reverses every few million years.
  - Evidence of these reversals are found in basalts resulting from volcanic activity.
  - The origin of the reversals is not understood.

Magnetic Fields

- When a charged particle is moving through a magnetic field, a magnetic force acts on it.
  - This force has a maximum value when the charge moves perpendicularly to the magnetic field lines.
  - This force is zero when the charge moves along the field lines.

Magnetic Fields, Cont.

- One can define a magnetic field in terms of the magnetic force exerted on a test charge moving in the field with velocity. $\vec{\mathbf{v}}$
  - Similar to the way electric fields are defined
  - The magnitude of the magnetic force is $F = q\,v\,B \sin\theta$
- This gives the magnitude of the magnetic field as

$$B \equiv \frac{F}{qv \sin\theta}$$

Units of Magnetic Field

- The SI unit of magnetic field is the *Tesla* (T)
-
- $$T = \frac{Wb}{m^2} = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}$$

– Wb is a Weber

- The cgs unit is a *Gauss* (G)

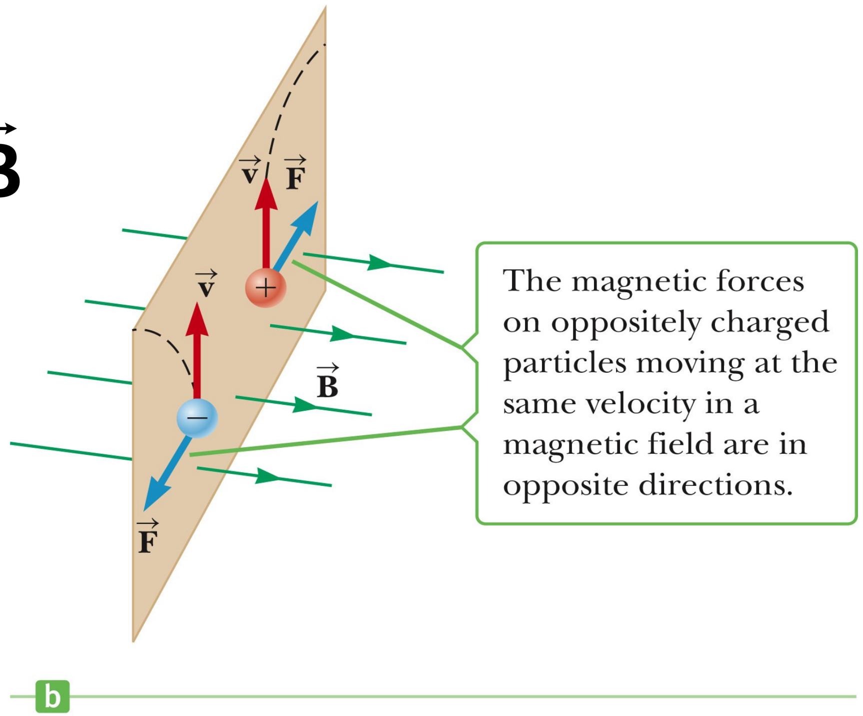
– 1 T = 10^4 G

A Few Typical B Values

- Conventional laboratory magnets
  - 25000 G or 2.5 T
- Superconducting magnets
  - 300000 G or 30 T
- Earth's magnetic field
  - 0.5 G or 5×10^{-5} T

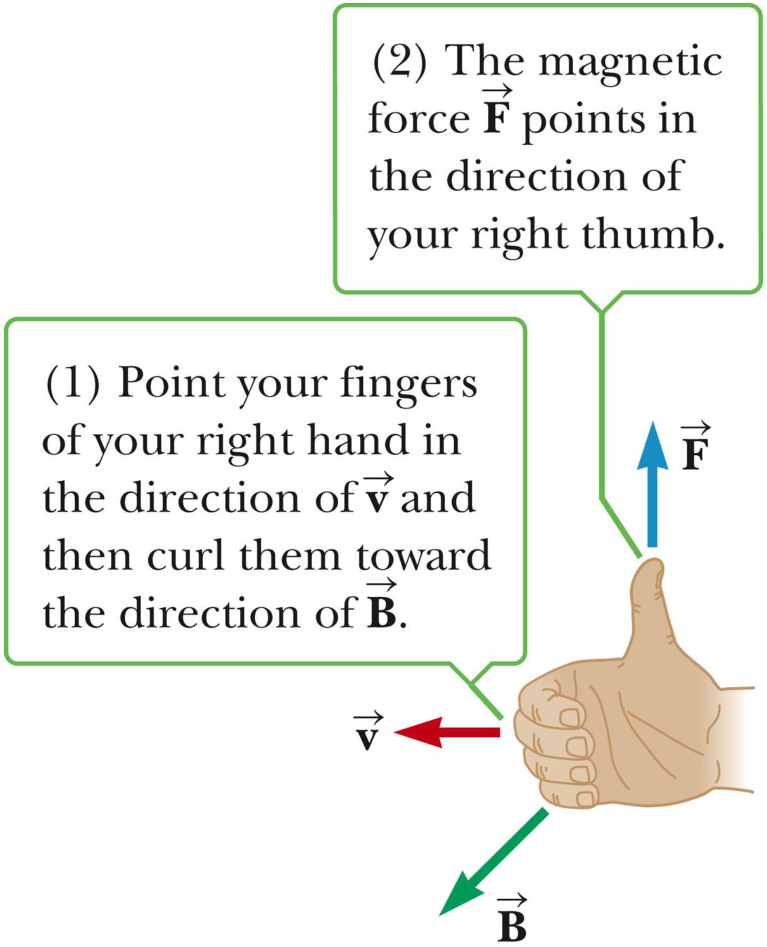
Finding the Direction of Magnetic Force

- Experiments show that the direction of the magnetic force is always perpendicular to both $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$
- F_{max} occurs when the particle's motion is perpendicular to the field.
- F = 0 when the particle's motion is parallel to the field.



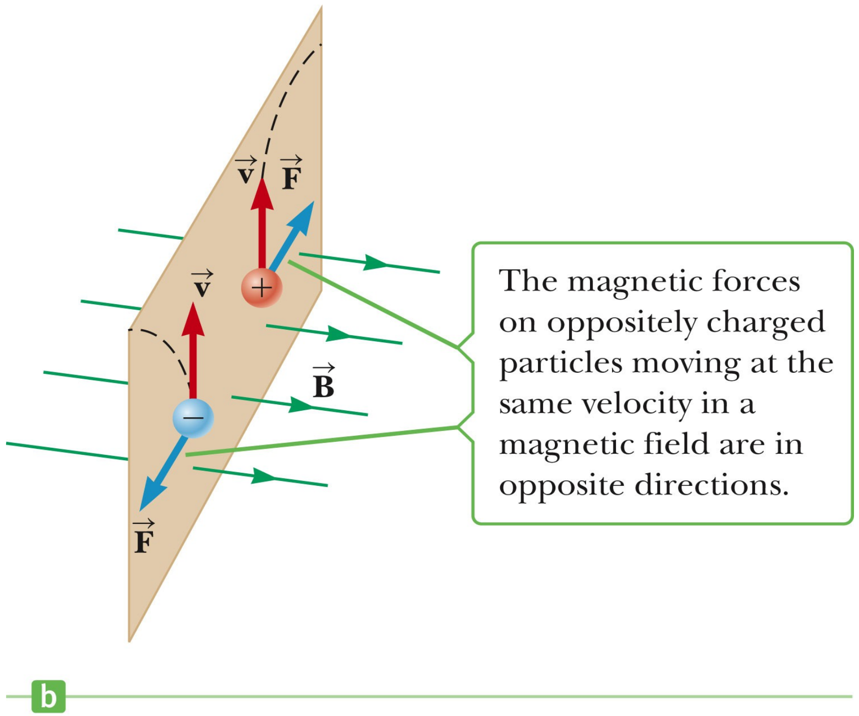
Right Hand Rule #1

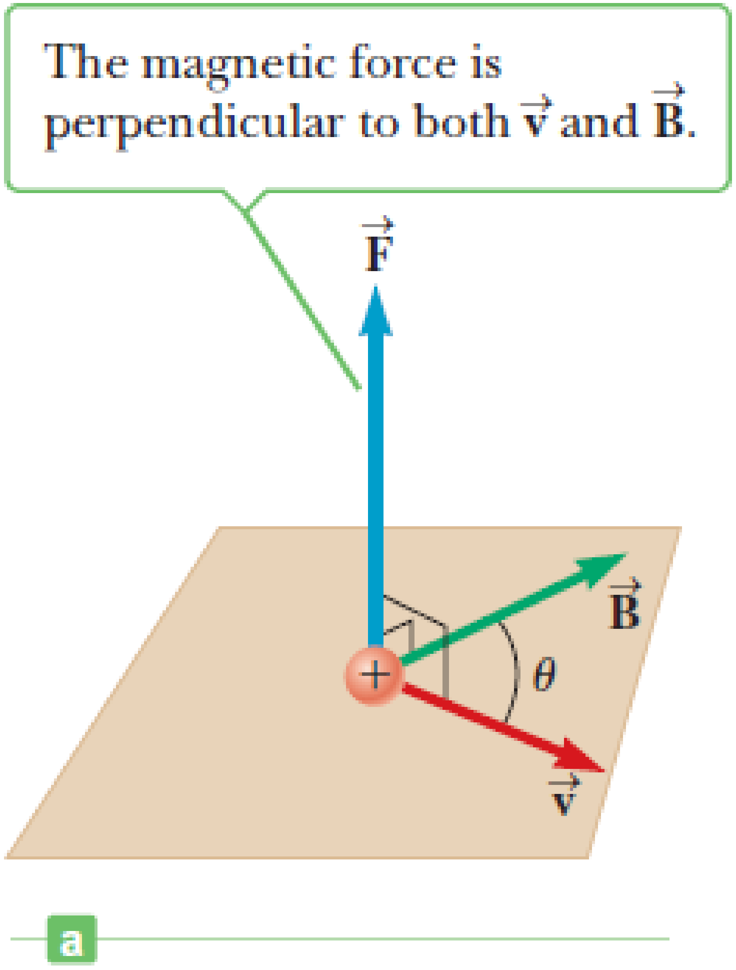
- Point your fingers in the direction of the velocity.
- Curl the fingers in the direction of the magnetic field, $\vec{B}$
- Your thumb points in the direction of the force on a positive charge.



Force on a Negative Charge

- If the charge is negative rather than positive, the force is directed *opposite* that obtained from the right-hand rule.




The magnetic force is perpendicular to both $\vec{v}$ and $\vec{B}$.
$\vec{F}$
$\vec{B}$
θ
$\vec{v}$
a

Magnetic Force on a Current Carrying Conductor

- A force is exerted on a current-carrying wire placed in a magnetic field.
  – The current is a collection of many charged particles in motion.
- The direction of the force is given by right hand rule #1.

Section 19.4

A proton moves with a speed of 1.00 x 10^5 m/s through Earth's magnetic field, which has a value of 55.0 mT at a particular location. When the proton moves eastward, the magnetic force acting on it is directed straight upward, and when it moves northward, no magnetic force acts on it. **(a)** What is the direction of the magnetic field, and **(b)** what is the strength of the magnetic force when the proton moves eastward

(a) Find the direction of the magnetic field. No magnetic force acts on the proton when it's going north, so the angle such a proton makes with the magnetic field direction must be either 0° or 180°. Therefore, the magnetic field **B** must point either north or south. Now apply the right-hand rule. When the particle travels east,

(b) Find the magnitude of the magnetic force.

$$\vec{F} = q\,\vec{v} \times \vec{B} = q v B \sin\theta$$

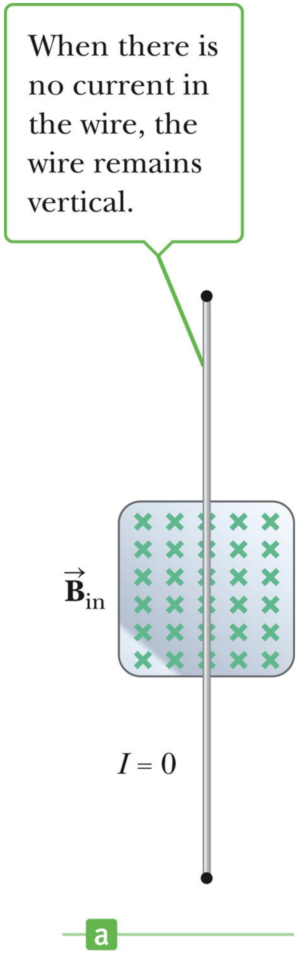
$$= (1.60 \times 10^{-19}\,C)(1 \times 10^{5}\,m/s)(55.0 \times 10^{-6}\,T)\sin 90^\circ$$

$$= 8.80 \times 10^{-19}\,N$$

Recalculate the forces when an electron travels the same manner with the same velocity.

