Lecture 5

Chapter 19 The magnetic Field

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 19^{th} 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.

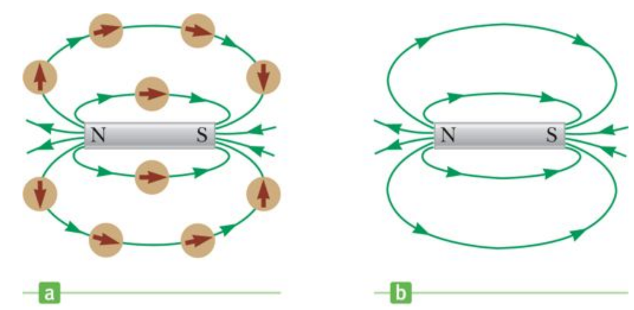
Sources of Magnetic Fields

- 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.

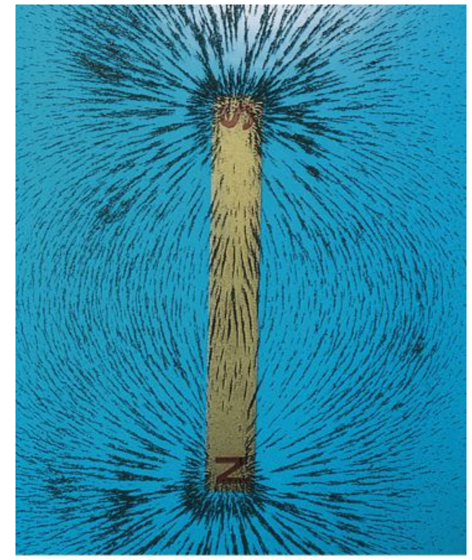
Magnetic Field Lines, Sketch



- 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

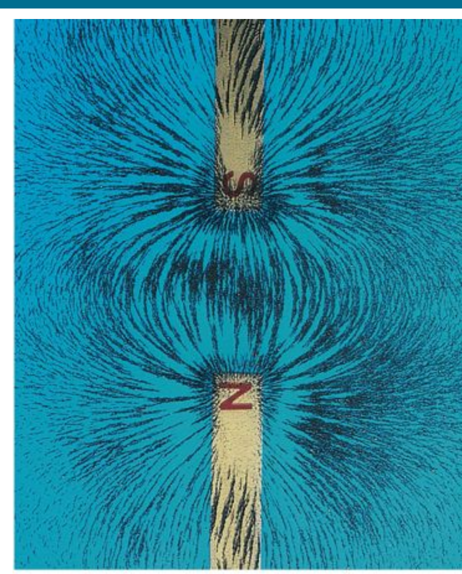
- Iron filings are used to show the pattern of the magnetic field lines.
- The direction of the field is the direction a north pole would point.



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



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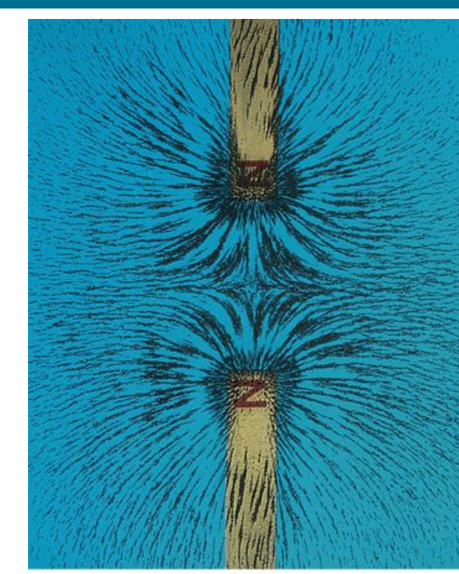
Magnetic Field Lines, Like Poles

- 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 like charges



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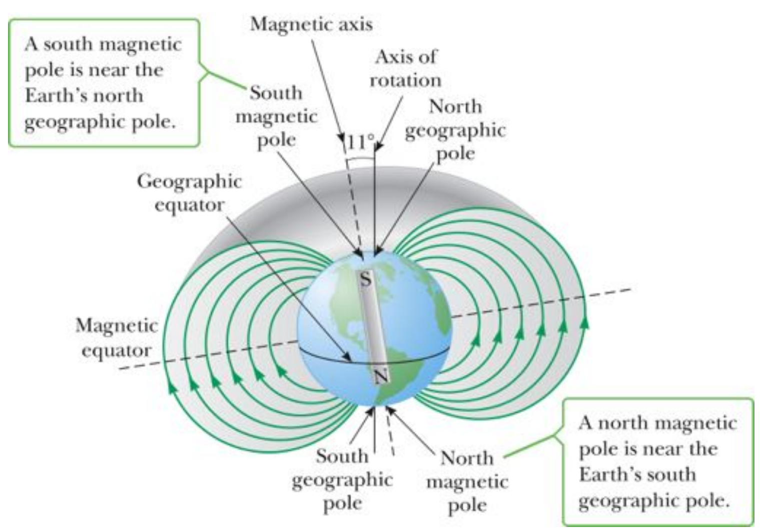
Earth's Magnetic Field

- 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.



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.*

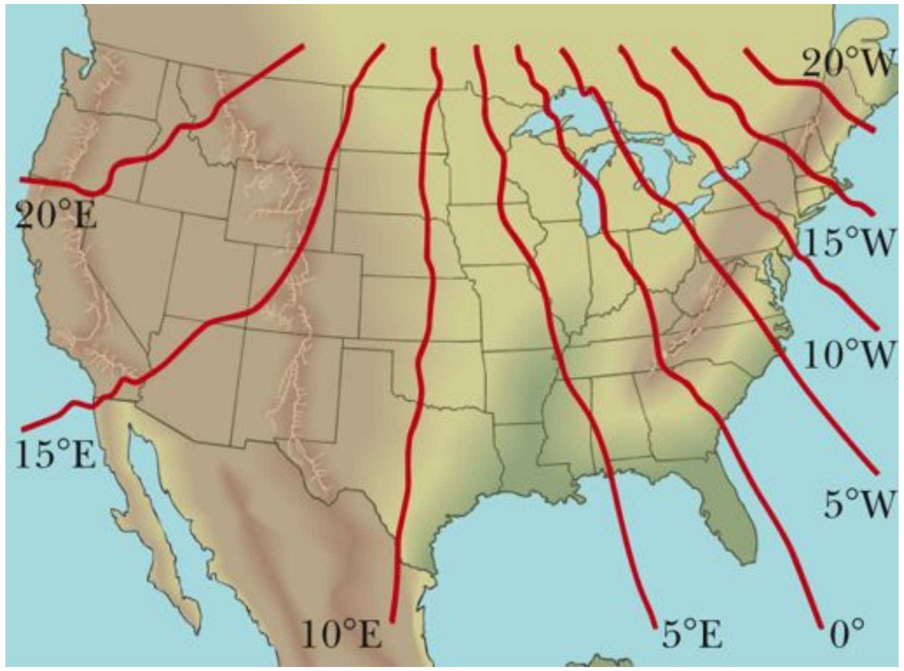
Dip Angle, Cont.

- 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

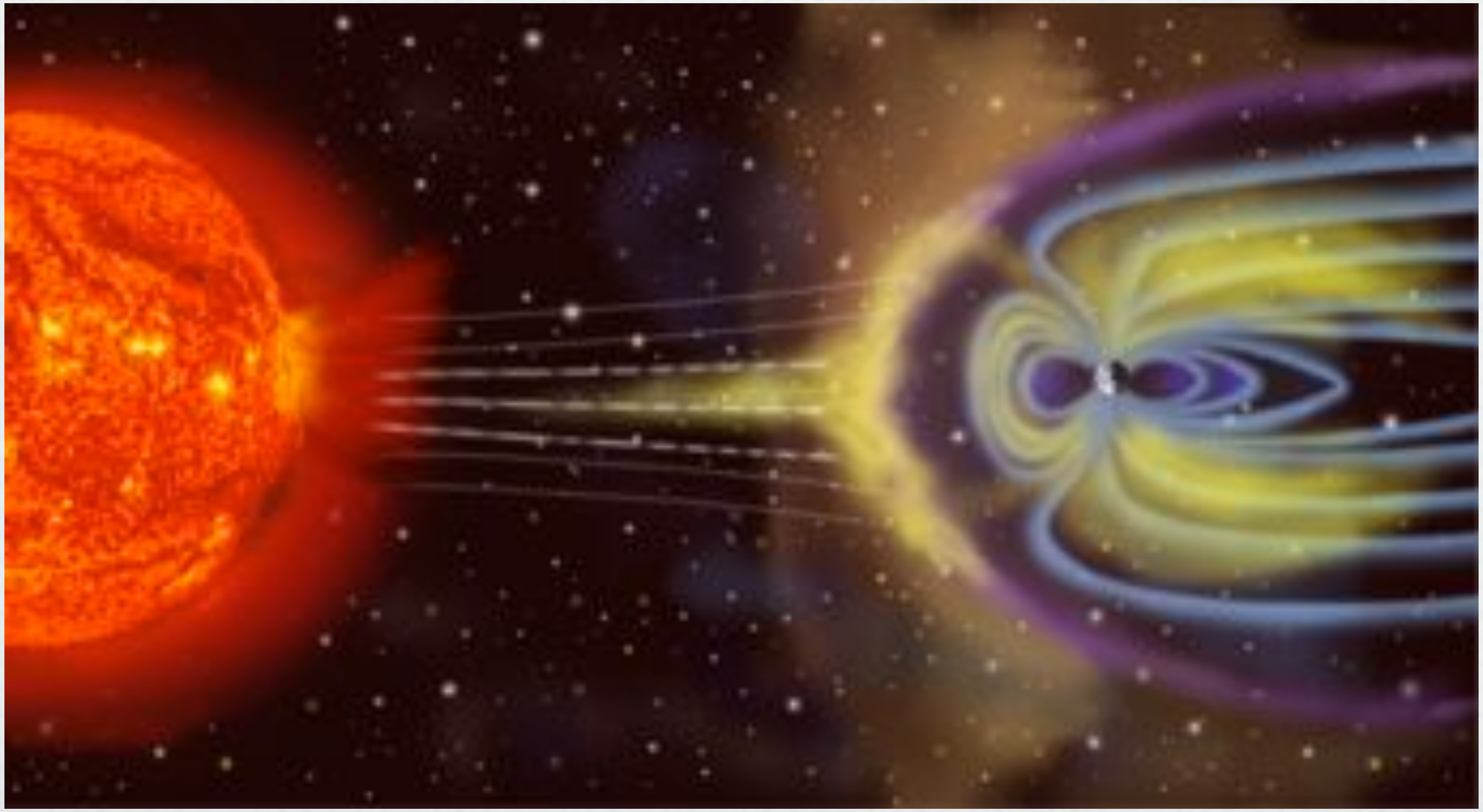
- The dip angle of 90° is found at a point just north of Hudson Bay in Canada.
  - This is considered to be the location of the south magnetic pole.
- The magnetic and geographic poles are not in the same exact location.
  - The difference between true north, at the geographic north pole, and magnetic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

