Chapter 21
Magnetic Forces and Magnetic Fields

1

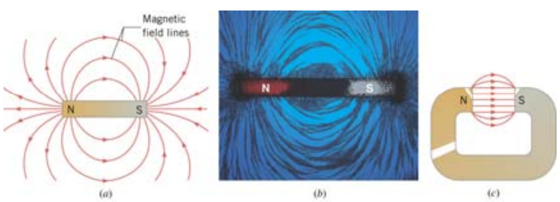
Goals for Chapter 21

- **To observe and visualize magnetic fields and forces.**
- **To study the motion of a charged particle in a magnetic field.**
- **To evaluate the magnetic force on a current-carrying conductor.**
- **To study the fields generated by long, straight conductors.**
- **To observe the changes in the field with the conductor in loops (forming the solenoid).**
- **To calculate the magnetic field due to a straight current-carrying wire.**
- **To understand magnetic materials.**

2

21.1 Magnetic Fields

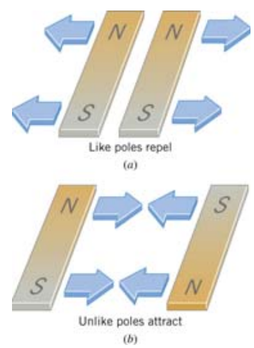
Permanent magnet can produce a magnetic field.



3

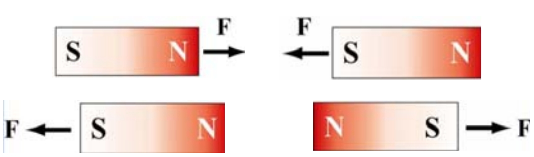
21.1 Magnetic Fields

The behavior of magnetic poles is similar to that of like and unlike electric charges.

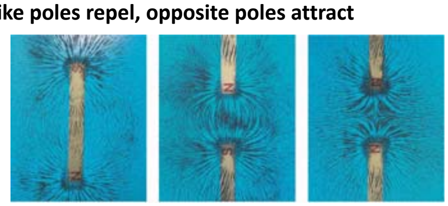


4

Bar Magnet

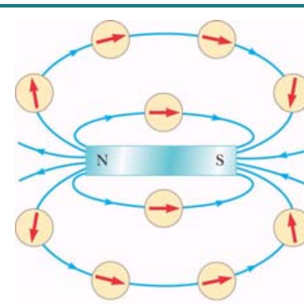


Like poles repel, opposite poles attract



5

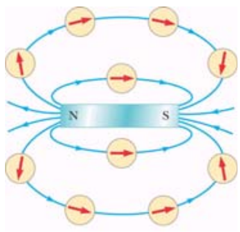
21.1 Magnetic Fields



A magnet has two poles, North (N) and South (S)
Magnetic field lines leave from N, end at S

6

Bar Magnets are Dipoles !



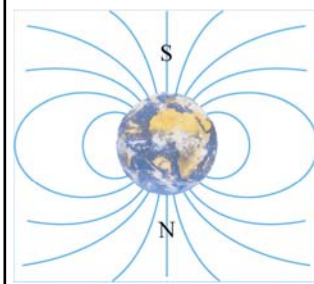
Create Dipole Field

Rotate to orient with Field

Is there magnetic "charge" ?

NO ! Magnetic monopoles do not exist in isolation

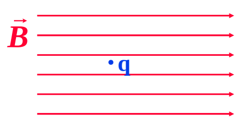
Magnetic Field of the Earth



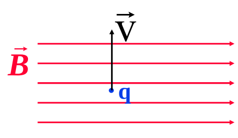
Also a magnetic dipole !

North magnetic pole located in southern hemisphere

What force does a magnetic field exert on charges?

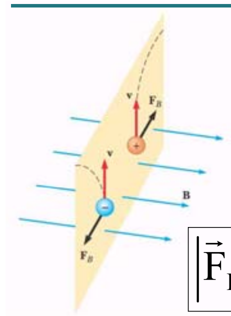


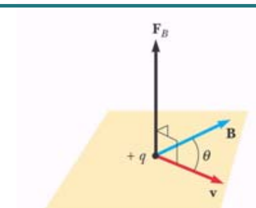
- **NONE!**
- ***(If the charge is not moving with respect to field)***



- If the charge is moving, however, there is a force on the charge, *perpendicular* to both $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$.