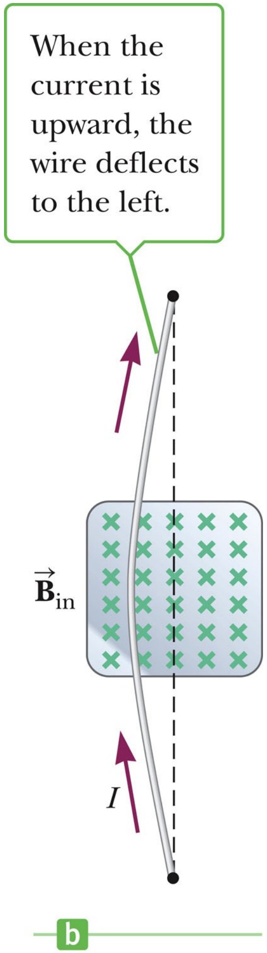
Force on a Wire

- The green x's indicate the magnetic field is directed *into* the page.
  - The x represents the tail of the arrow.
- Green dots would be used to represent the field directed *out of* the page.
  - The • represents the head of the arrow.
- In this case, there is no current, so there is no force.



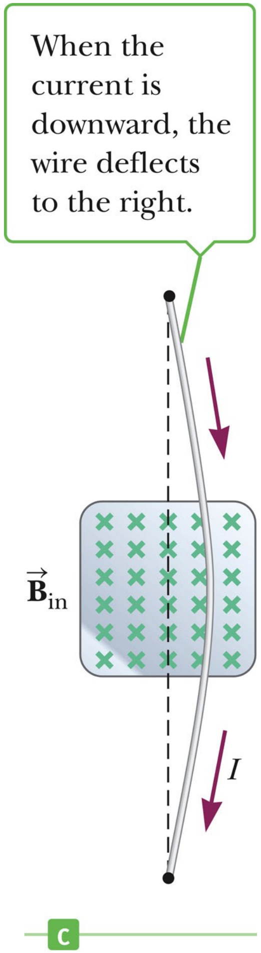
Force on a Wire, Cont.

- B is into the page.
- The current is up the page.
- The force is to the left.



Force on a Wire, Final

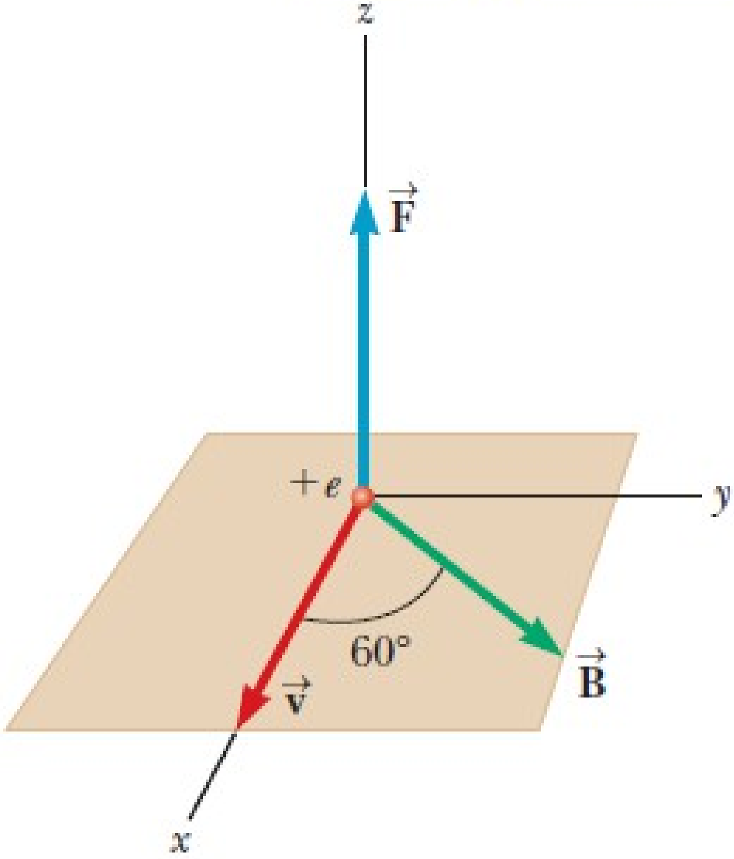
- B is into the page.
- The current is down the page.
- The force is to the right.



Force on a Wire, Equation

- The magnetic force is exerted on each moving charge in the wire.
- The total force is the sum of all the magnetic forces on all the individual charges producing the current.
- $F = B\, I\, \ell \sin\theta$
  - θ is the angle between $\vec{\mathbf{B}}$ and the direction of I
  - The direction is found by the right hand rule. placing your fingers in the direction of I instead of $\vec{\mathbf{v}}$

A proton moves at 8.00 x 10^6 m/s along the *x*-axis. It enters a region in which there is a magnetic field of magnitude 2.50 T, directed at an angle of 60.0° with the *x*-axis and lying in the *xy*-plane (Fig. 19.8). **(a)** Find the initial magnitude and direction of the magnetic force on the proton. **(b)** Calculate the proton's initial acceleration.



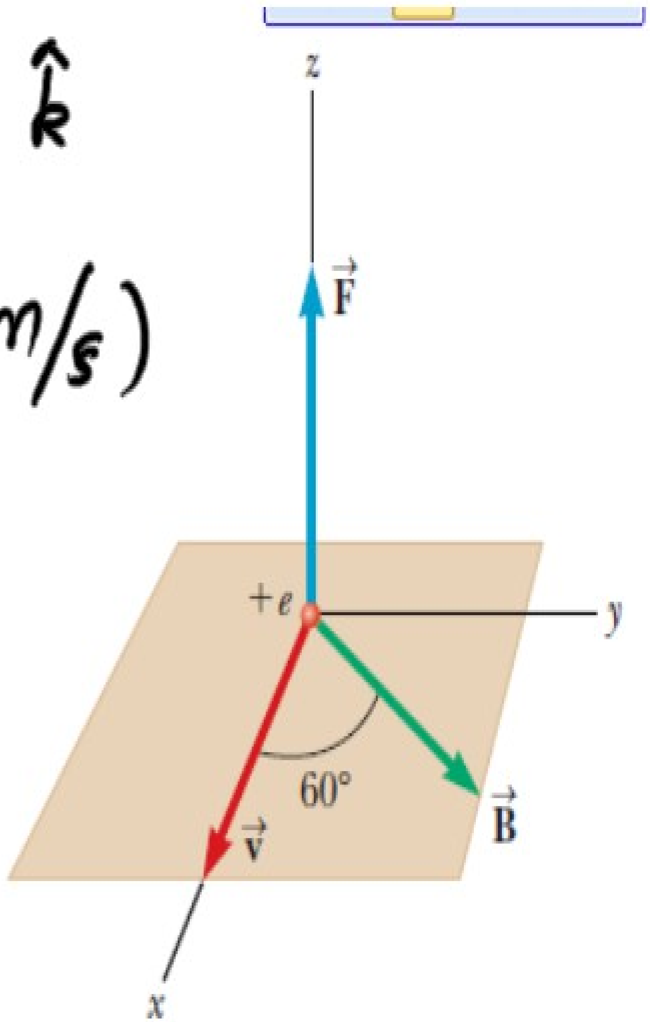
z
F
+e
y
60°
B
v
x

$$\vec{F} = q\,\vec{v} \times \vec{B} = qvB\sin\theta\ \hat{k}$$

$$= (1.60 \times 10^{-19}\,C)(8.00 \times 10^{6}\,m/s)$$

$$\times (2.50\,T)\sin 60^\circ$$

$$= 2.77 \times 10^{-12}\,N\ \hat{k}$$



(b) $F = ma = (1.67 \times 10^{-27}\,kg)\,a$

$= 2.77 \times 10^{-12}\,N$

$\therefore a = 1.66 \times 10^{15}\ m/s^2$

$\vec{a} = 1.66 \times 10^{15}\ \frac{m}{s^2}\ \hat{k}$

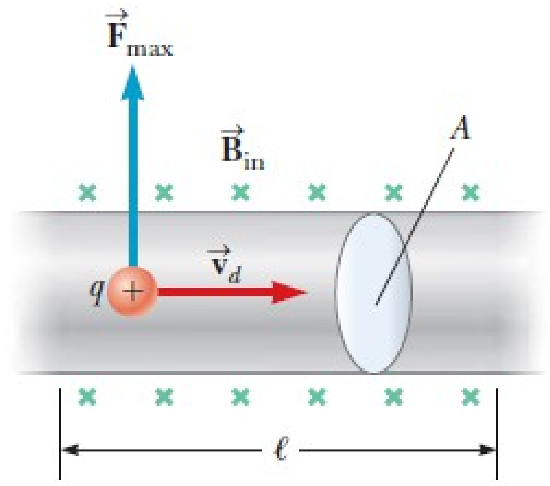


Figure 19.11 A section of a wire containing moving charges in an external magnetic field $\vec{B}$.

Total force = force on each charge carrier × total number of carriers

$$F_{max} = (qv_d B)(nA\ell)$$

From Chapter 17, however, we know that the current in the wire is given by the expression $I = nqv_d A$, so

$$F_{max} = BI\ell \qquad [19.5]$$

This equation can be used only when the current and the magnetic field are at right angles to each other.

In a lightning strike there is a rapid movement of negative charge from a cloud to the ground. In what direction is a lightning strike deflected by Earth’s magnetic field?

In a lightning strike there is a rapid movement of negative charge from a cloud to the ground. In what direction is a lightning strike deflected by Earth's magnetic field?

Negative charges flowing down is the same as current upwards

In a lightning strike there is a rapid movement of negative charge from a cloud to the ground. In what direction is a lightning strike deflected by Earth's magnetic field?

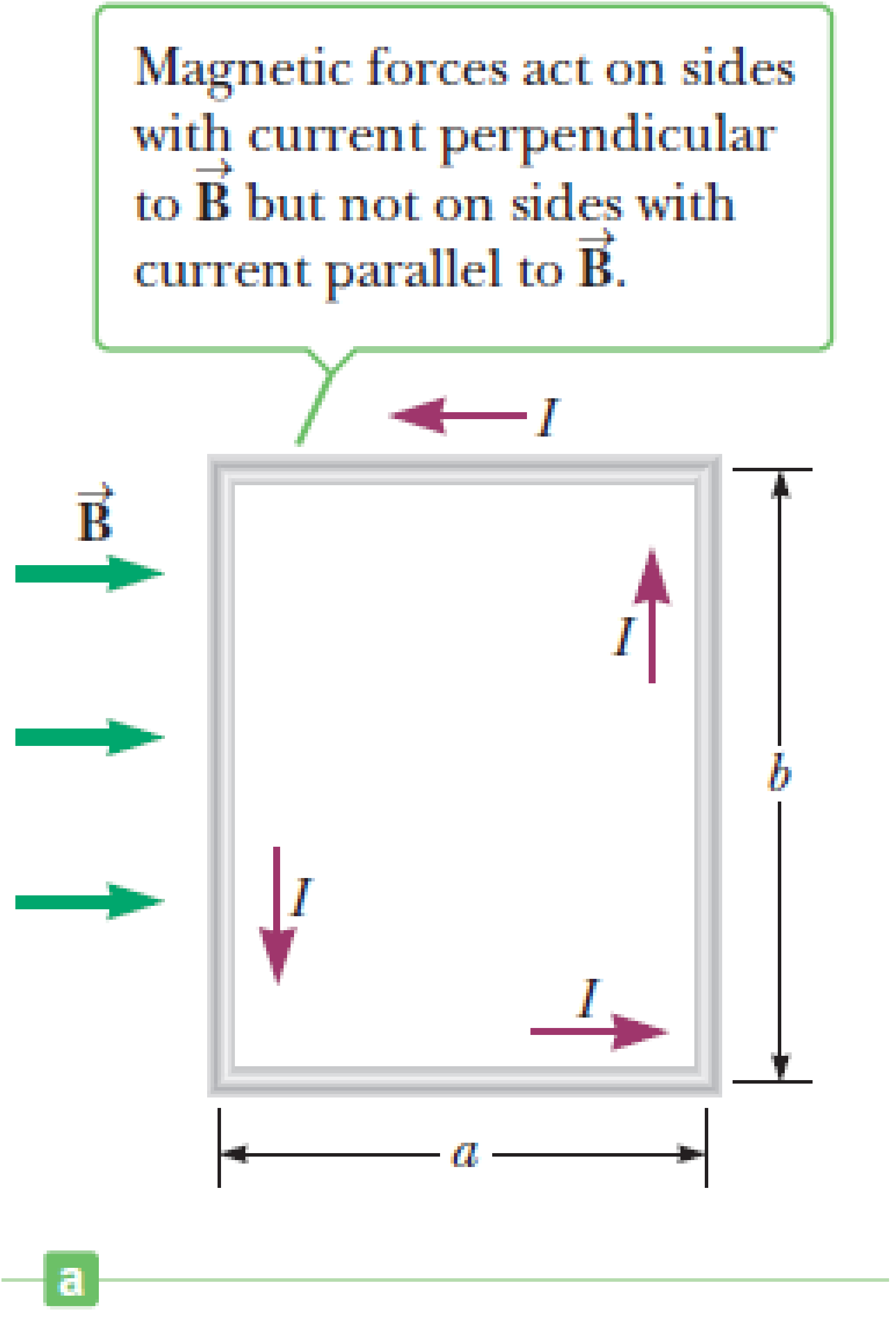
Negative charges flowing down is the same as current upwards