Earth's Magnetic Declination



The Earth's magnetic Field

* Comes from a molten core inside of our rotating planet - dynamo theory
* Flips direction every few million years
* The earth is surrounded by the magnetosphere



Magnetic forces

* magnetic fields only effect the motion of charged particles in directions perpendicular to their motion. Motion in the direction of the magnetic field is unaffected
* The magnetic force is given by

$$F = qvBsin\theta$$

Units of Magnetic Field

- The SI unit of magnetic field is the *Tesla* (T)

$$T = \frac{Wb}{m^2} = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}$$

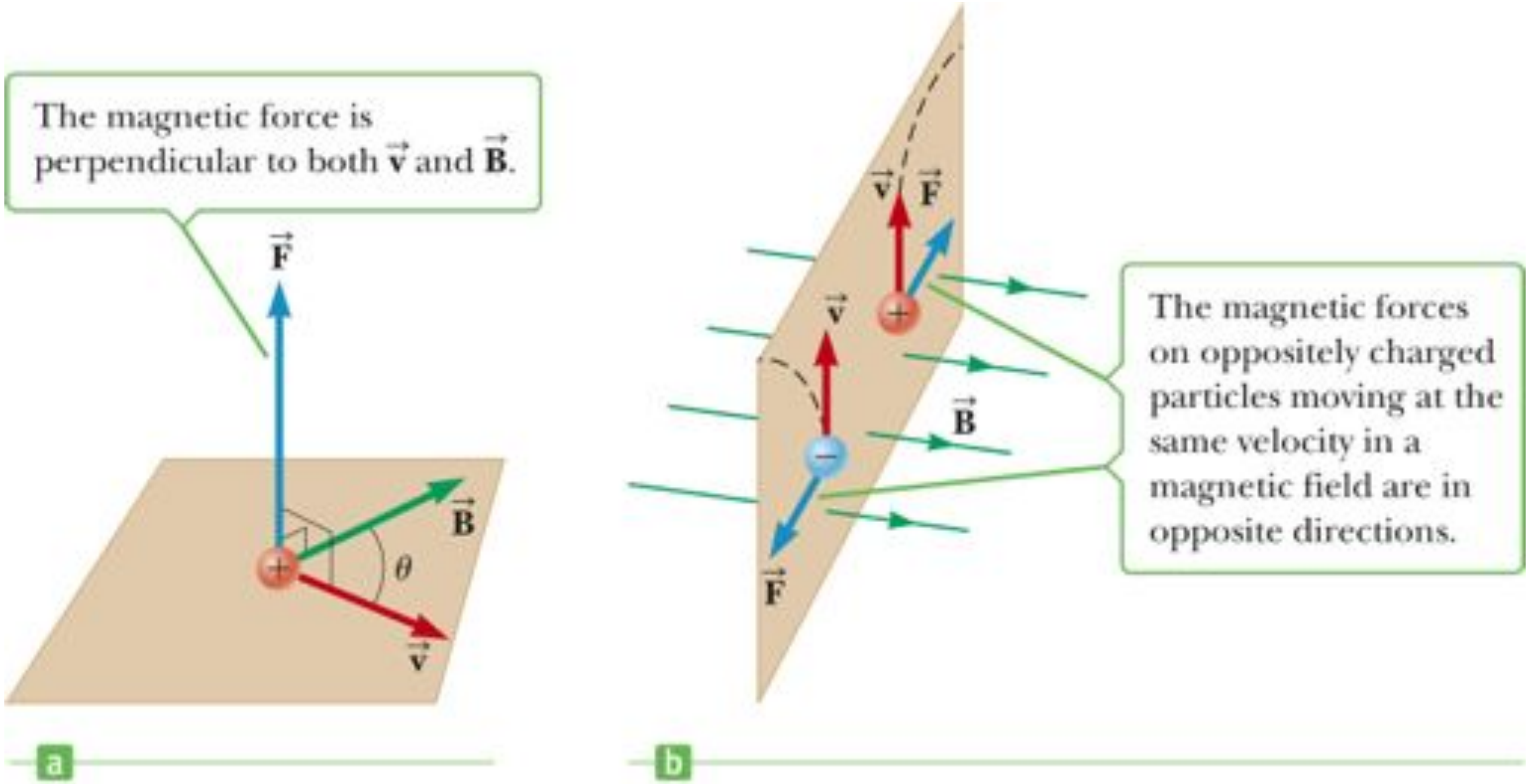
  – Wb is a Weber
- The cgs unit is a *Gauss* (G)
  – 1 T = 10^4 G

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 x 10^{-5} T

Section 19.3

The magnetic field of a magnetar is 10^8 to 10^{11} tesla enough to shred you to pieces



The magnetic force is perpendicular to both $\vec{v}$ and $\vec{B}$.
$\vec{F}$
$\vec{B}$
θ
$\vec{v}$
a
$\vec{v}$
$\vec{F}$
$\vec{v}$
$\vec{B}$
$\vec{F}$
The magnetic forces on oppositely charged particles moving at the same velocity in a magnetic field are in opposite directions.
b

Fig. 19-6, p. 653

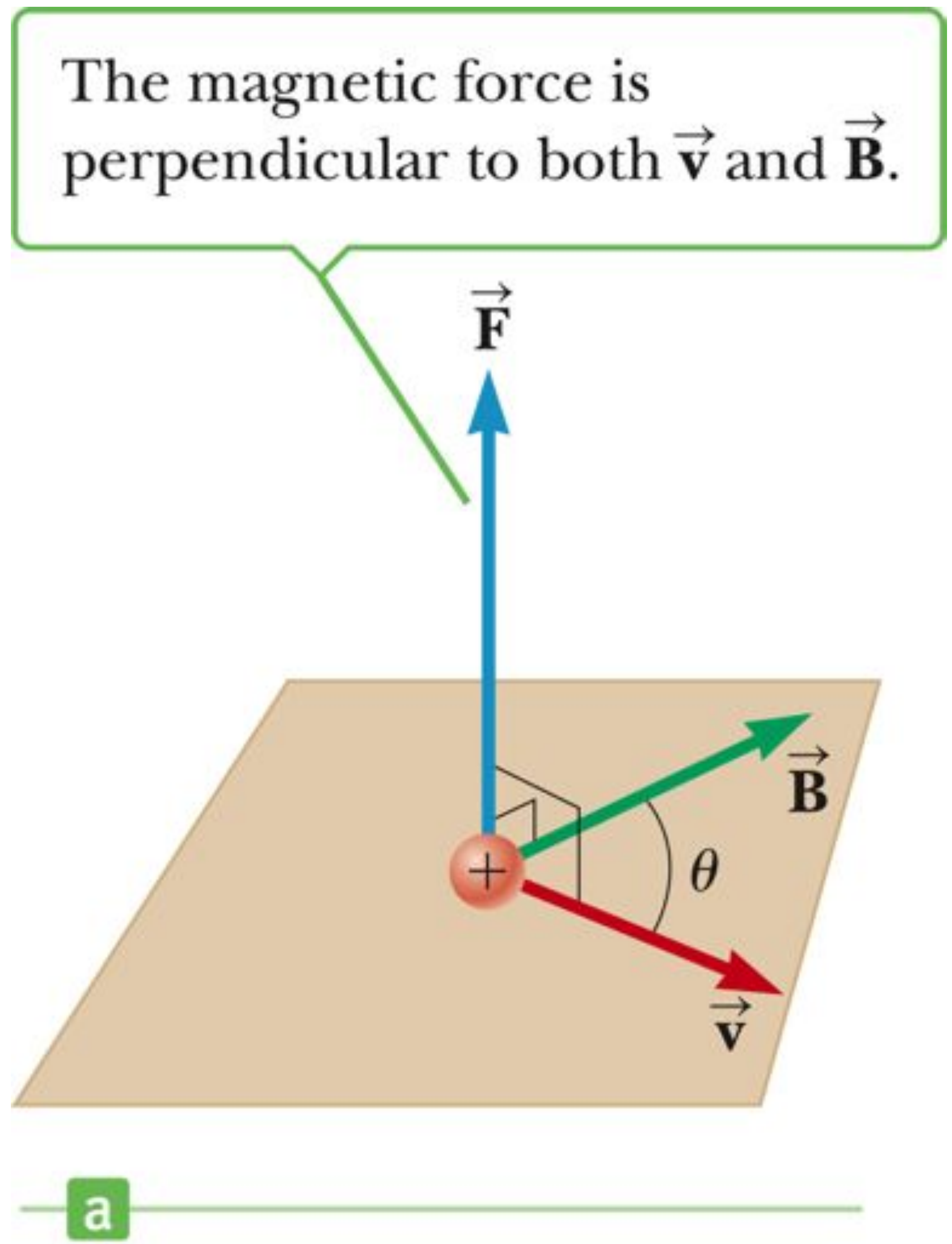
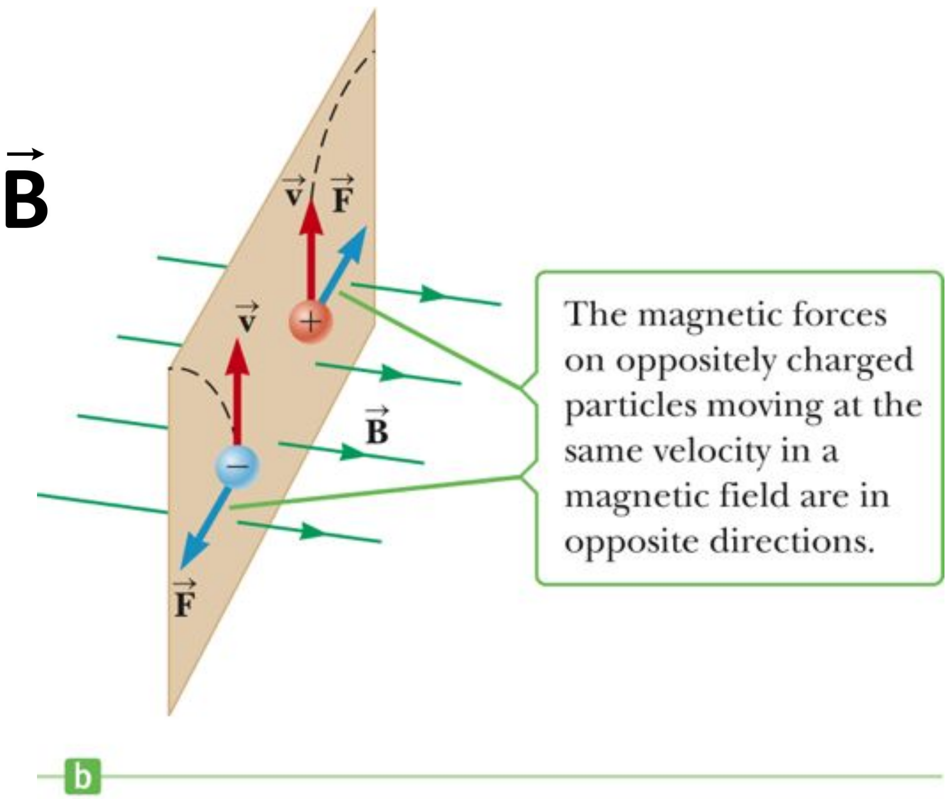