21.2 The force that a B field exerts on a moving Charge





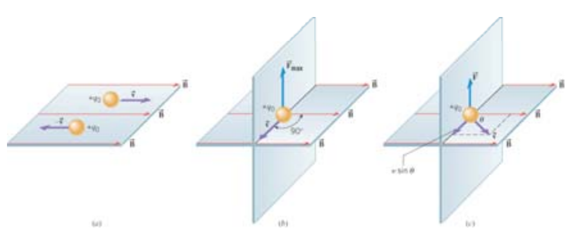
$$\left|\vec{F}_B\right| = q\,\left|\vec{v}\right|\,\left|\vec{B}\right|\ \sin\ \theta$$

Magnetic force perpendicular both to:
Velocity $\underline{v}$ of charge and magnetic field $\underline{B}$

21.2 The Force That a Magnetic Field Exerts on a Charge

The following conditions must be met for a charge to experience a magnetic force when placed in a magnetic field:

1. **The charge must be moving.**
2. **The velocity of the charge must have a component that is perpendicular to the direction of the magnetic field.**

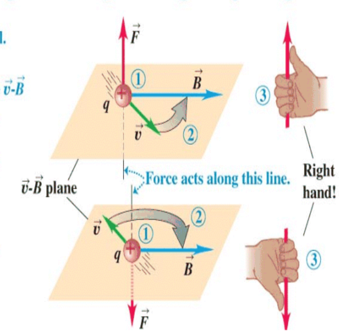


Right-hand rule for the direction of magnetic force on a **positive** charge moving in a magnetic field:

① Place the $\vec{v}$ and $\vec{B}$ vectors tail to tail.

② Imagine turning $\vec{v}$ toward $\vec{B}$ in the $\vec{v}$-$\vec{B}$ plane (through the smaller angle).

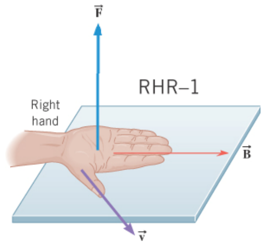
③ The force acts along a line perpendicular to the $\vec{v}$-$\vec{B}$ plane. Curl the fingers of your *right hand* around this line in the same direction you rotated $\vec{v}$. Your thumb now points in the direction the force acts.



21.2 The Force That a Magnetic Field Exerts on a Charge

Right Hand Rule No. 1. Extend the right hand so the fingers point along the direction of the magnetic field and the thumb points along the velocity of the charge. The palm of the hand then faces in the direction of the magnetic force that acts on a positive charge.

If the moving charge is negative, the direction of the force is opposite to that predicted by RHR-1.



13

The magnetic force is *different* from the electric force.

Whereas the electric force acts in the same direction as the field:

$$\vec{F} = q\vec{E}$$

The magnetic force acts in a direction orthogonal to the field:

$$\left|\vec{F}_B\right| = q\left|\vec{v}\right|\left|\vec{B}\right| \sin\theta$$

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

(Use "Right-Hand" Rule to determine direction of)

And --- the charge must be moving !!

14

Definition of a magnetic field

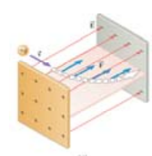
$$B = \frac{F}{|q_o|(v\sin\theta)} \qquad (21.1)$$

SI unit of magnetic field: $\dfrac{newton \cdot second}{coulomb \cdot meter} = 1\; tesla(T)$

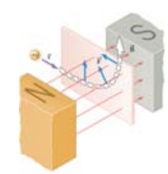
15

21.3 The Motion of a Charged Particle in a Magnetic Field

Charged particle in an electric field.



Charged particle in a magnetic field.



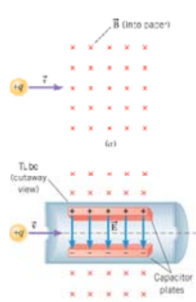
16

21.3 The Motion of a Charged Particle in a Magnetic Field

Conceptual Example 2 **A Velocity Selector**

A velocity selector is a device for measuring the velocity of a charged particle. The device operates by applying electric and magnetic forces to the particle in such a way that these forces balance.

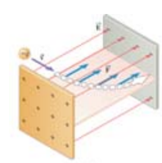
How should an electric field be applied so that the force it applies to the particle can balance the magnetic force?



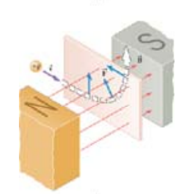
17

21.3 The Motion of a Charged Particle in a Magnetic Field

The electrical force *can* do work on a charged particle.



The magnetic force *cannot* do work on a charged particle.



18

21.3 The Motion of a Charged Particle in a Magnetic Field

The magnetic force always remains perpendicular to the velocity and is directed toward the center of the circular path.