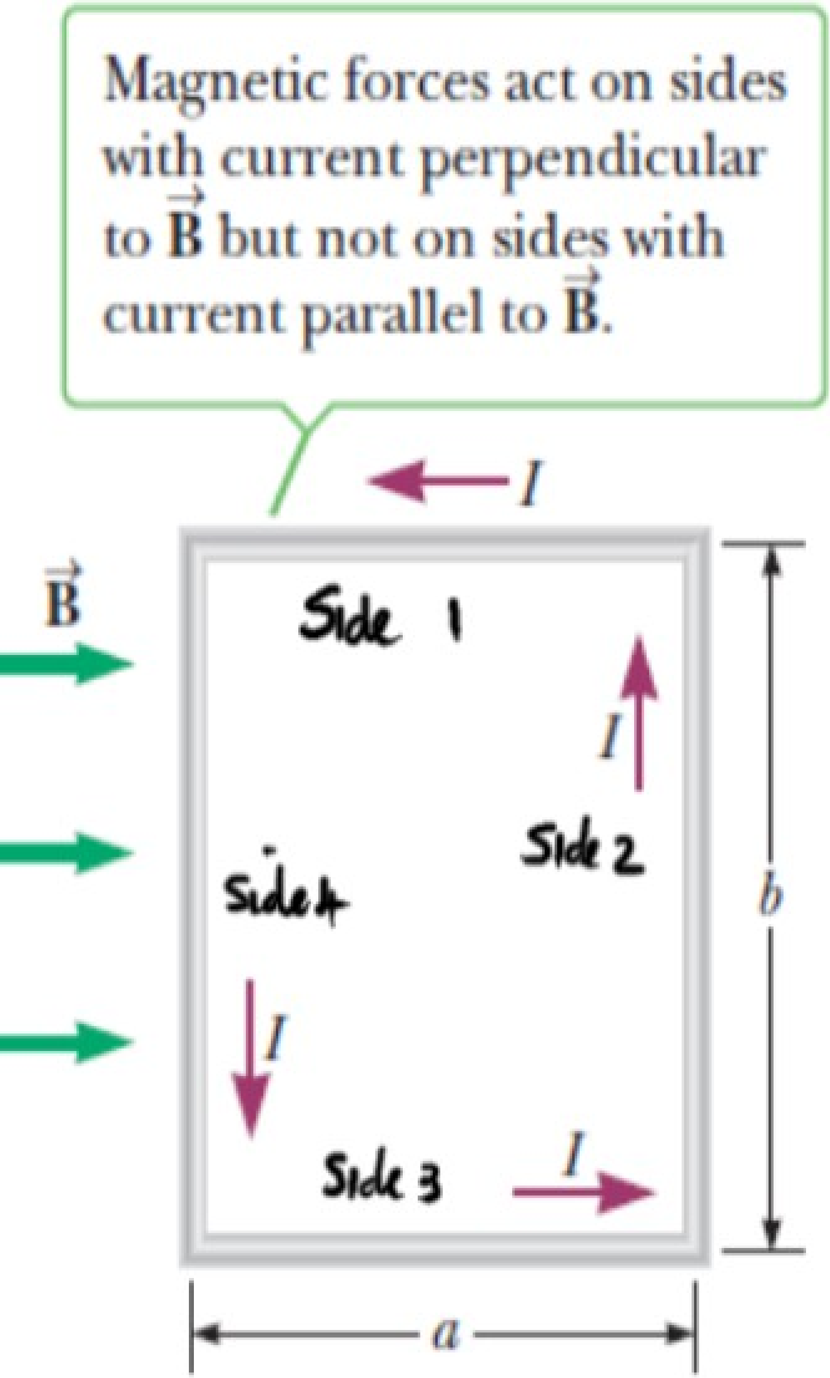
$$\vec{F} = q\,\vec{v} \wedge \vec{B}$$

$$= q v \hat{j} \times B(-\hat{k})$$

$$= qvB(-\hat{i})$$

Westwards!


Magnetic forces act on sides with current perpendicular to $\vec{B}$ but not on sides with current parallel to $\vec{B}$.
I
$\vec{B}$
I
I
I
b
a
a



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

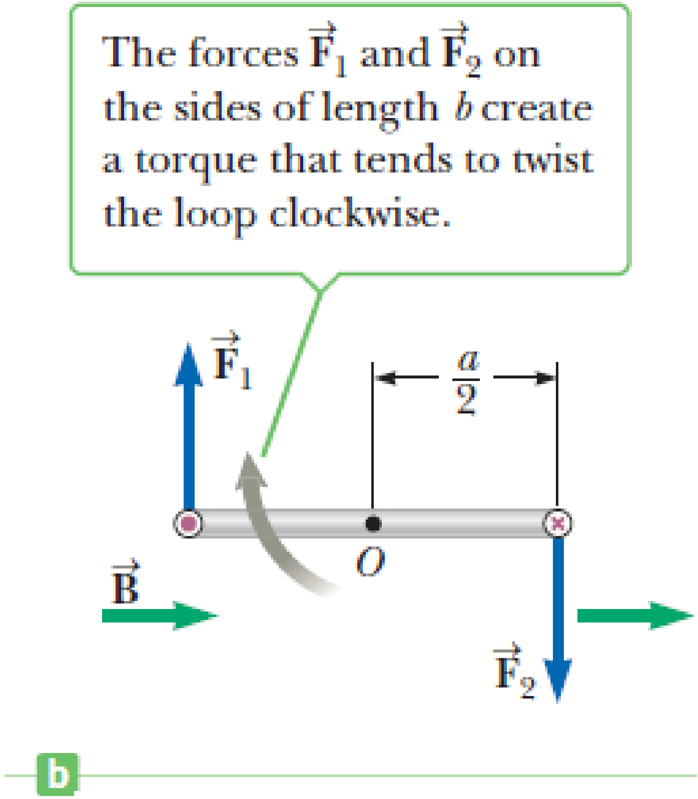
$$= I\,\vec{dl} \times \vec{B} = I\,dl\,B\sin\theta$$

$$= 0 \text{ for side 1 \& 3}$$

$$= I\,dl\,B\,(\hat{j} \times \hat{i}) \text{ (side 2)}$$

$$= IbB\,(-\hat{k}) \text{ (into paper)}$$

$$= IbB\,(\hat{k}) \text{ (out of paper for side 4.)}$$



$$\tau_{\max} = F_1 \frac{a}{2} + F_2 \frac{a}{2} = (BIb)\frac{a}{2} + (BIb)\frac{a}{2} = BIab$$

where the moment arm about O is $a/2$ for both forces. Because the area of the loop is $A = ab$, the maximum torque can be expressed as

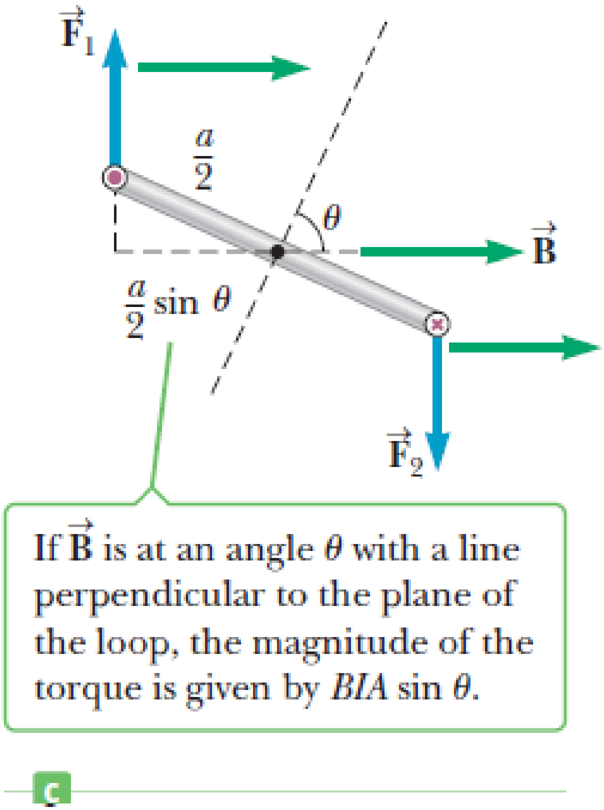
$$\tau_{\max} = BIA \qquad [19.7]$$

$$\tau_{max} = F_1 \frac{a}{2} + F_2 \frac{a}{2} = (BIb)\frac{a}{2} + (BIb)\frac{a}{2} = BIab$$

where the moment arm about O is $a/2$ for both forces. Because the area of the loop is $A = ab$, the maximum torque can be expressed as

$$\tau_{max} = BIA \qquad [19.7]$$

This result is valid only when the magnetic field is *parallel* to the plane of the loop,

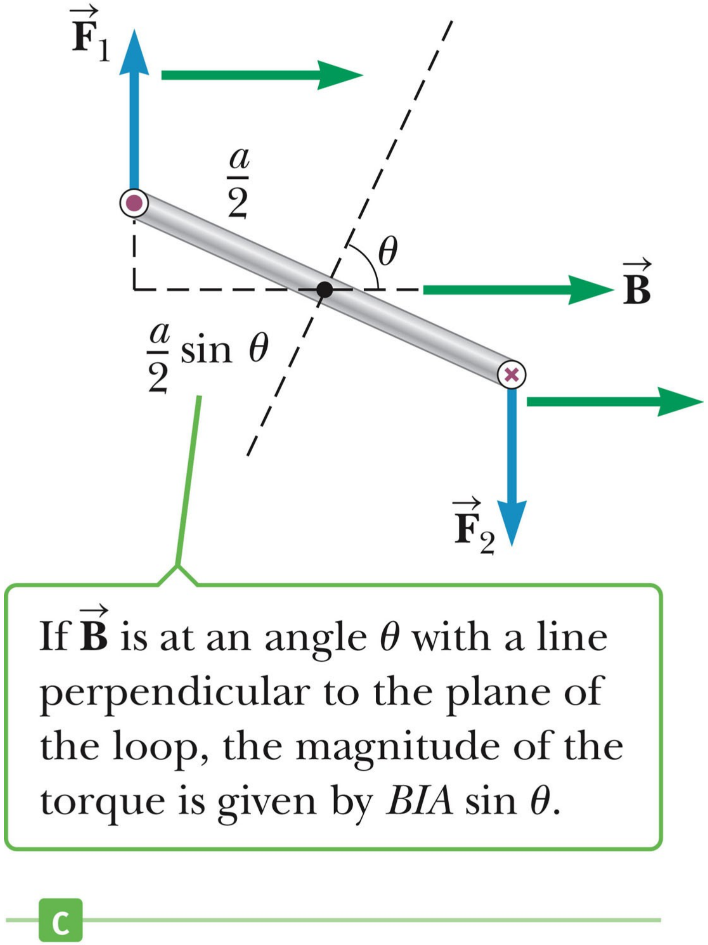


$$\tau = BIA\sin\theta \qquad [19.8]$$

This result shows that the torque has the *maximum* value BIA when the field is parallel to the plane of the loop ($\theta = 90°$) and is *zero* when the field is perpendicular to the plane of the loop ($\theta = 0$). As seen in Figure 19.15c, the loop tends to rotate to smaller values of θ (so that the normal to the plane of the loop rotates toward the direction of the magnetic field).

Torque on a Current Loop

- ≥ = B I A N sin ≥
  - Applies to any shape loop
  - N is the number of turns in the coil
  - Torque has a maximum value of NBIA
- When ≥ = 90°
  - Torque is zero when the field is parallel to the plane of the loop.