Fig. 19-6a, p. 653

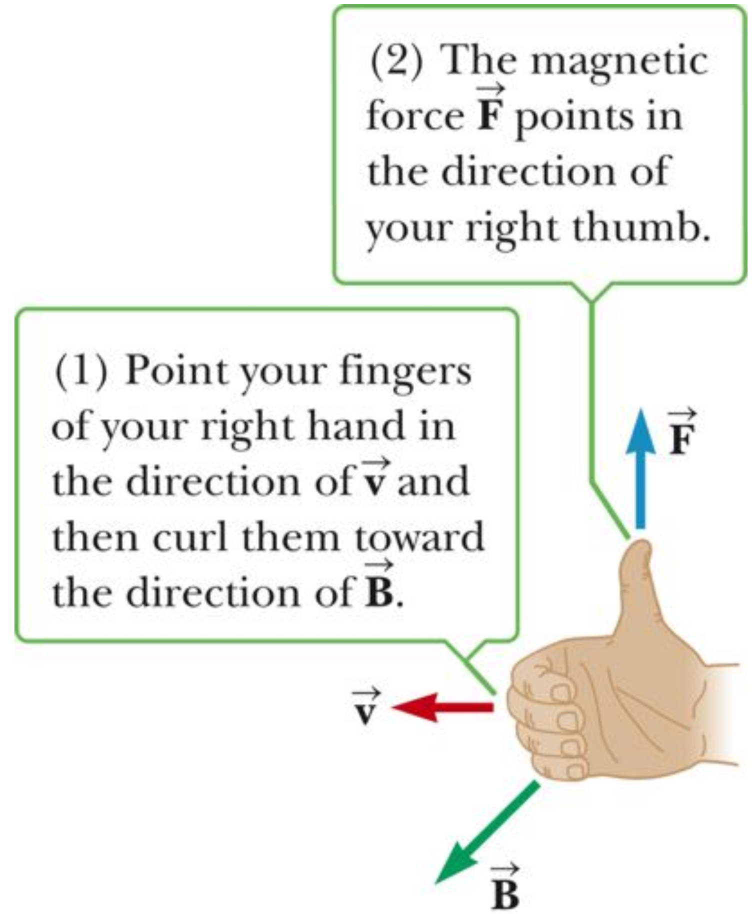
Finding the Direction of Magnetic Force

- 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, $\vec{\mathbf{B}}$
- Your thumb points in the direction of the force on a positive charge.



The direction a negatively charged particle would move is the opposite of this (use your left hand)

6. The magnetic field of the Earth is believed responsible for which of the following?

a. deflection of both charged and uncharged cosmic rays

b. deflection of charged cosmic rays

c. ozone in the upper atmosphere

d. solar flares

An electron which moves with a speed of 3.0×10^4 m/s parallel to a uniform magnetic field of 0.40 T experiences a force of what magnitude? ($e = 1.6 \times 10^{-19}$ C)

a. 4.8×10^{-14} N

b. 1.9×10^{-15} N

c. 2.2×10^{-24} N

d. zero

The force on a charged particle created by its motion in a magnetic field is maximum at what angle between the particle velocity and field?

a.zero

b.180°

c.90°

d.45°

A proton is released such that its initial velocity is from right to left across this page. The proton's path, however, is deflected in a direction toward the bottom edge of the page due to the presence of a uniform magnetic field. What is the direction of this field?

a. out of the page
b. into the page
c. from bottom edge to top edge of the page
d. from right to left across the page

A proton is released such that it has an initial speed of 4.0×10^{5} m/s from left to right across the page. A magnetic field of 1.2 T is present at an angle of 30° to the horizontal direction (or positive x axis). What is the magnitude of the force experienced by the proton? ($q_p = 1.6 \times 10^{-19}$ C)

a. 4.8×10^{-25} N
b. 1.3×10^{-19} N
c. 3.8×10^{-14} N
d. 7.5×10^{3} N

The force on a charged particle created by its motion in a magnetic field is maximum at what angle between the particle velocity and field?

a.zero

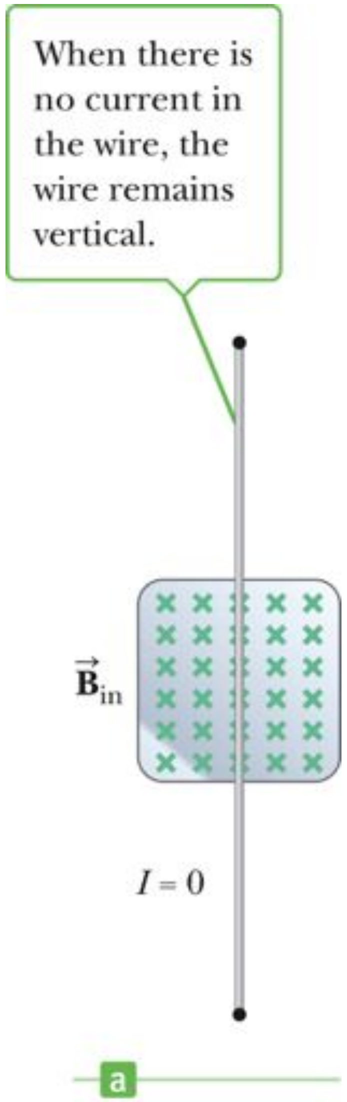
b.180°

c.90°

d.45°

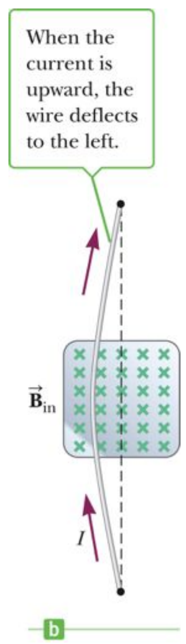
Force on a Wire

- 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.

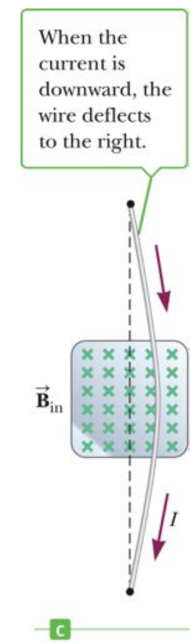
- B is into the page.
- The current is up the page.
- The force is to the left.