Magnetic Moment

- The vector $\vec{\mu}$ s called the magnetic moment of the coil
- Its magnitude is given by ≥ = IAN
- The vector always points perpendicular to the plane of the loop(s).
- The angle is between the moment and the field.
- The equation for the magnetic torque can be written as ≥ = ≥ B sin≥

Although the foregoing analysis was for a rectangular loop, a more general derivation shows that Equation 19.8 applies regardless of the shape of the loop. Further, the torque on a coil with N turns is

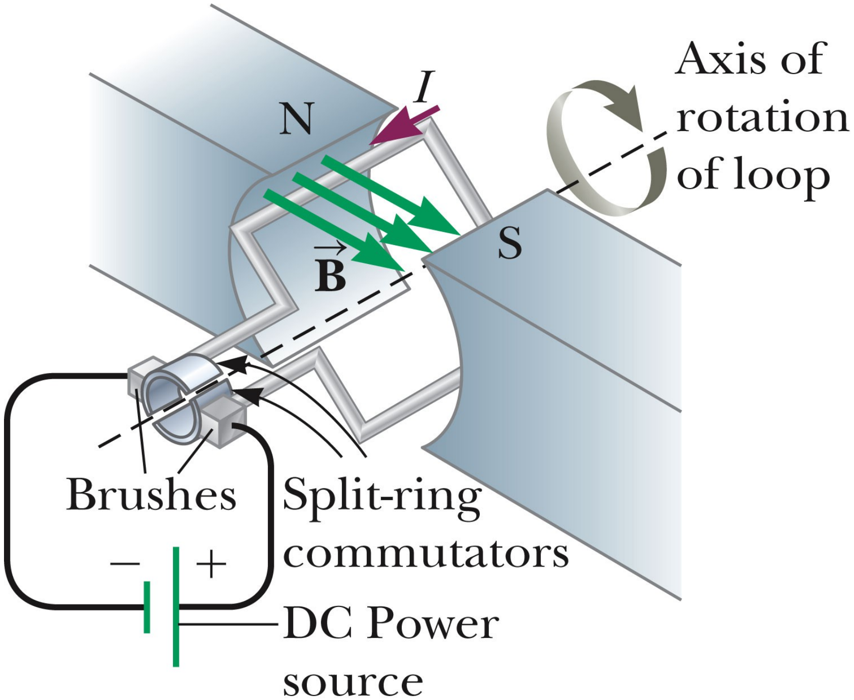
$$\tau = BIAN \sin \theta \qquad [19.9a]$$

The quantity $\mu = IAN$ is defined as the magnitude of a vector $\vec{\mu}$ called the *magnetic moment* of the coil. The vector $\vec{\mu}$ always points perpendicular to the plane of the loop(s) and is such that if the thumb of the right hand points in the direction of $\vec{\mu}$, the fingers of the right hand point in the direction of the current. The angle θ in Equations 19.8 and 19.9 lies between the directions of the magnetic moment $\vec{\mu}$ and the magnetic field $\vec{\mathbf{B}}$. The magnetic torque can then be written

$$\tau = \mu B \sin \theta \qquad [19.9b]$$

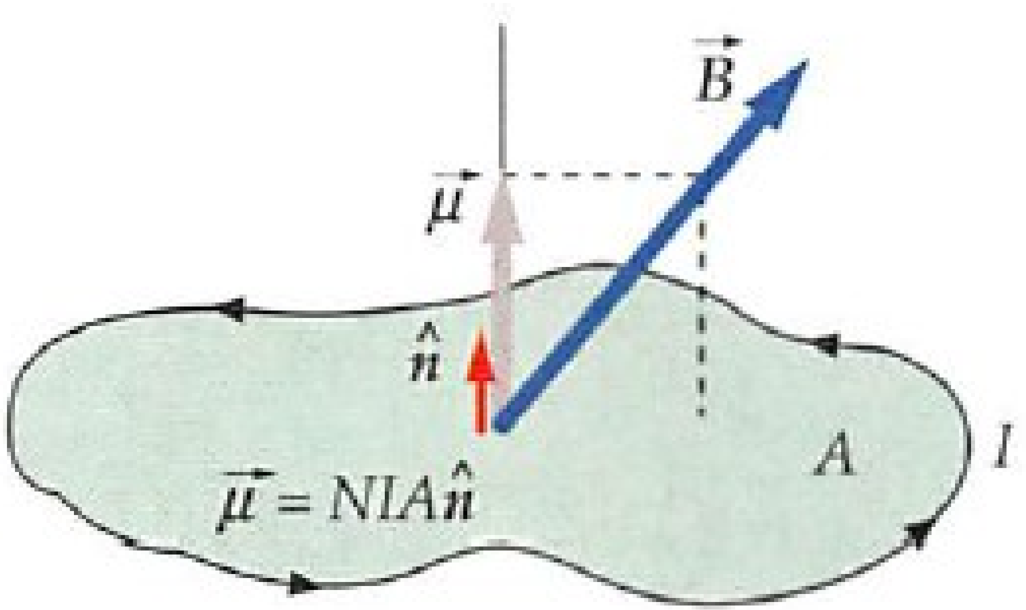
Electric Motor

- An electric motor converts electrical energy to mechanical energy.
  - The mechanical energy is in the form of rotational kinetic energy.



The SI unit of magnetic moment is the ampere-square meter ($A \cdot m^2$). In terms of the magnetic dipole moment, the torque on the current loop is given by

$$\vec{\tau} = \vec{\mu} \times \vec{B} \qquad 26\text{-}15$$



Electric Motor, 2

- An electric motor consists of a rigid current-carrying loop that rotates when placed in a magnetic field.
- The torque acting on the loop will tend to rotate the loop to smaller values of θ until the torque becomes 0 at $\theta = 0°$
- If the loop turns past this point and the current remains in the same direction, the torque reverses and turns the loop in the opposite direction.

Electric Motor, 3

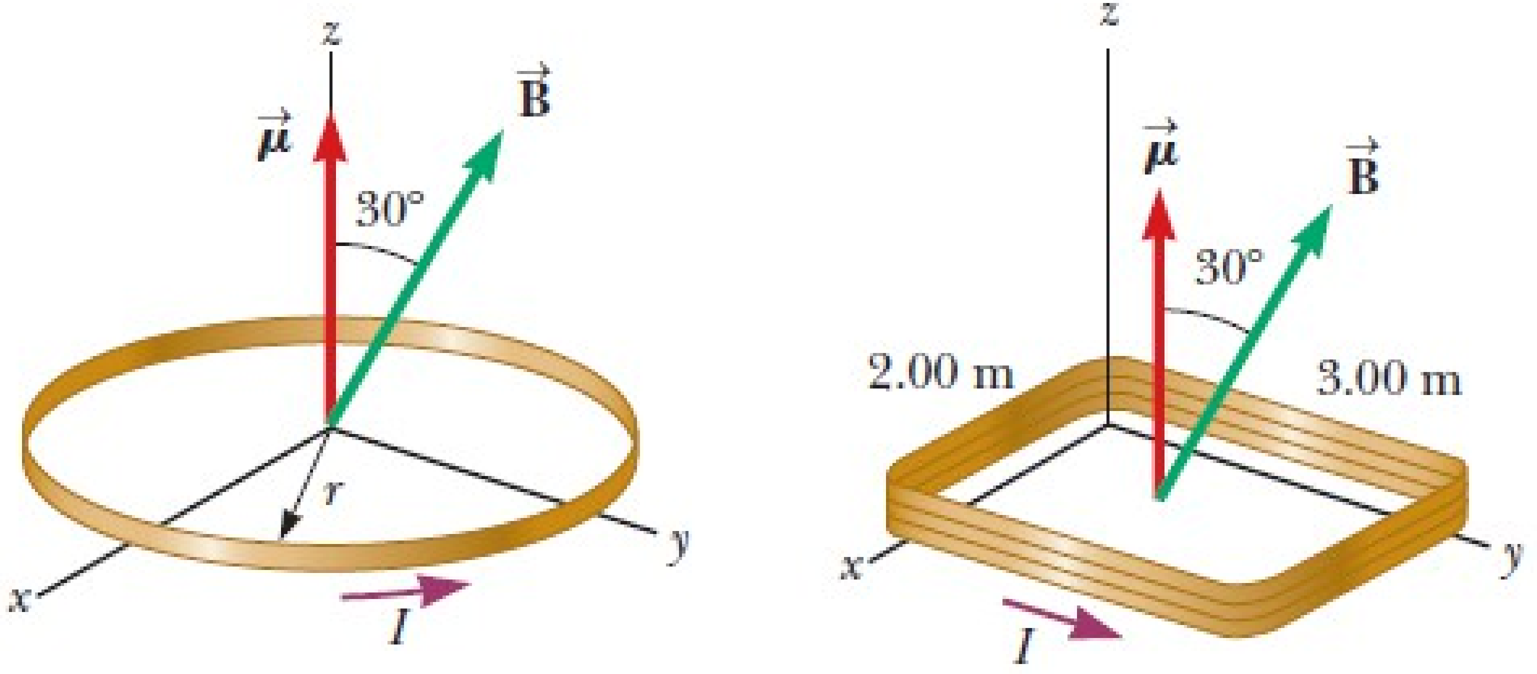
- To provide continuous rotation in one direction, the current in the loop must periodically reverse.
  - In ac motors, this reversal naturally occurs.
  - In dc motors, a *split-ring commutator* and brushes are used.
- Actual motors would contain many current loops and commutators.

Electric Motor, Final

- Just as the loop becomes perpendicular to the magnetic field and the torque becomes 0, inertia carries the loop forward and the brushes cross the gaps in the ring, causing the current loop to reverse its direction.
  - This provides more torque to continue the rotation.
  - The process repeats itself.

A circular wire loop of radius 1.00 m is placed in a magnetic field of magnitude 0.500 T. The normal to the plane of the loop makes an angle of 30.0° with the magnetic field (Fig. 19.16a). The current in the loop is 2.00 A in the direction shown.

(a) Find the magnetic moment of the loop and the magnitude of the torque at this instant. **(b)** The same current is carried by the rectangular 2.00-m by 3.00-m coil with three loops shown in Figure 19.16b. Find the magnetic moment of the coil and the magnitude of the torque acting on the coil at that instant.



a

b

$$A = \pi r^2 = \pi(1.00\ \text{m})^2 = 3.14\ \text{m}^2$$

$$\mu = IAN = (2.00\ \text{A})(3.14\ \text{m}^2)(1) = 6.28\ \text{A} \cdot \text{m}^2$$

$$\tau = \mu B \sin\theta = (6.28\ \text{A} \cdot \text{m}^2)(0.500\ \text{T})(\sin 30.0°)$$

$$= 1.57\ \text{N} \cdot \text{m}$$

$$A = L \times H = (2.00\ \text{m})(3.00\ \text{m}) = 6.00\ \text{m}^2$$

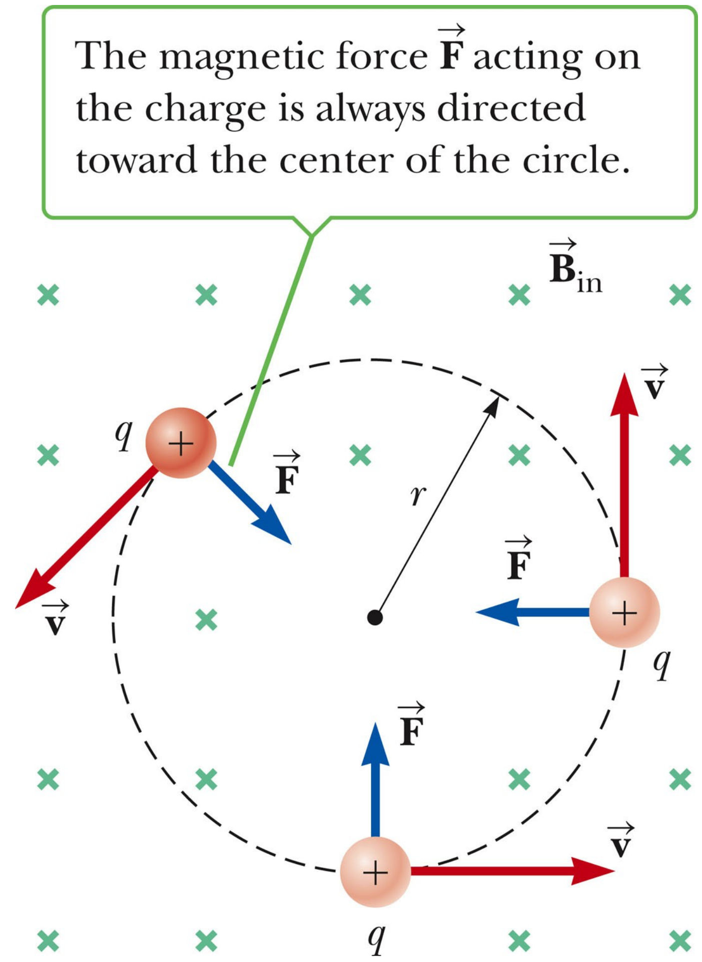
$$\mu = IAN = (2.00\ \text{A})(6.00\ \text{m}^2)(3) = 36.0\ \text{A} \cdot \text{m}^{2)}$$

$$\tau = \mu B \sin\theta = (0.500\ \text{T})(36.0\ \text{A} \cdot \text{m}^2)(\sin 30.0°)$$

$$= 9.00\ \text{N} \cdot \text{m}$$

Force on a Charged Particle in a Magnetic Field

- Consider a particle moving in an external magnetic field so that its velocity is perpendicular to the field.
- The force is always directed toward the center of the circular path.
- The magnetic force causes a centripetal acceleration, changing the direction of the velocity of the particle.



Force on a Charged Particle

- Equating the magnetic and centripetal forces:

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

- Solving for r:

$$r = \frac{mv}{qB}$$

– r is proportional to the momentum of the particle and inversely proportional to the magnetic field.

– Sometimes called the cyclotron equation

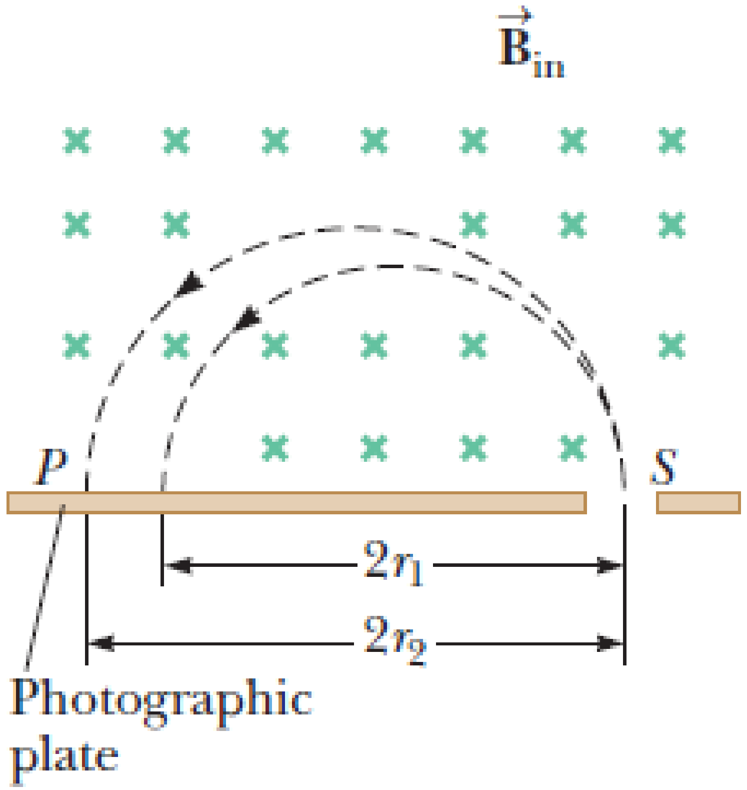


Figure 19.22 (Example 19.6) Two isotopes leave the slit at point *S* and travel in different circular paths before striking a photographic plate at *P*.

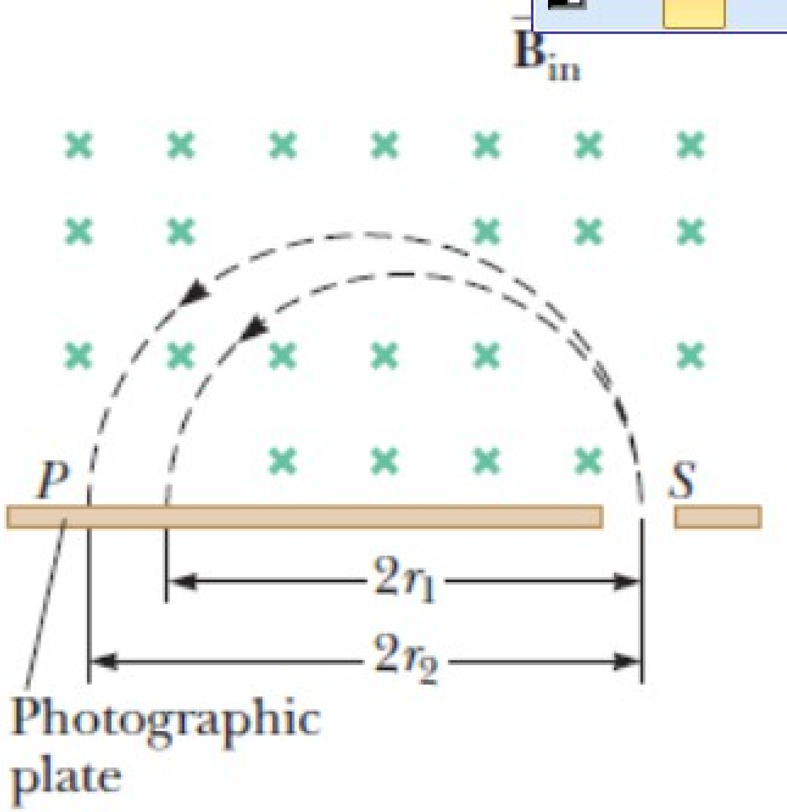
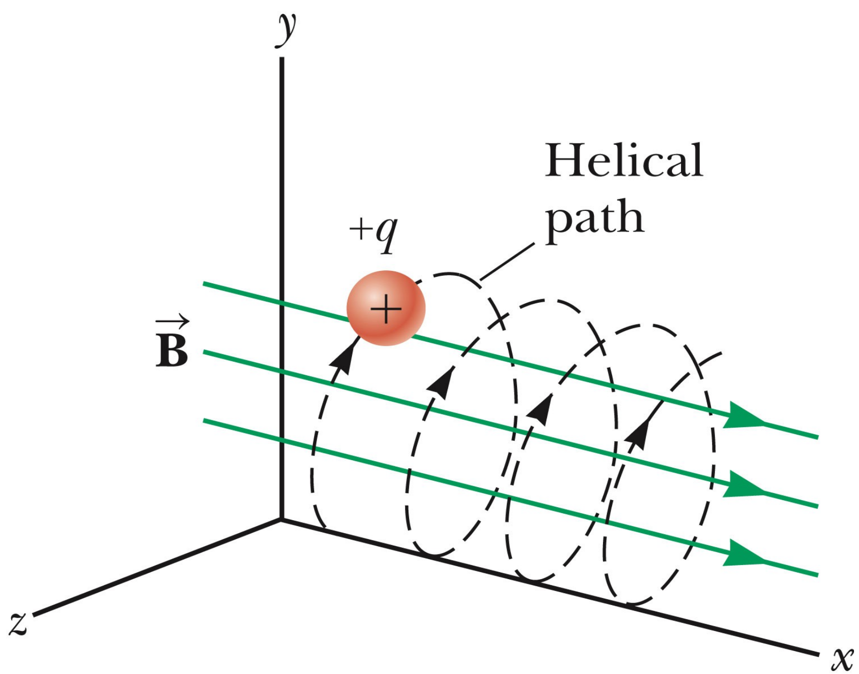


Figure 19.22 (Example 19.6) Two isotopes leave the slit at point S and travel in different circular paths before striking a photographic plate at P.

$$r = \frac{mv}{qB}$$

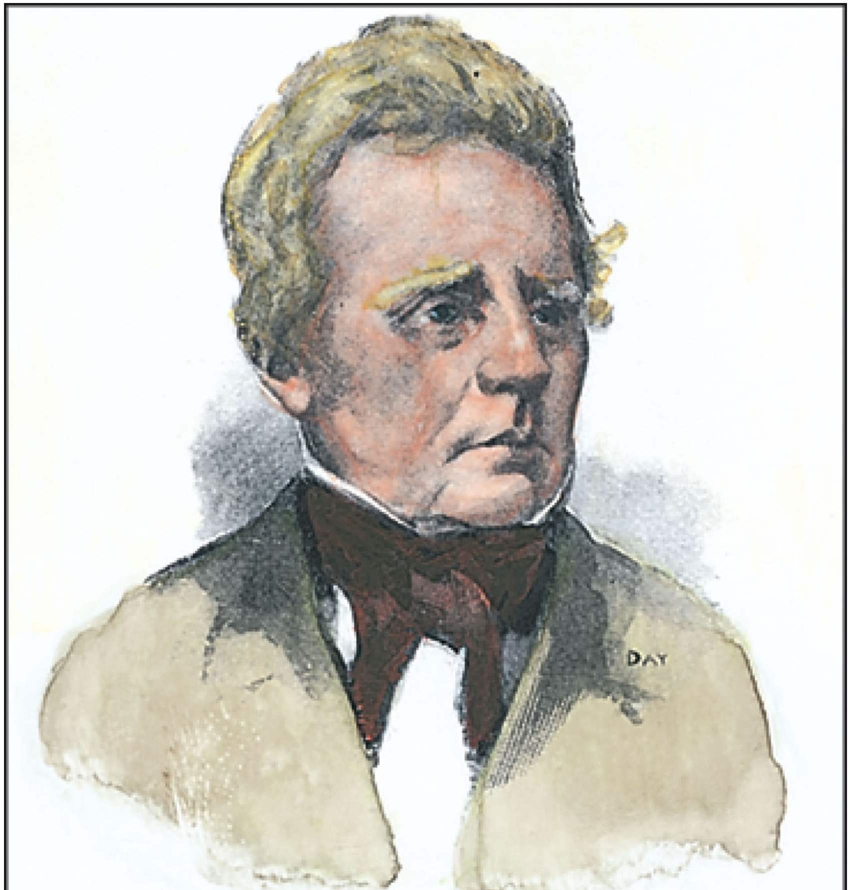
Particle Moving in an External Magnetic Field

- If the particle's velocity is not perpendicular to the field, the path followed by the particle is a spiral.
  - –The spiral path is called a helix.



Hans Christian Oersted

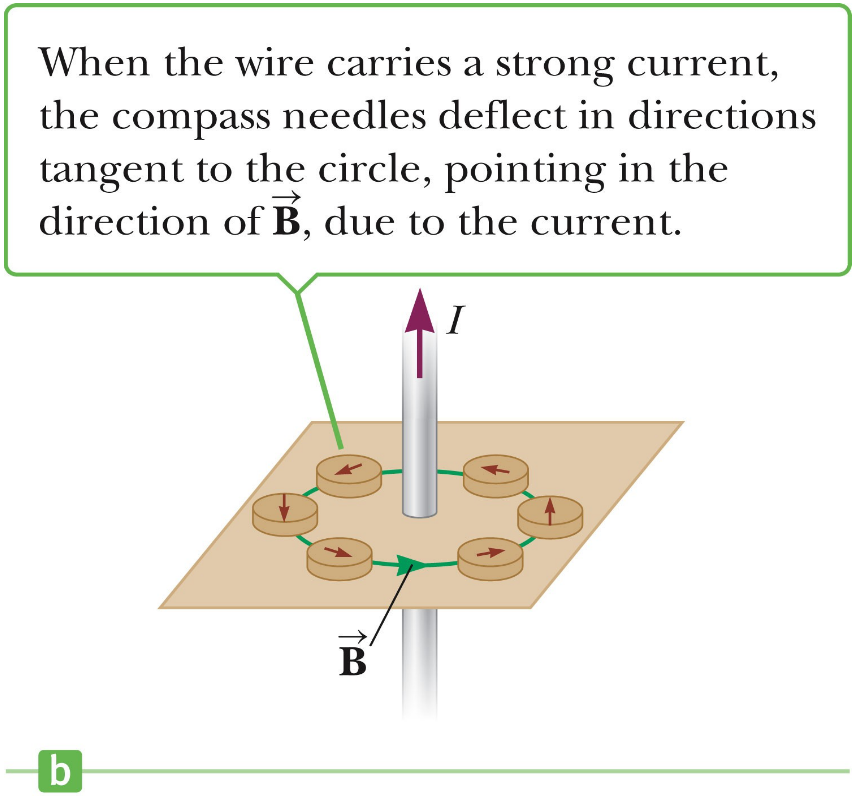
- 1777 – 1851
- Best known for observing that a compass needle deflects when placed near a wire carrying a current
  - First evidence of a connection between electric and magnetic phenomena



HANS CHRISTIAN OERSTED.

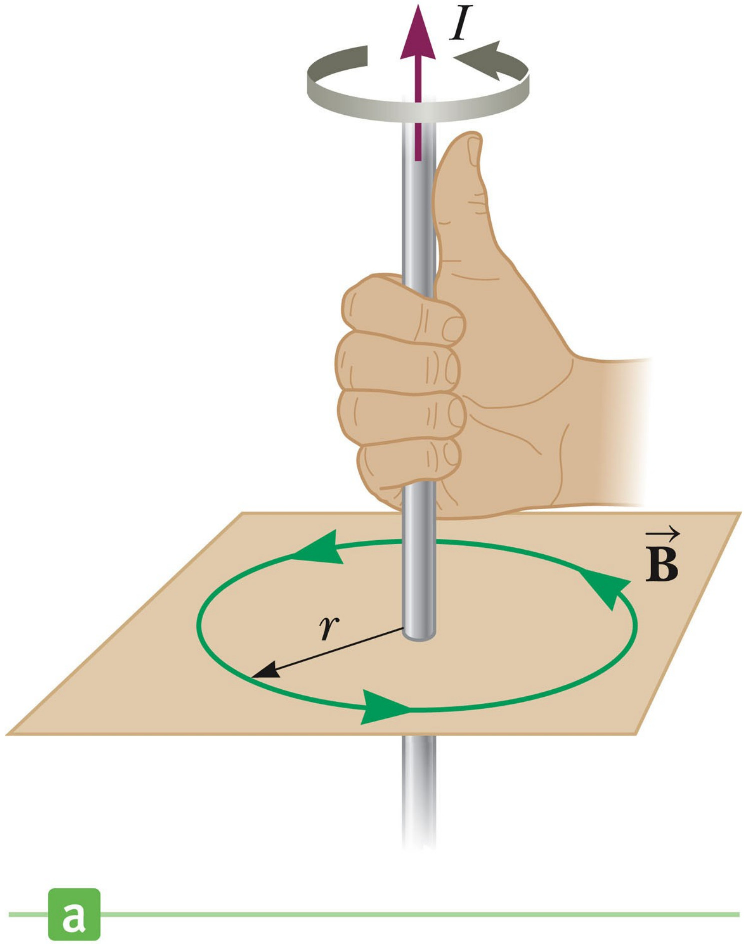
Magnetic Fields – Long Straight Wire

- A current-carrying wire produces a magnetic field.
- The compass needle deflects in directions tangent to the circle.
  - The compass needle points in the direction of the magnetic field produced by the current.



Direction of the Field of a Long Straight Wire

- Right Hand Rule #2
  - Grasp the wire in your right hand.
  - Point your thumb in the direction of the current.
  - Your fingers will curl in the direction of the field.