Section 19.4

Force on a Wire,Final

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



Section 19.4

We could have guessed this. Let's envision the wire as a flow of charge and try the right hand rule

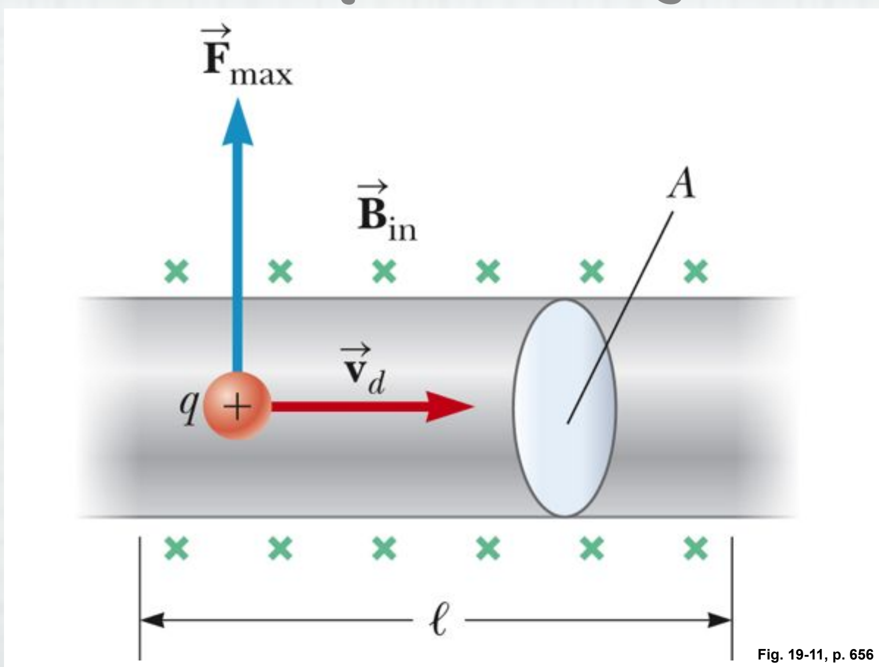


Fig. 19-11, p. 656

Force on a Wire, Equation

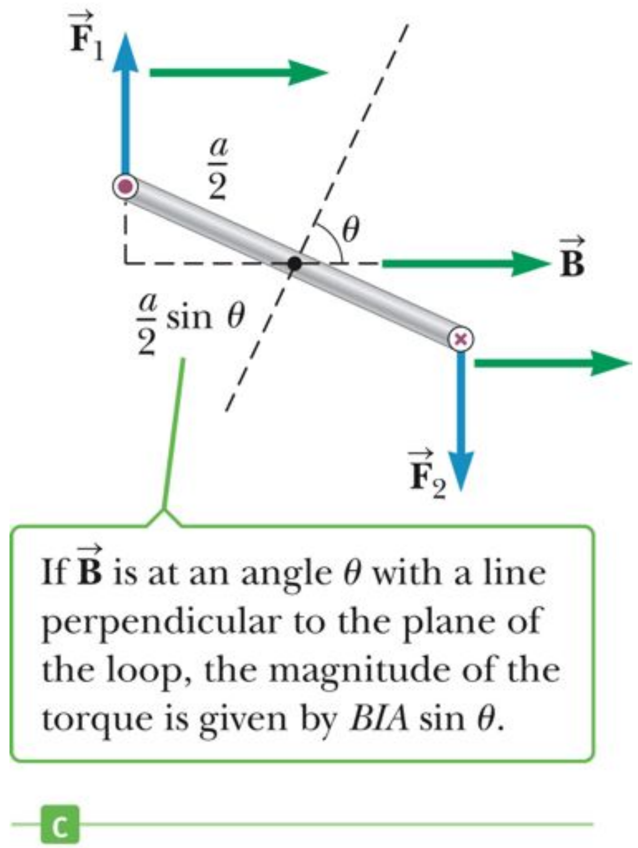
- The magnetic force is exerted on each moving charge in the wire.
- The total force is the sum of all the magnetic forces on all the individual charges producing the current.
- $F = B\, I\, \ell \sin\theta$
  - θ is the angle between $\vec{\mathbf{B}}$ and the direction of I
  - The direction is found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

A current-carrying wire of length 50 cm is positioned perpendicular to a uniform magnetic field. If the current is 10.0 A and it is determined that there is a resultant force of 3.0 N on the wire due to the interaction of the current and field, what is the magnetic field strength?
a.0.60 T
b.1.5 T
c.1.8×10^{-3} T
d.6.7×10^{-3} T

A copper wire of length 25 cm is in a magnetic field of 0.20 T. If it has a mass of 10 g, what is the minimum current through the wire that would cause a magnetic force equal to its weight?
a.1.3 A
b.1.5 A
c.2.0 A
d.4.9 A

Torque on a Current Loop

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



Section 19.5

Remember torque? The tendency of a force, applied in a given way to cause rotation

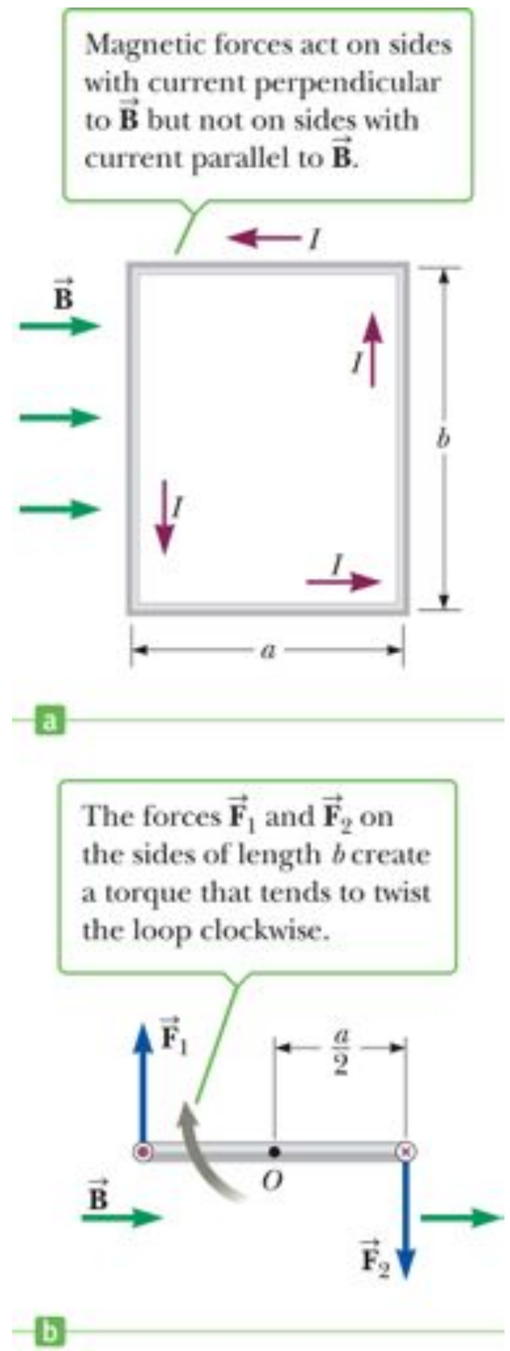


Fig. 19-15ab, p. 659

- This torque acts on non rectangular configurations as well.
- We can define the magnetic moment of a current loop as the product of its current, area, and number of turns

$$\mu = IAN$$

Magnetic Moment

- The vector $\vec{\mu}$ is called the magnetic moment of the coil
- Its magnitude is given by μ = 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 $\tau = \mu B \sin\theta$

Section 19.5

* Lets do it for a 5 tesla field with a 2 ampere current

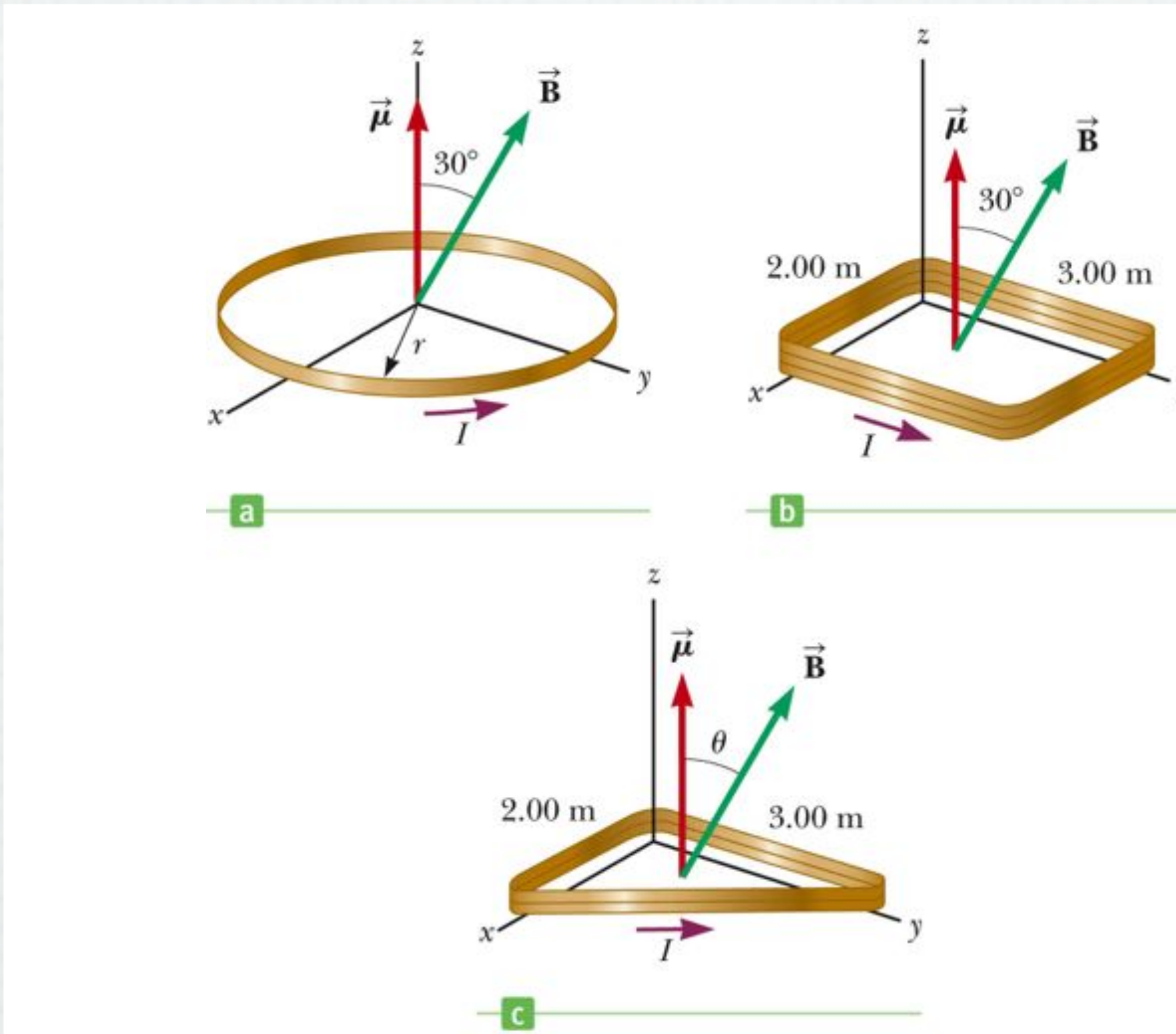


Fig. 19-16, p. 660

A circular loop carrying a current of 1.0 A is oriented in a magnetic field of 0.35 T. The loop has an area of 0.24 m^2 and is mounted on an axis, perpendicular to the magnetic field, which allows the loop to rotate. If the plane of the loop is oriented parallel to the field, what torque is created by the interaction of the loop current and the field?