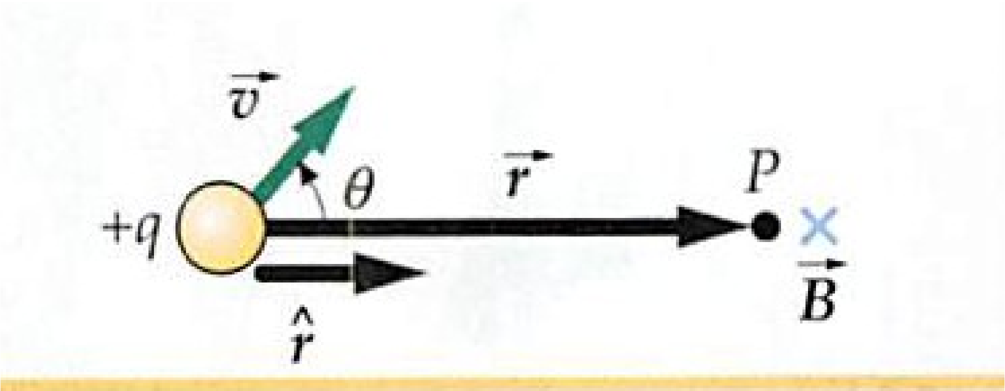


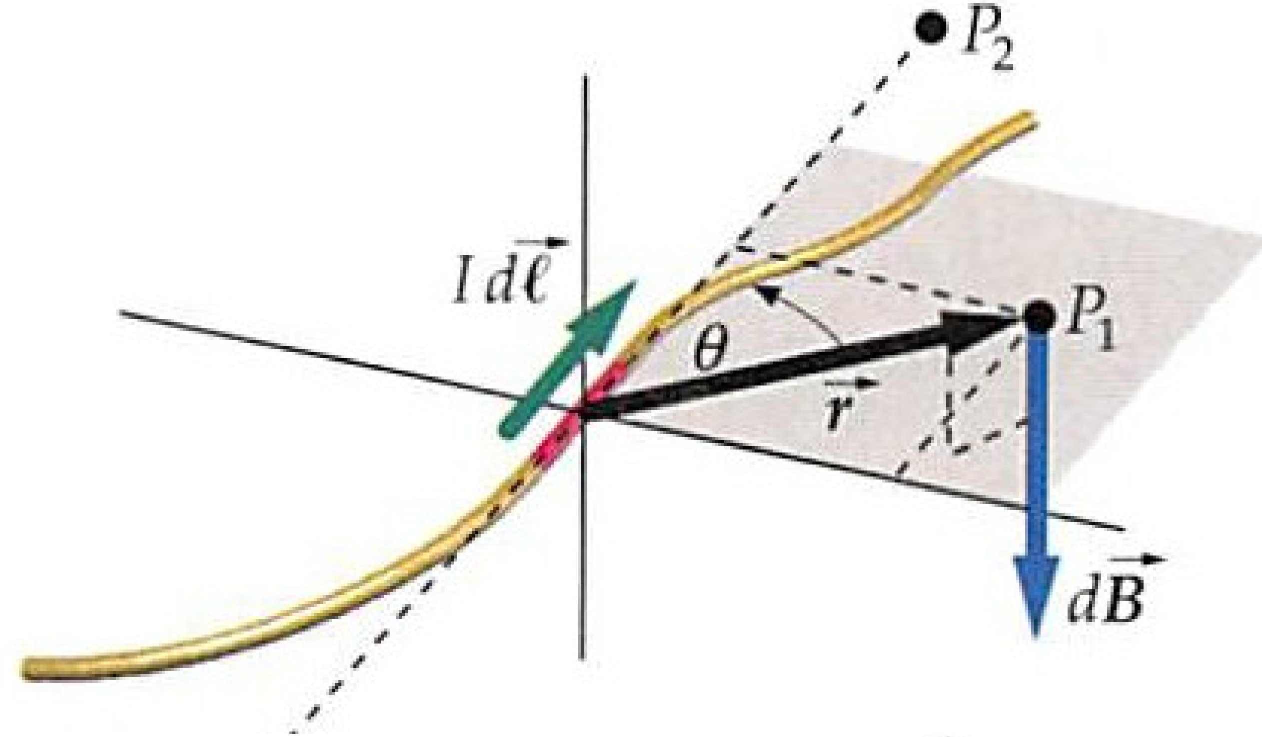
Magnitude of the Field of a Long Straight Wire

- The magnitude of the field at a distance r from a wire carrying a current of I is
- $$B = \frac{\mu_o I}{2\pi r}$$
-
- $\mu_o = 4 \geq \quad x\ 10^{-7}\ T\cdot m / A$
   - μ_o is called the *permeability of free space*

When a point charge q moves with velocity $\vec{v}$, the moving point charge produces a magnetic field $\vec{B}$ in space, given by*

$$\vec{B} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \hat{r}}{r^2} \qquad 27\text{-}1$$





$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\vec{r}}{r^2} = \frac{\mu_0}{4\pi}\, q\,\frac{\frac{d\vec{l}}{t}\times\vec{r}}{r^2} = \frac{\mu_0}{4\pi}\left(\frac{q}{t}\right)\frac{d\vec{l}\times\vec{r}}{r^2}$$

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{\ell}\times\hat{r}}{r^2}$$

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} = \frac{\mu_0}{4\pi}\, q\,\frac{\frac{\vec{dl}}{t}\times\hat{r}}{r^2} = \frac{\mu_0}{4\pi}\left(\frac{q}{t}\right)\frac{\vec{dl}\times\hat{r}}{r^2}$$

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{\ell}\times\hat{r}}{r^2}$$

Equation 27-3, known as the **Biot–Savart law**, was also deduced by Ampère.

analogous to Coulomb's law for the electric field of a point charge.

André-Marie Ampère

- 1775 – 1836
- Credited with the discovery of electromagnetism
  - Relationship between electric currents and magnetic fields

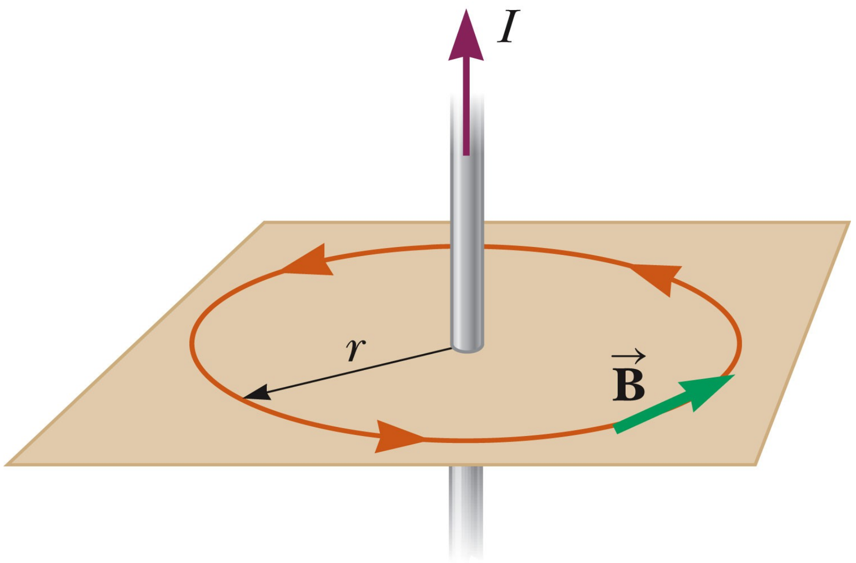
Ampère's Law

- Ampère found a procedure for deriving the relationship between the current in an arbitrarily shaped wire and the magnetic field produced by the wire.
- Ampère's Circuital Law
  - $\geq \quad B_{||} \, \Delta\ell = \mu_o \, I$
  - Sum over the closed path
  -

Ampère's Law to Find B for a Long Straight Wire

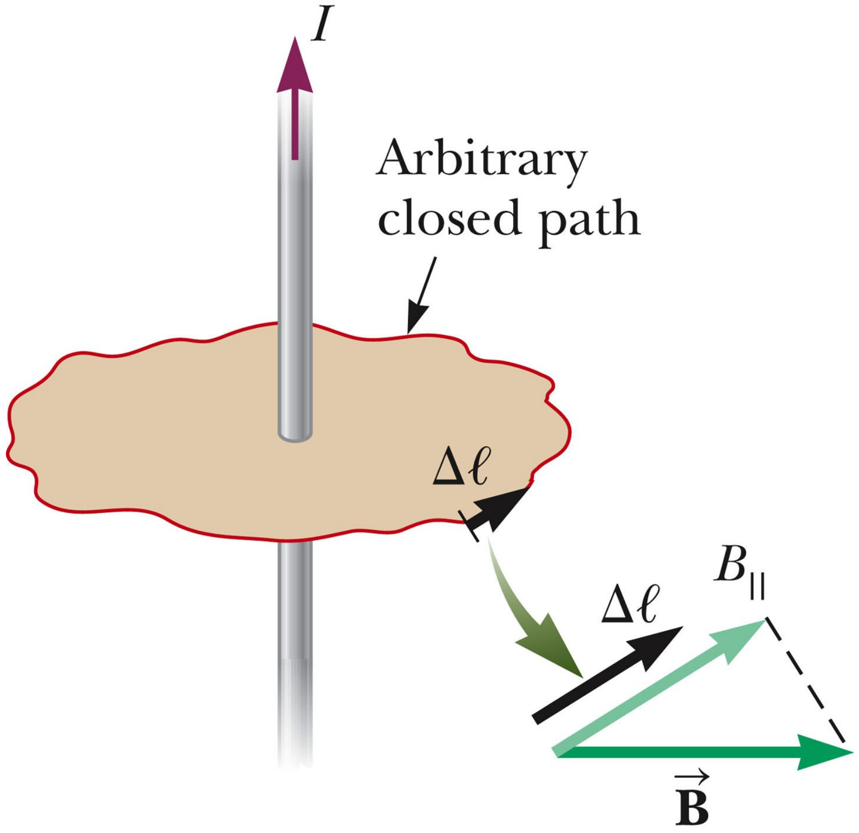
- Use a closed circular path.
- The circumference of the circle is 2 ≥ r
-
- $$B = \frac{\mu_o I}{2\pi r}$$
-

–This is identical to the result previously obtained.



Ampère’s Law, Cont.

- Choose an arbitrary closed path around the current.
- Sum all the products of $B_{||}\,\Delta\ell$ around the closed path.



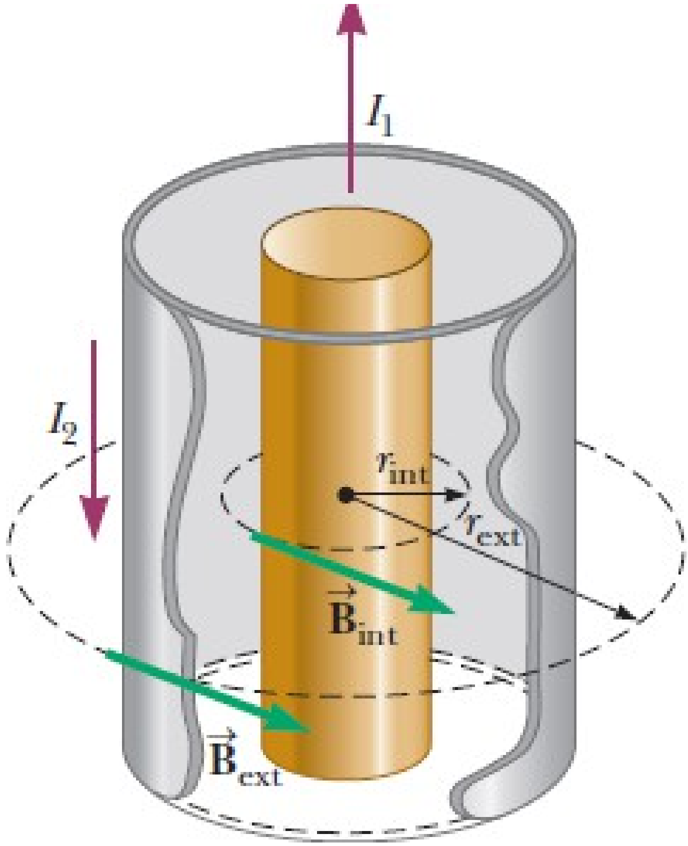
$$\oint_C B_t \, d\ell = \oint_C \vec{B} \cdot d\vec{\ell} = \mu_0 I_C \quad \text{C is any closed curve}$$

AMPÈRE'S LAW

Ampère's law holds *as long as the currents are steady and continuous.*

$\geq \; B_{||} \, \Delta\ell = \mu_o \, I$

PROBLEM A coaxial cable consists of an insulated wire carrying current $I_1 = 3.00$ A surrounded by a cylindrical conductor carrying current $I_2 = 1.00$ A in the opposite direction, as in Figure 19.27. (a) Calculate the magnetic field inside the cylindrical conductor at $r_{int} = 0.500$ cm. (b) Calculate the magnetic field outside the cylindrical conductor at $r_{ext} = 1.50$ cm.