a.5.8 Nm

b.0.68 Nm

c.0.084 Nm

d.0.017 Nm

A circular coil (radius = 0.40 m) has 160 turns and is in a uniform magnetic field. If the orientation of the coil is varied through all possible positions, the maximum torque on the coil by magnetic forces is 0.16 Nm when the current in the coil is 4.0 mA. What is the magnitude of the magnetic field?

a.0.37 T

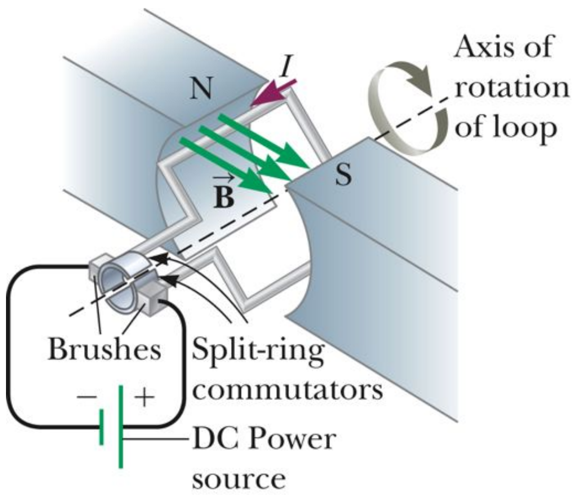
b.1.6 T

c.0.50 T

d.1.2 T

Electric Motor

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



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 θ = 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

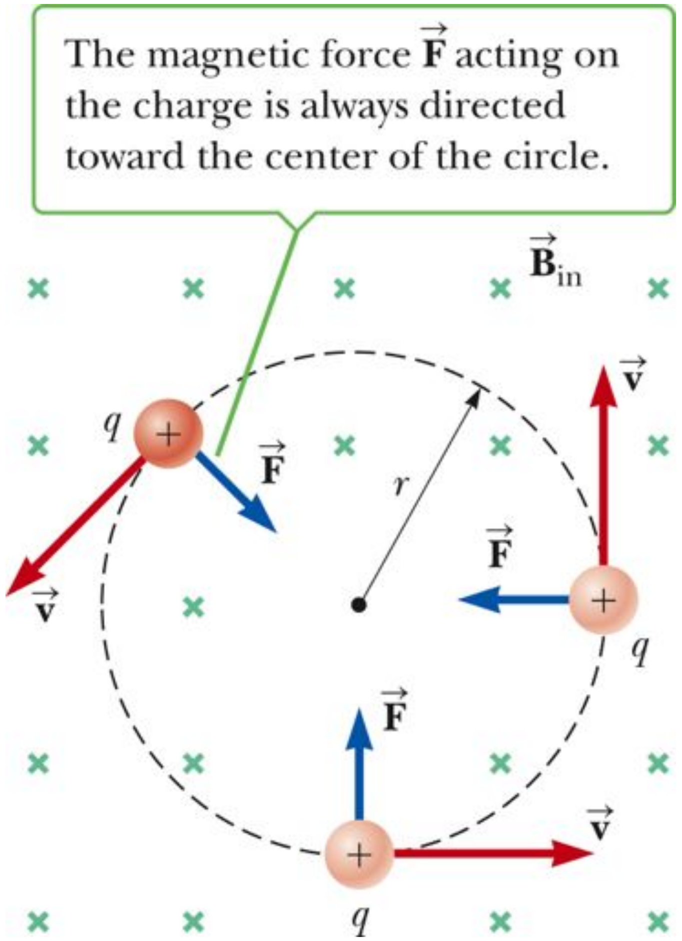
- Just as the loop becomes perpendicular to the magnetic field and the torque becomes 0, inertia carries the loop forward and the brushes cross the gaps in the ring, causing the current loop to reverse its direction.
  - This provides more torque to continue the rotation.
  - The process repeats itself.

Stop and think

* What happens if we manually crank this configuration with no initial current?

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.



Section 19.6

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

A proton, which moves perpendicular to a magnetic field of 1.2 T in a circular path of radius 0.080 m, has what speed? ($q_p = 1.6 \times 10^{-19}$ C and $m_p = 1.67 \times 10^{-27}$ kg)

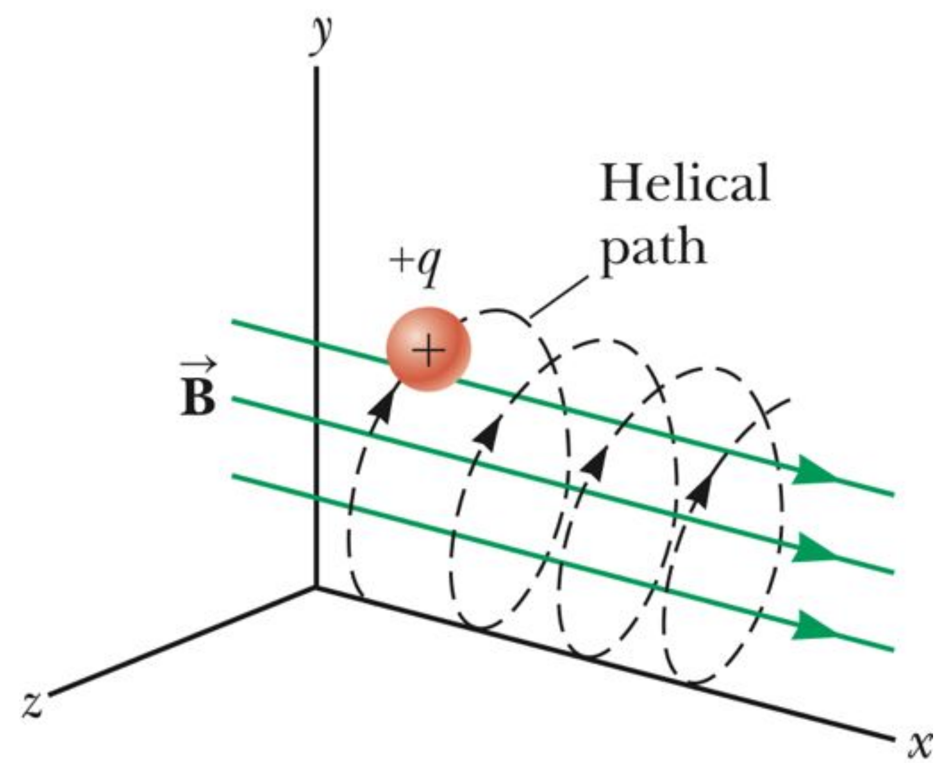
a. 3.4×10^6 m/s
b. 4.6×10^6 m/s
c. 9.6×10^6 m/s
d. 9.2×10^6 m/s

Two singly ionized isotopes, X and Y, of the same element move with the same speed perpendicular to a uniform magnetic field. Isotope X follows a path of radius 3.35 cm while isotope Y moves along a path 3.43 cm in radius. What is the ratio of the two isotope masses, m_X/m_Y?

a. 0.977
b. 1.02
c. 1.05
d. 0.954

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.



Right hand rule practice

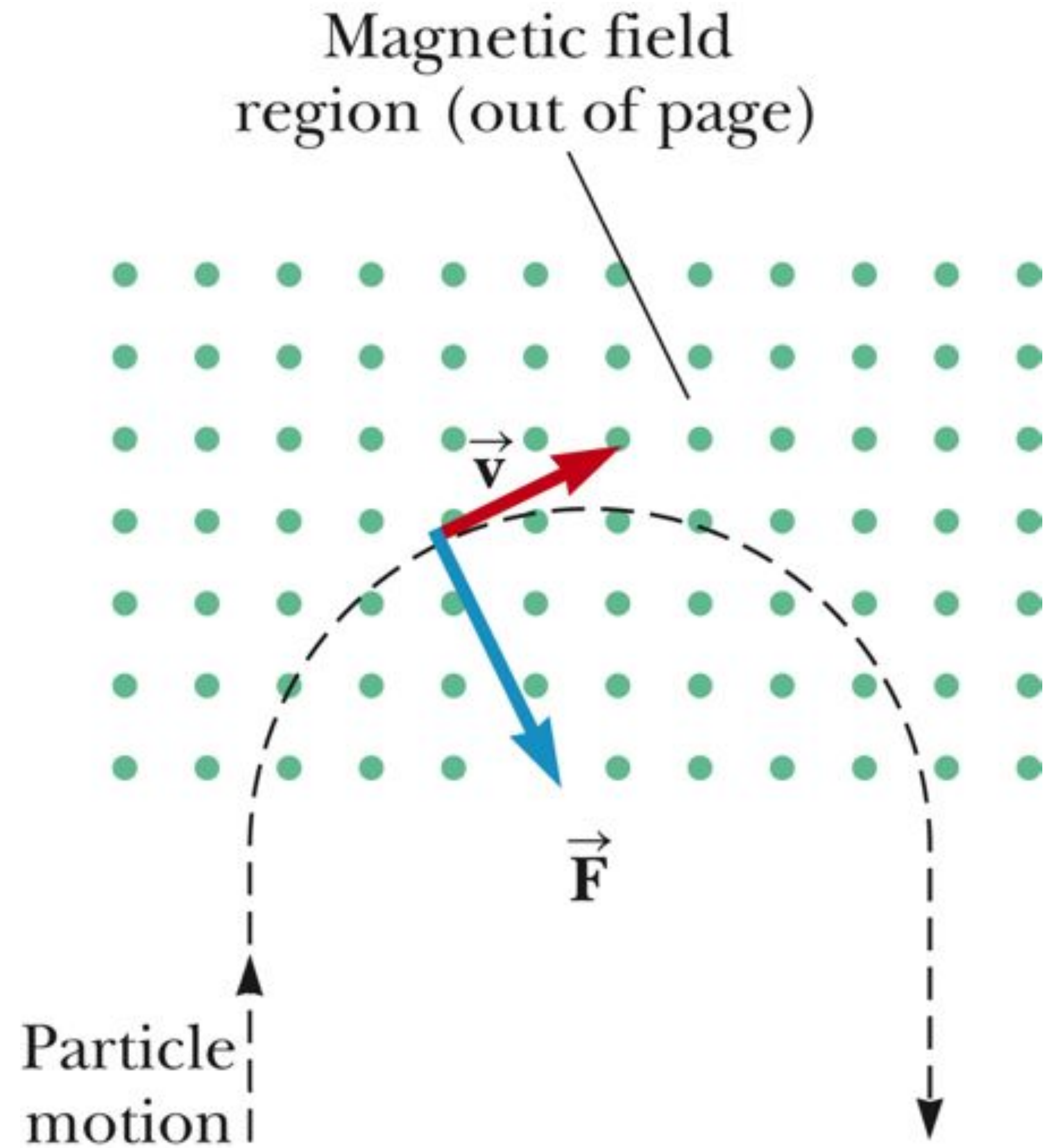
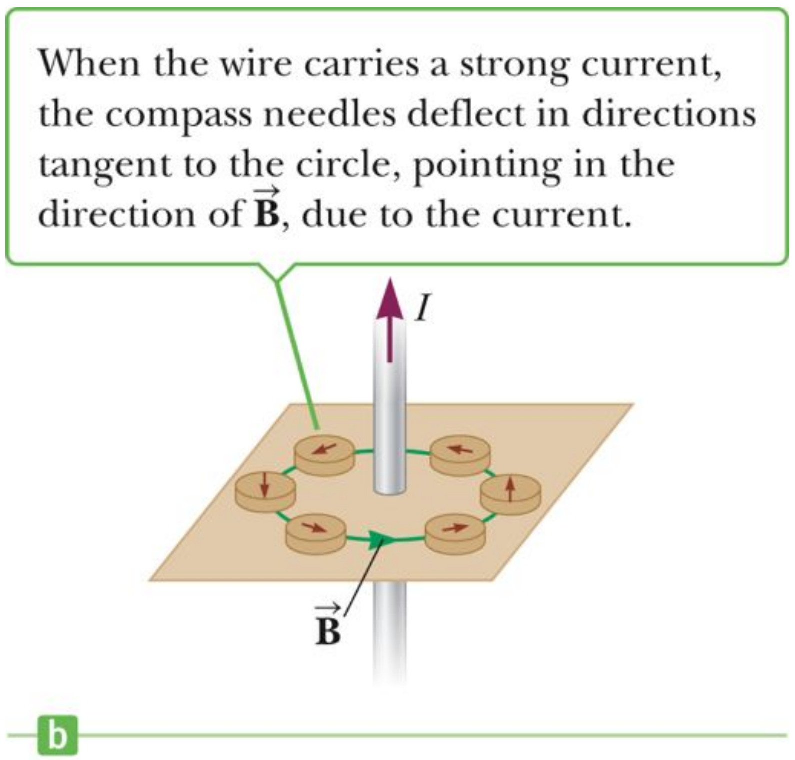


Fig. 19-21, p. 662

Remember the formula for r?
This is how mass spectrometers work

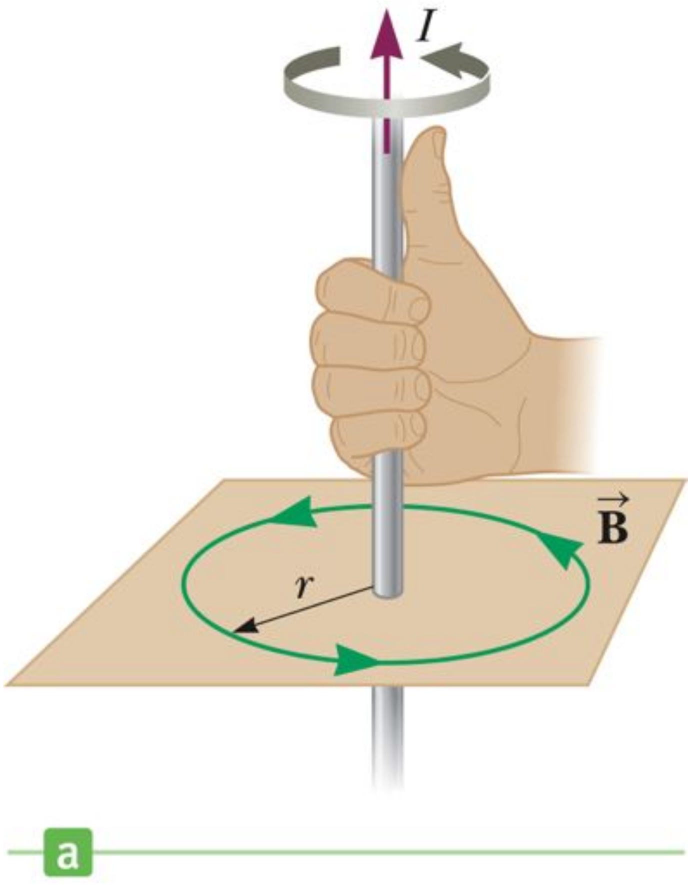
Magnetic Fields – Long Straight Wire

- 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

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

- $\mu_o = 4 \pi \times 10^{-7}$ T·m / A
  - μ_o is called the *permeability of free space*

A superconducting wire carries a current of 10^4 A. Find the magnetic field at a distance of 1.0 m from the wire.

a. 2×10^{-3} T

b. 8×10^{-3} T

c. 1.6×10^{-2} T

d. 3.2×10^{-2} T

An incredible amount of electrical energy passes down the funnel of a large tornado every second. Measurements taken in Oklahoma at a distance of 9.00 km from a large tornado showed an almost constant magnetic field of 1.50×10^{-8} T associated with the tornado. What was the average current going down the funnel?

a. 450 A

b. 675 A

c. 950 A

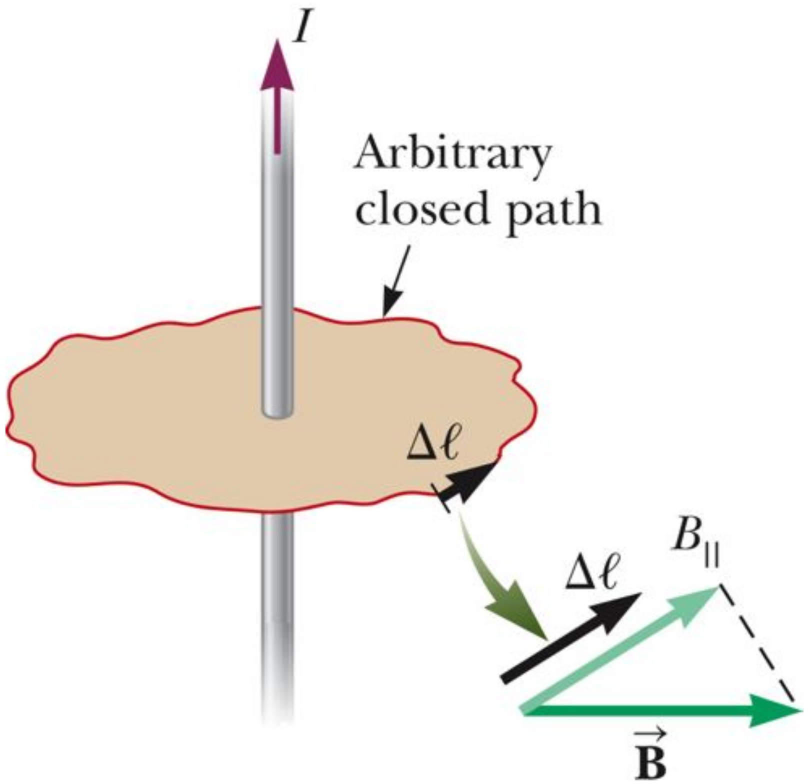
d. 1 500 A

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
  - $\Sigma B_{||} \Delta \ell = \mu_o I$
  - Sum over the closed path

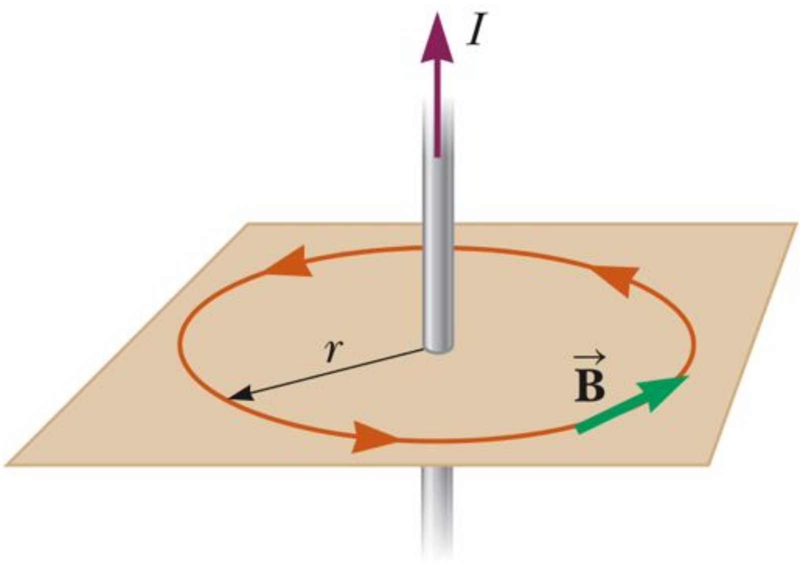
Ampère's Law, Cont.