$$\sum B_{\parallel} \Delta \ell = \mu_0 I$$

$$B_{\text{int}} (2\pi r_{\text{int}}) = \mu_0 I_1$$

$$B_{\text{int}} = \frac{\mu_0 I_1}{2\pi r_{\text{int}}} = \frac{(4\pi \times 10^{-7}\,\text{T}\cdot\text{m/A})(3.00\,\text{A})}{2\pi(0.005\,\text{m})}$$

$$= 1.20 \times 10^{-4}\,\text{T}$$

$$\sum B_{\parallel} \Delta \ell = \mu_0 I$$

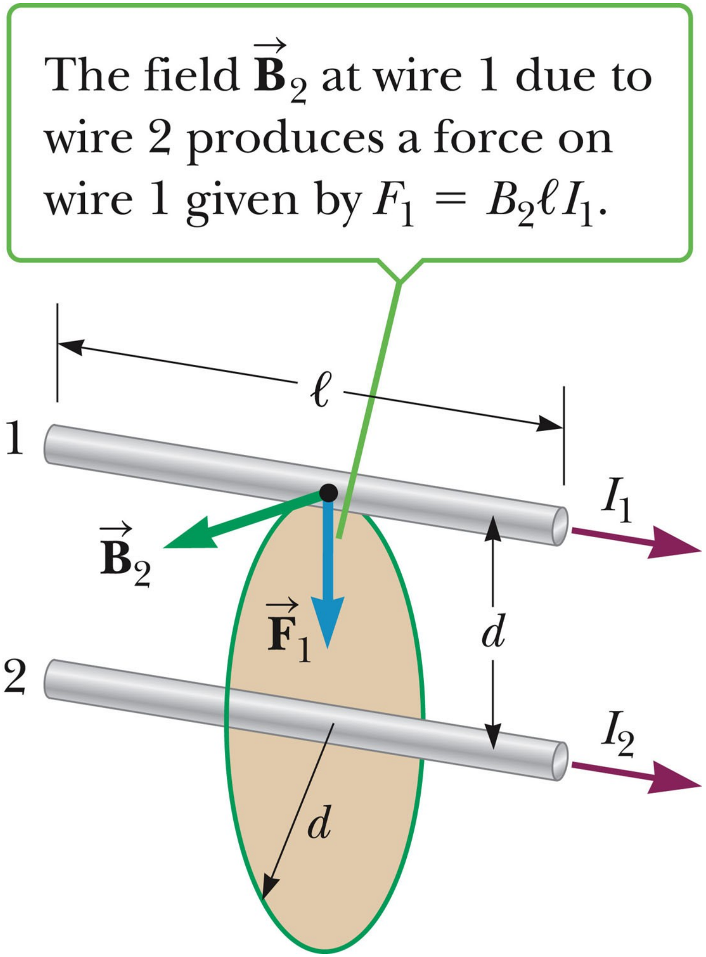
$$B_{\text{ext}}(2\pi r_{\text{ext}}) = \mu_0(I_1 - I_2)$$

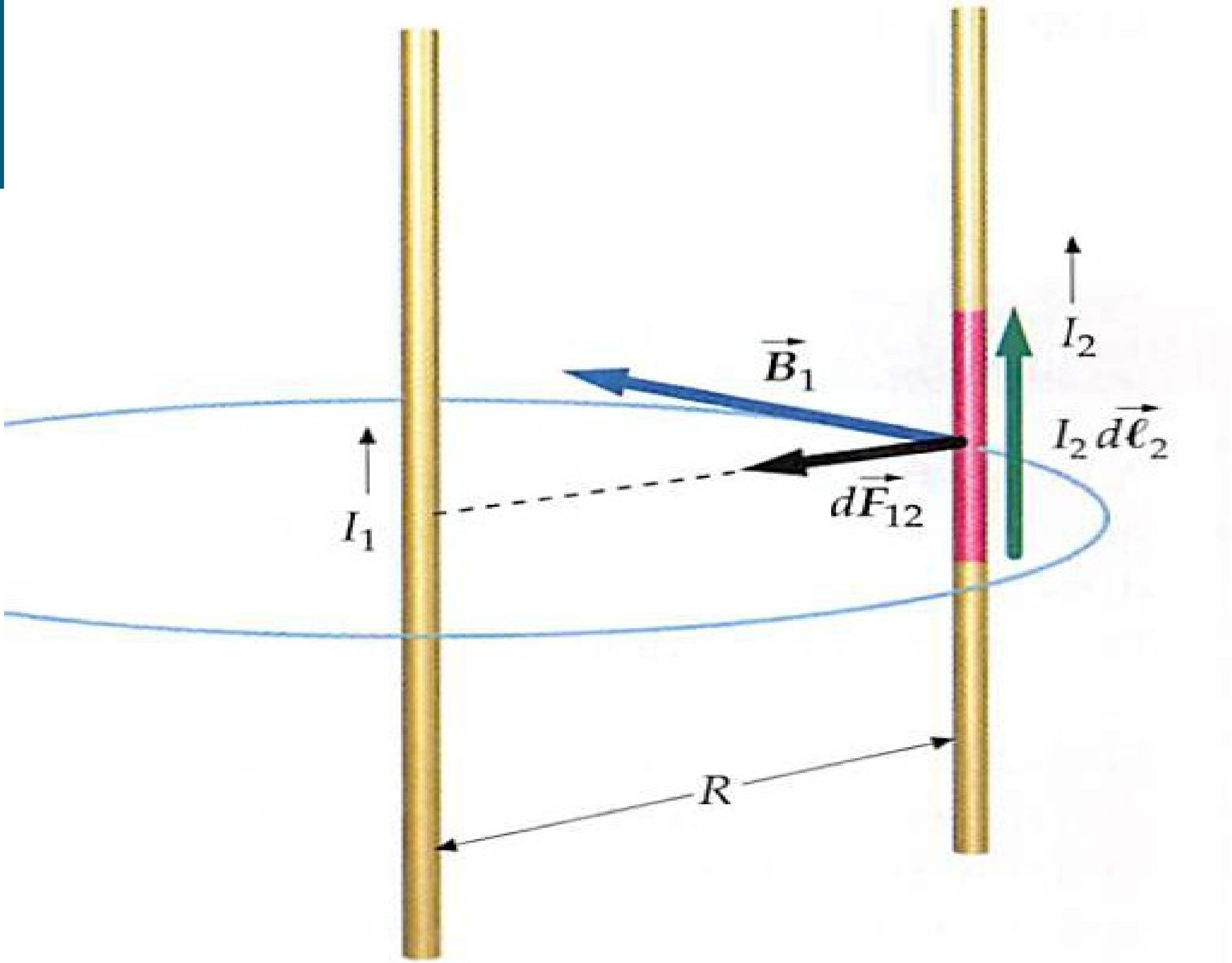
$$B_{\text{ext}} = \frac{\mu_0(I_1 - I_2)}{2\pi r_{\text{ext}}} = \frac{(4\pi \times 10^{-7}\,\text{T}\cdot\text{m/A})(3.00\,\text{A} - 1.00\,\text{A})}{2\pi(0.015\,\text{m})}$$

$$= \boxed{2.67 \times 10^{-5}\,\text{T}}$$

Magnetic Force Between Two Parallel Conductors

- The force on wire 1 is due to the current in wire 1 and the magnetic field produced by wire 2.
- The force per unit length is:
- $$\frac{F}{\ell} = \frac{\mu_o I_1 I_2}{2 \pi d}$$





$\vec{B}_1$
I_2
$I_2\, d\vec{\ell}_2$
$d\vec{F}_{12}$
I_1
R

The magnitude of the magnetic force on the current element $I_2\, d\vec{\ell}_2$ is

$$dF_{12} = \left| I_2\, d\vec{\ell}_2 \times \vec{B}_1 \right|$$

Because the magnetic field at current element $I_2\, d\vec{\ell}_2$ is perpendicular to the current element, we have

$$dF_{12} = I_2\, d\ell_2 B_1$$

$$dF_{12} = I_2\, d\ell_2 \frac{\mu_0 I_1}{2\pi R}$$

$$\frac{dF_{12}}{d\ell_2} = \frac{\mu_0}{2\pi} \frac{I_1 I_2}{R}$$

Force Between Two Conductors, Cont.

- Parallel conductors carrying currents in the same direction attract each other.
- Parallel conductors carrying currents in the opposite directions repel each other.
-

Defining Ampere and Coulomb

- The force between parallel conductors can be used to define the Ampere (A).
  - If two long, parallel wires 1 m apart carry the same current, and the magnitude of the magnetic force per unit length is 2 x 10^{-7} N/m, then the current is defined to be 1 A.
- The SI unit of charge, the Coulomb (C), can be defined in terms of the Ampere.
  - If a conductor carries a steady current of 1 A, then the quantity of charge that flows through any cross section in 1 second is 1 C.

PROBLEM Two wires, each having a weight per unit length of 1.00×10^{-4} N/m, are parallel with one directly above the other. Assume the wires carry currents that are equal in magnitude and opposite in direction. The wires are 0.10 m apart, and the sum of the magnetic force and gravitational force on the upper wire is zero. Find the current in the wires. (Neglect Earth's magnetic field.)

$$\vec{\mathbf{F}}_{\text{grav}} + \vec{\mathbf{F}}_{\text{mag}} = 0$$

$$-mg + \frac{\mu_0 I_1 I_2}{2\pi d}\ell = 0$$

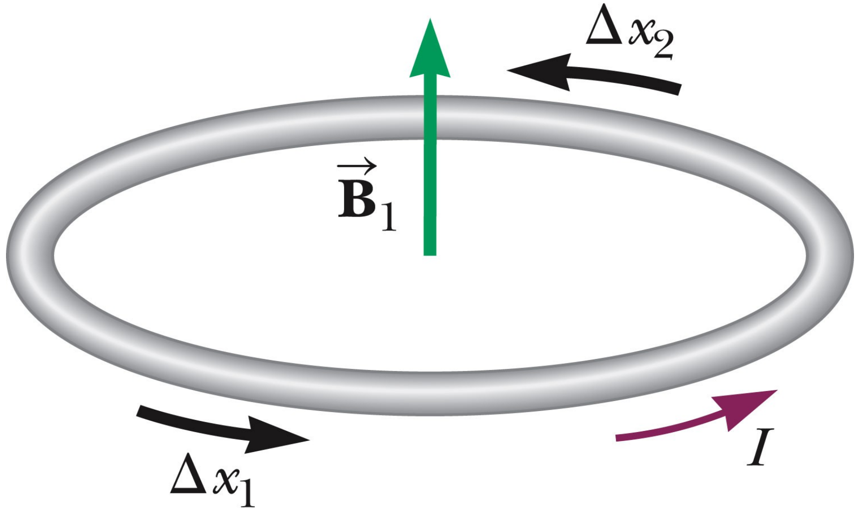
$$\frac{\mu_0 I^2}{2\pi d}\ell = mg \quad \rightarrow \quad I^2 = \frac{(2\pi d)(mg/\ell)}{\mu_0}$$

$$I^2 = \frac{(2\pi \cdot 0.100\ \text{m})(1.00 \times 10^{-4}\ \text{N/m})}{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m})} = 50.0\ \text{A}^2$$

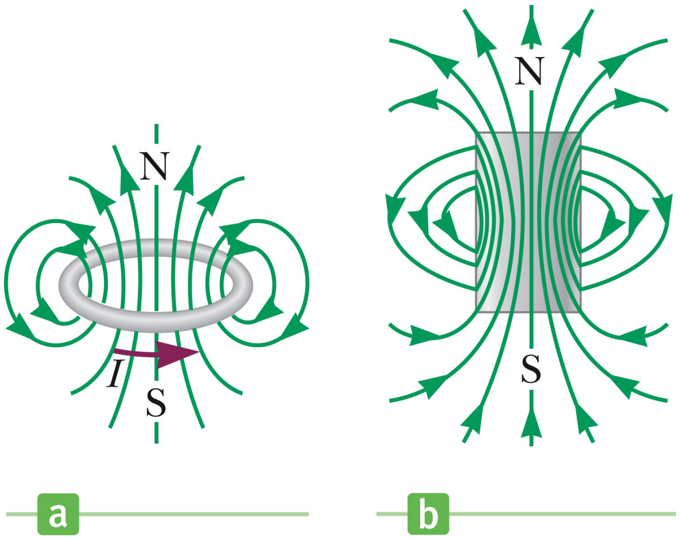
$$I = \boxed{7.07\ \text{A}}$$

Magnetic Field of a Current Loop

- The strength of a magnetic field produced by a wire can be enhanced by forming the wire into a loop.
- All the segments, Δx, contribute to the field, increasing its strength.



Magnetic Field of a Current Loop



- The magnetic field lines for a current loop resemble those of a bar magnet.
- One side of the loop acts as a north pole and the other side acts as a south pole.

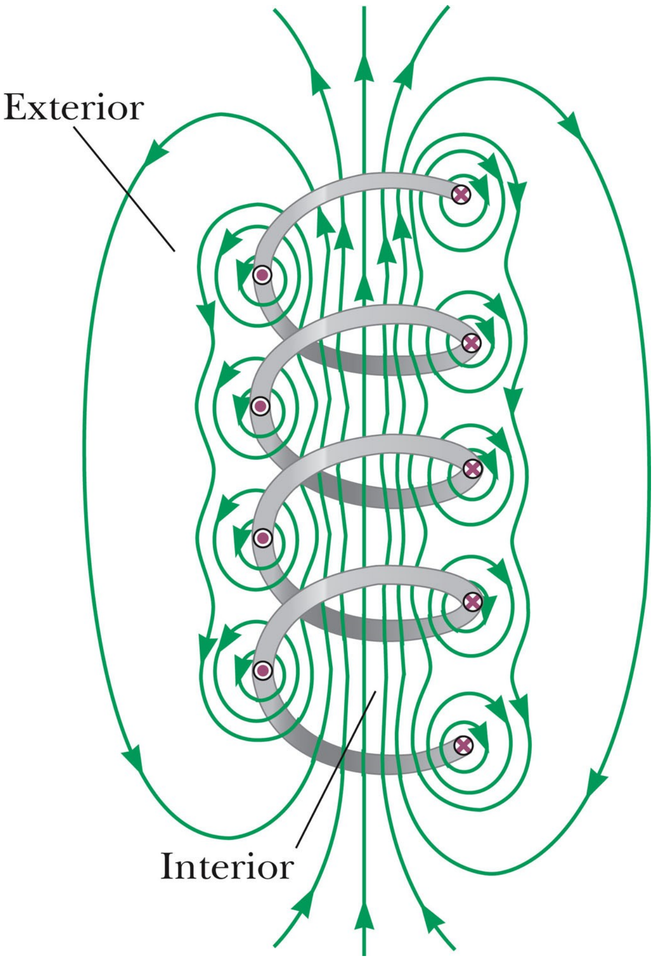
Magnetic Field of a Current Loop – Equation

- The magnitude of the magnetic field at the center of a circular loop with a radius R and carrying current I is
-
$$B = \frac{\mu_o I}{2R}$$
-
- With N loops in the coil, this becomes

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

Magnetic Field of a Solenoid

- If a long straight wire is bent into a coil of several closely spaced loops, the resulting device is called a *solenoid.*
- It is also known as an electromagnet since it acts like a magnet only when it carries a current.



Magnetic Field of a Solenoid, 2

- The field lines inside the solenoid are nearly parallel, uniformly spaced, and close together.
  - This indicates that the field inside the solenoid is strong and nearly uniform.
- The exterior field is nonuniform, much weaker than the interior field, and in the opposite direction to the field inside the solenoid.

Magnetic Field in a Solenoid, 3

- The field lines of a closely spaced solenoid resemble those of a bar magnet.
- One end of the solenoid acts as a north pole and the other end as a south pole.
-

Magnetic Field in a Solenoid, Magnitude

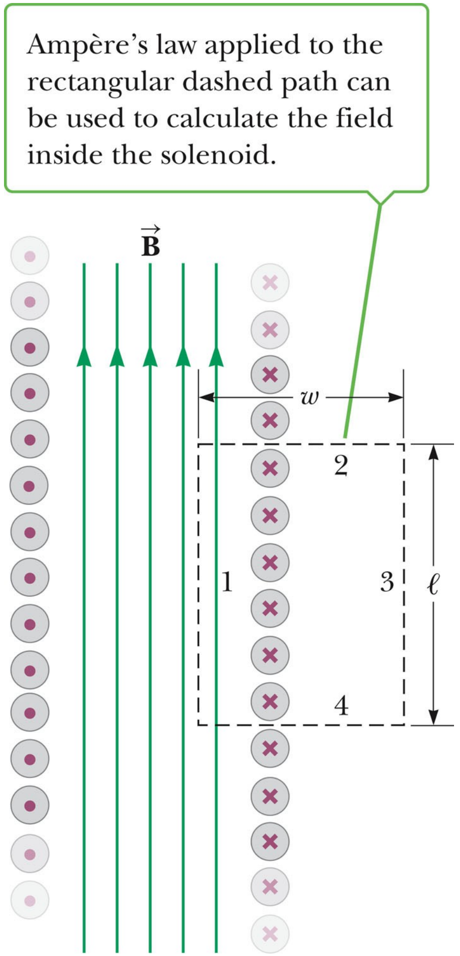
- The magnitude of the field inside a solenoid is constant at all points far from its ends.
- $B = \mu_o n I$
  - n is the number of turns per unit length
  - $n = N / \ell$
- The same result can be obtained by applying Ampère's Law to the solenoid.

Magnetic Field in a Solenoid from Ampère's Law

- A cross-sectional view of a tightly wound solenoid
- If the solenoid is long compared to its radius, we assume the field inside is uniform and outside is zero.
- Apply Ampère's Law to the blue dashed rectangle.
- Gives same result as previously found

$$\sum B_{\parallel}\,\Delta\ell = BL = \mu_0 NI$$

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



Magnetic Effects of Electrons – Orbits

- An individual atom should act like a magnet because of the motion of the electrons about the nucleus.
  - Each electron circles the atom once in about every 10^{-16} seconds.
  - This would produce a current of 1.6 mA and a magnetic field of about 20 T at the center of the circular path.
- However, the magnetic field produced by one electron in an atom is often canceled by an oppositely revolving electron in the same atom.

Magnetic Effects of Electrons – Orbits

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  - This would produce a current of 1.6 mA and a magnetic field of about 20 T at the center of the circular path.
- However, the magnetic field produced by one electron in an atom is often canceled by an oppositely revolving electron in the same atom.

$$i = 1.6 \times 10^{-19}\,C / 10^{-16}\,s = 1.6 \times 10^{-3}\,A$$

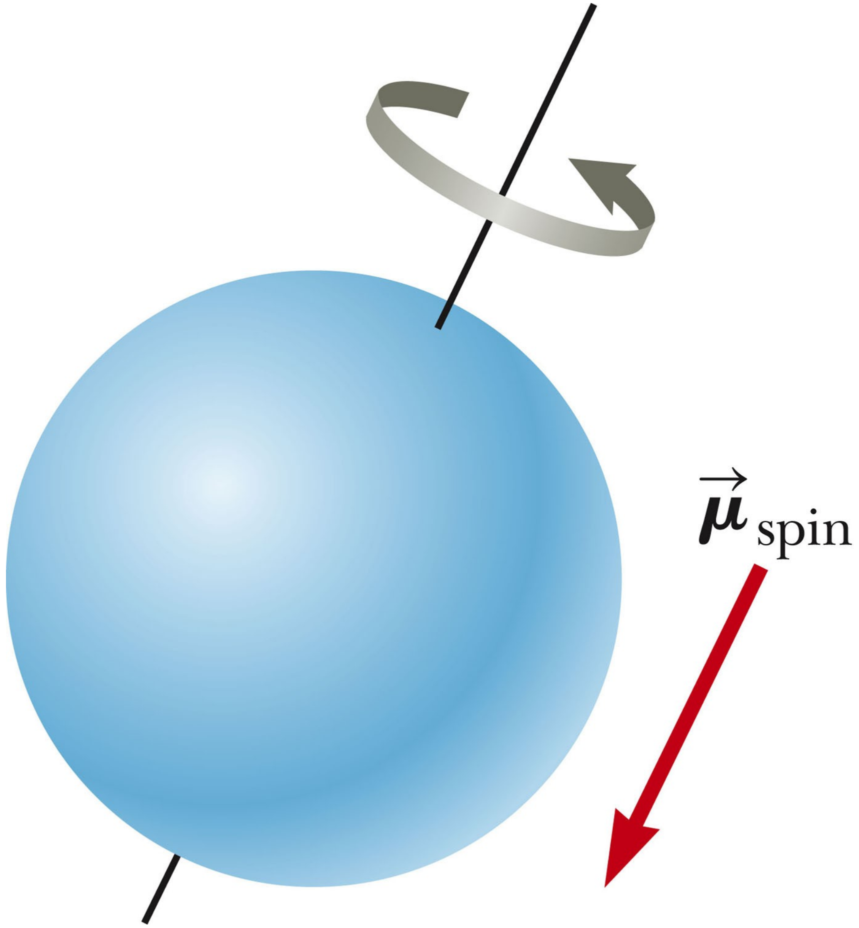
$$B = \frac{\mu_0 I}{2R} = \frac{4\pi \times 10^{-7}\,(Tm/A) \times 1.6 \times 10^{-3}\,A}{2 \times 50 \times 10^{-9}\,m} = 20\,T\,!$$

Magnetic Effects of Electrons – Orbits, Cont.

- The net result is that the magnetic effect produced by electrons orbiting the nucleus is either zero or very small for most materials.

Magnetic Effects of Electrons – Spins

- Electrons also have spin.
  - The classical model is to consider the electrons to spin like tops.
  - It is actually a quantum effect



Magnetic Effects of Electrons – Spins, Cont.

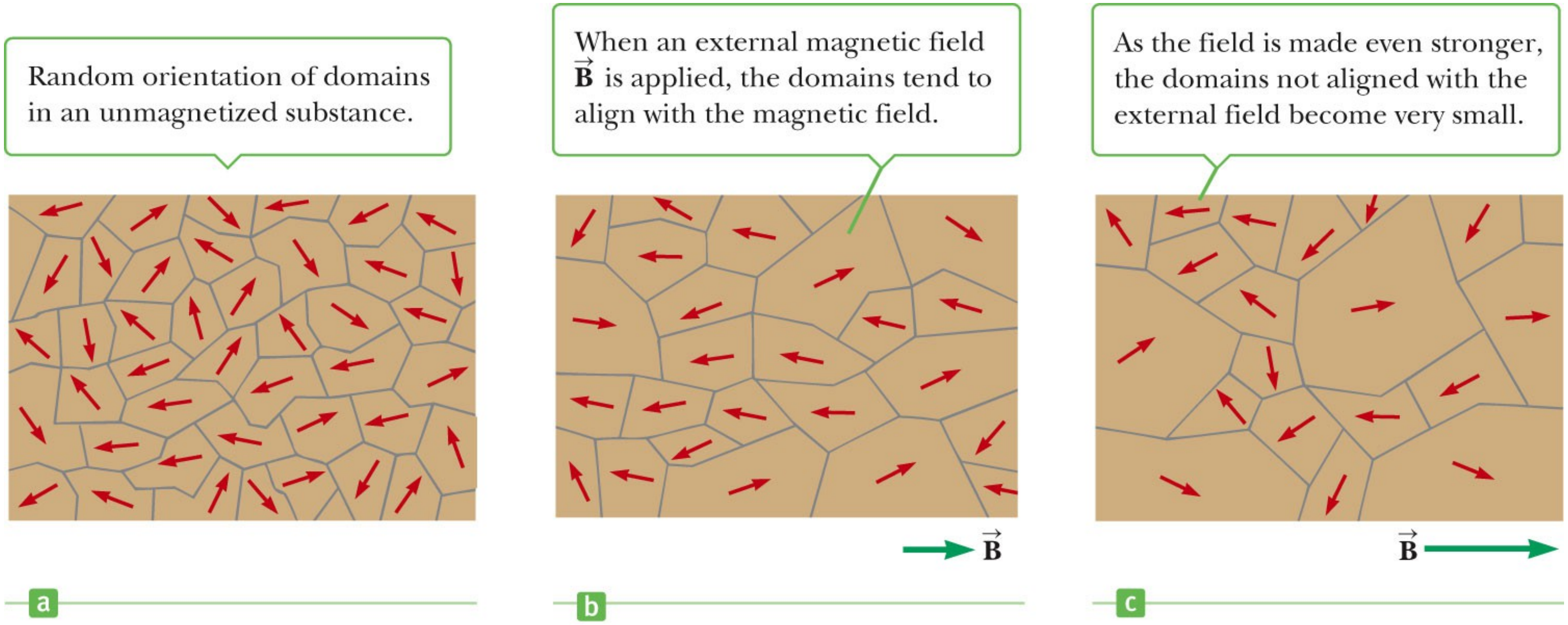
- The field due to the spinning is generally stronger than the field due to the orbital motion.
- Electrons usually pair up with their spins opposite each other, so their fields cancel each other.
  - That is why most materials are not naturally magnetic.

Magnetic Effects of Electrons – Domains

- In some materials, the spins do not naturally cancel.
  - Such materials are called *ferromagnetic*
- Large groups of atoms in which the spins are aligned are called *domains.*
- When an external field is applied, the domains that are aligned with the field tend to grow at the expense of the others.
  - This causes the material to become magnetized.

Domains, Cont.

- Random alignment (a) shows an unmagnetized material.
- When an external field is applied, the domains aligned with B grow (b) and those not aligned become small (c).



Domains and Permanent Magnets

- In hard magnetic materials, the domains remain aligned after the external field is removed.
  - The result is a permanent magnet.
- In soft magnetic materials, once the external field is removed, thermal agitation causes the materials to quickly return to an unmagnetized state.
- With a core in a loop, the magnetic field is enhanced since the domains in the core material align, increasing the magnetic field.

Types of Magnetic Materials

- Ferromagnetic
  - Have permanent magnetic moments that align readily with an externally applied magnetic field
- Paramagnetic
  - Have magnetic moments that tend to align with an externally applied magnetic field, but the response is weak compared to a ferromagnetic material
- Diamagnetic
  - An externally applied field induces a very weak magnetization that is opposite the direction of the applied field.