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



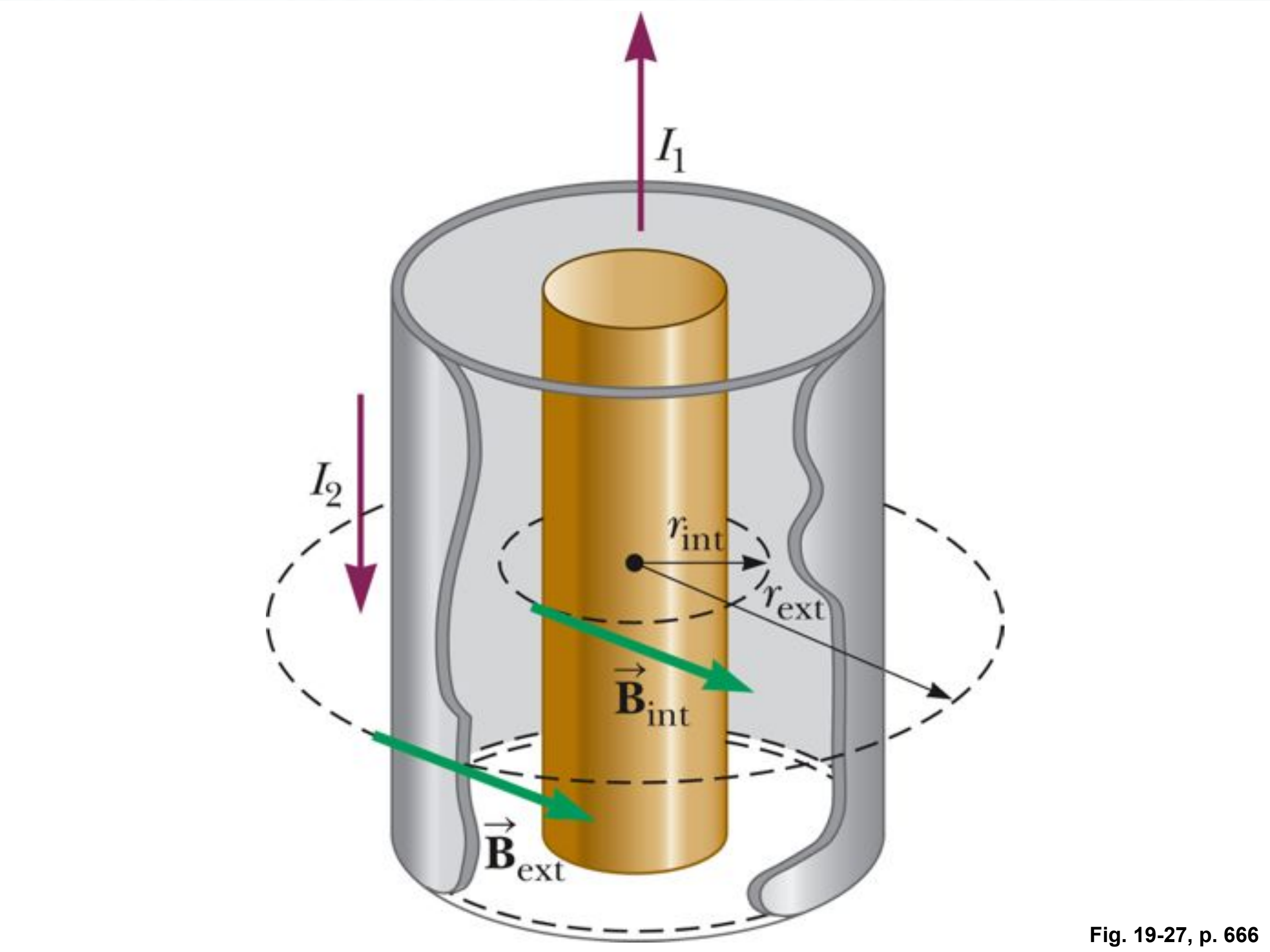
Ampère's Law to Find B for a Long Straight Wire

- Use a closed circular path.
- The circumference of the circle is 2 π r
- $$B = \frac{\mu_o I}{2\pi r}$$
  - This is identical to the result previously obtained.



Example

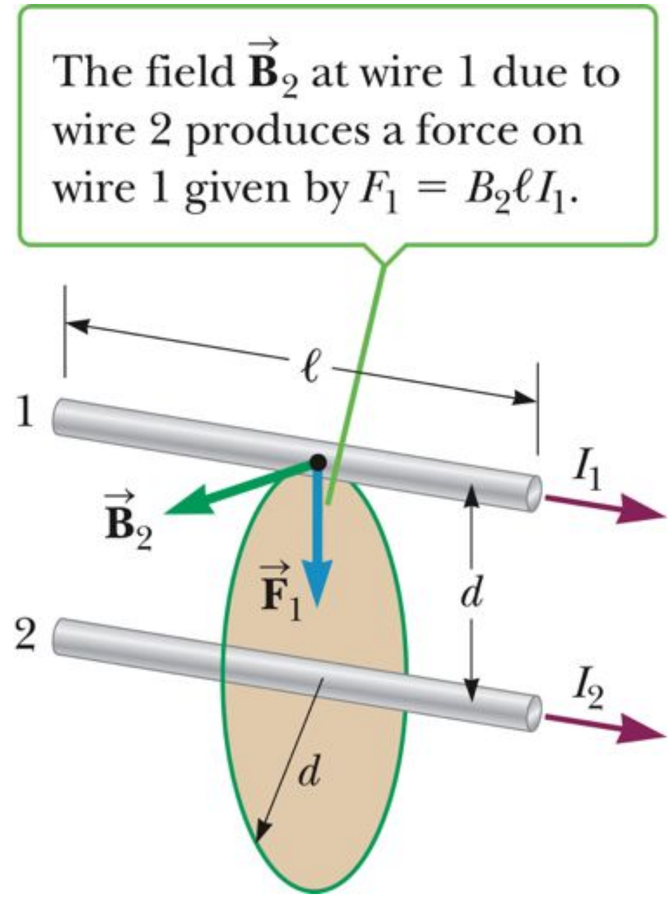
* $I_1 = 3$ A
* $I_2 = 1$A
* r_1=.5cm
* r_2=1.5cm



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:

$$\frac{F}{\ell} = \frac{\mu_o I_1 I_2}{2 \pi d}$$



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.

Two parallel conductors each of 0.50 m length, separated by 5.0×10^{-3} m and carrying 3.0 A in opposite directions, will experience what type and magnitude of mutual force? (magnetic permeability in empty space

a.attractive, $0.06 \times 10\text{-}^{4}$ N

b.repulsive, 0.60×10^{-4} N

c.attractive, 1.8×10^{-4} N

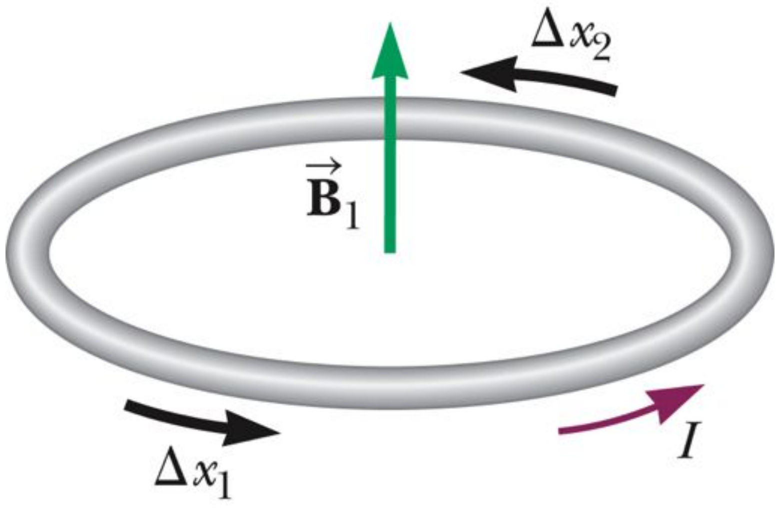
d.repulsive, 1.8×10^{-4} N

Defining Ampere and Coulomb

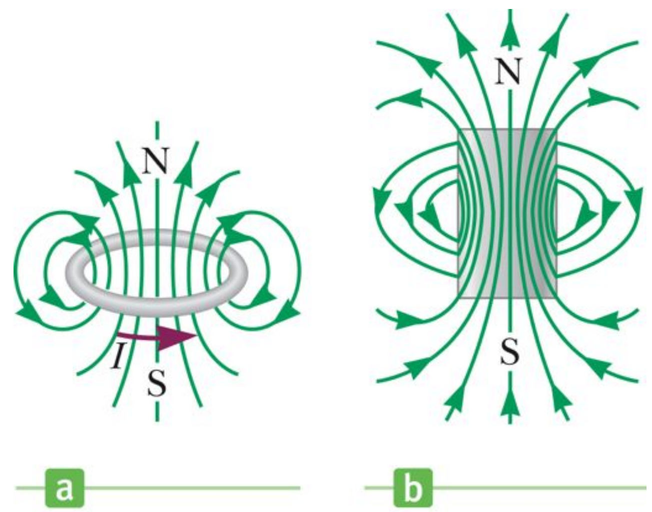
- The force between parallel conductors can be used to define the Ampere (A).
  - If two long, parallel wires 1 m apart carry the same current, and the magnitude of the magnetic force per unit length is 2×10^{-7} N/m, then the current is defined to be 1 A.
- The SI unit of charge, the Coulomb (C), can 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.

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.

Section 19.9

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

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

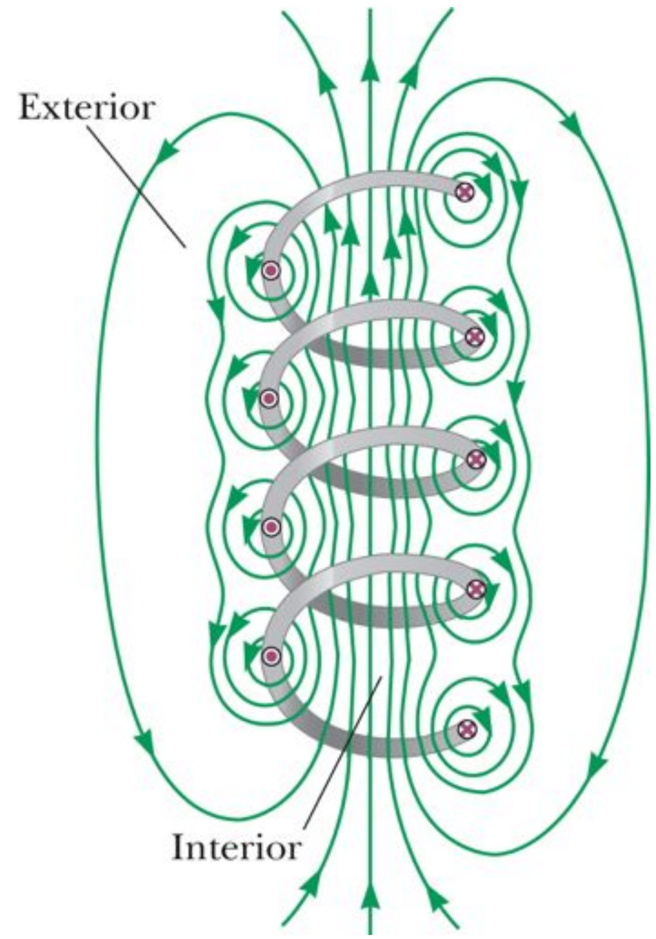
- With N loops in the coil, this becomes

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

Section 19.9

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.



Section 19.9

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, 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.

A solenoid with 500 turns, 0.10 m long, carrying a current of 4.0 A and with a radius of 10^{-2} m will have what strength magnetic field at its center?

a.31 x 10^{-4} T

b.62 x 10^{-4} T

c.125 x 10^{-4} T

d.250 x 10^{-4} T

A current in a solenoid coil creates a magnetic field inside that coil. The field strength is directly proportional to:

a.the coil area.

b.the current.

c.Both A and B are valid choices.

d.None of the above choices are valid.

Magnetic Effects of Electrons – Orbits

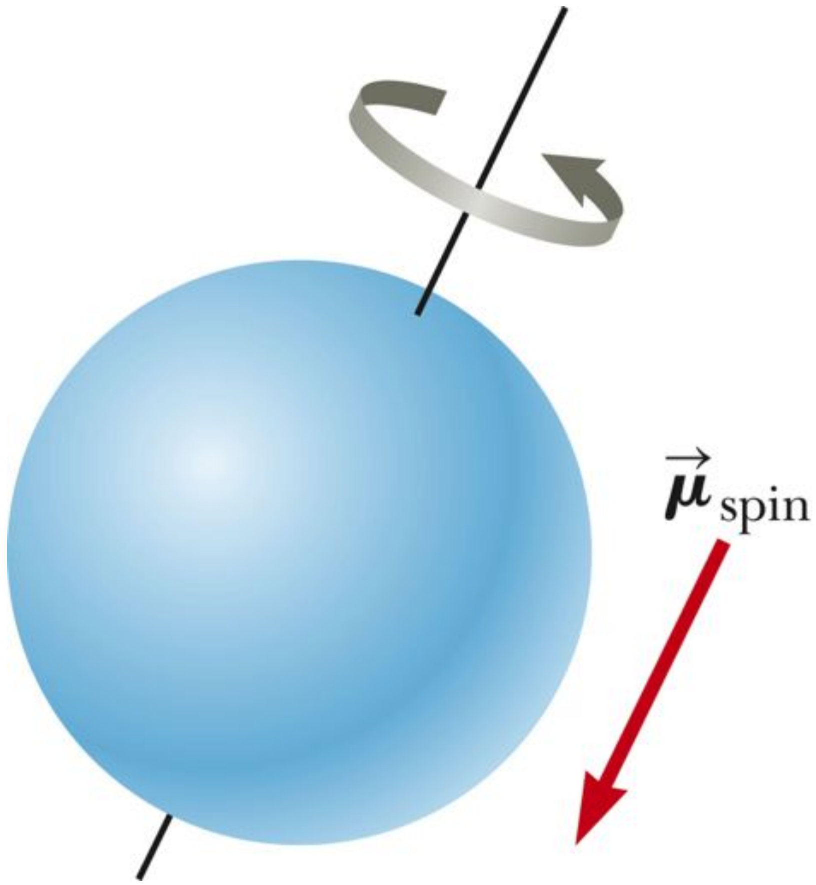
- An individual atom should act like a magnet because of the motion of the electrons about the nucleus.
  - Each electron circles the atom once in about every 10^{-16} seconds.
  - This would produce a current of 1.6 mA and a magnetic field of about 20 T at the center of the circular path.
- However,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

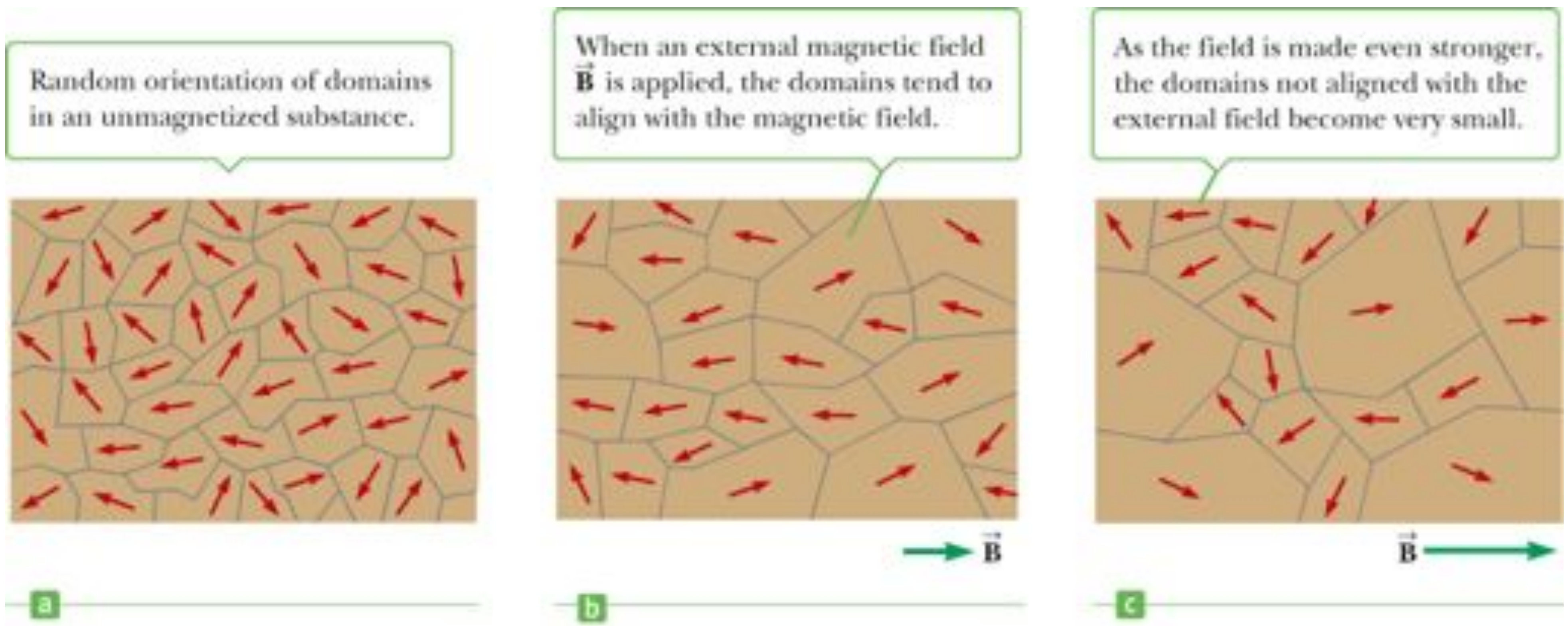
- The field due to the spinning is generally stronger than the field due to the orbital motion.
- Electrons usually pair up with their spins opposite each other, so their fields cancel each other.
  - That is why most materials are not naturally magnetic.

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).



Section 19.10

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.

Key Concepts

* The magnetic force acts perpendicular to the direction of a charged particle's motion
* The right hand rule
* There are no magnetic monopoles

Key Equations

$$F_{mag} = q|v||B|sin\theta$$

$$F = |B|Ilsin\theta$$ Magnetic force on current carrying conductor

$$\tau = BIAsin\theta$$ Torque on a current loop

$$\tau = BIANsin\theta = \mu Bsin\theta$$ Torque on a current loop

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

$$B = \frac{\mu_0 I}{2\pi r}$$ Magnetic field of a long, straight wire

$$\sum B_{||}\Delta l = \mu_0 I$$ Ampere's law

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi d}$$ Magnetic force per unit length between two long wires

$$B = N\frac{\mu_0 I}{2R}$$ Magnetic field inside N loops of radius R

$$B = \mu_0 \frac{N}{l} I$$ Magnetic field inside a solenoid