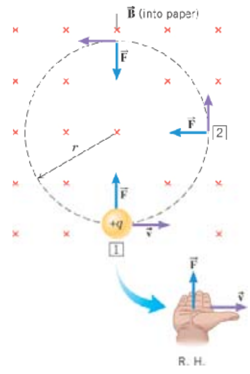
$$F_c = m\frac{v^2}{r}$$

$$\Downarrow$$

$$qvB = m\frac{v^2}{r}$$

$$\Downarrow$$

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

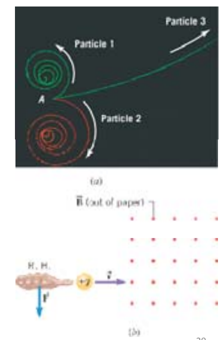


21.3 The Motion of a Charged Particle in a Magnetic Field

Conceptual Example 4 **Particle Tracks in a Bubble Chamber**

The figure shows the bubble-chamber tracks from an event that begins at point A. At this point a gamma ray travels in from the left, spontaneously transforms into two charged particles. The particles move away from point A, producing two spiral tracks. A third charged particle is knocked out of a hydrogen atom and moves forward, producing the long track.

The magnetic field is directed out of the paper. Determine the sign of each particle and which particle is moving most rapidly.



21.4 The Mass Spectrometer

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

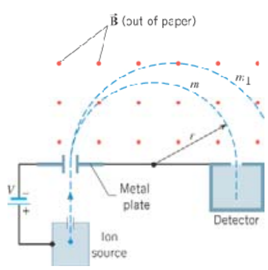
magnitude of electron charge

$$\tfrac{1}{2}mv^2 = eV$$

KE=PE

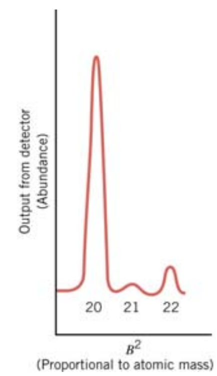
$$m = \frac{2eV}{v^2} = \frac{2eV}{(reB/m)^2} = \frac{2eV \cdot m^2}{(reB)^2}$$

$$m = \left(\frac{er^2}{2V}\right)B^2$$

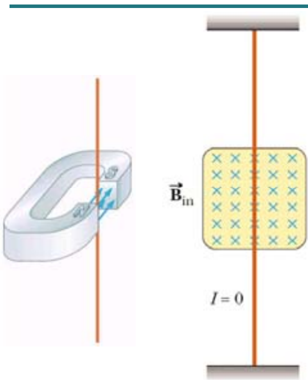


21.4 The Mass Spectrometer

The mass spectrum of naturally occurring neon, showing three isotopes.



21.5 The force on a current in a Magnetic Field

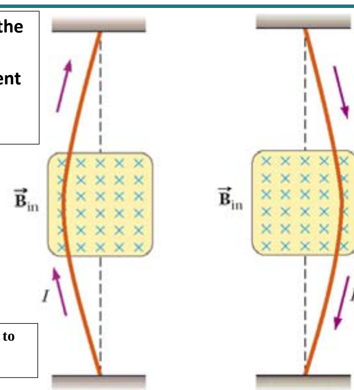


- **The blue x's indicate the magnetic field is directed *into* the page**
  - **The x represents the tail of the arrow**
- **Blue dots would be used to represent the field directed *out of* the page**
  - **The • represents the head of the arrow**
- **In this case, there is no current, so there is no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

Magnetic Force on Current-Carrying Wire

B is into the page
The current is up the page

B is into the page
The current is down the page

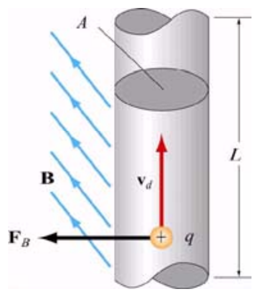


The force is to the left

The force is to the right

Magnetic Force on Current-Carrying Wire

Current is moving charges, and we know that moving charges feel a force in a magnetic field



$$F = q\,v\,B\sin\theta$$

$$= (I\Delta t)\,\frac{\ell}{\Delta t}\,B\sin\theta$$

The total force is the sum of all the magnetic forces on all the individual charges producing the current

$$F = I\,L\,B\sin\theta$$

$$F = I\,L\,B_{\perp}$$

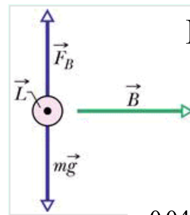
θ is the angle between the direction of B and the direction of I

right hand rule

25

Example: A straight, horizontal length of copper wire has a current I = 28 A through it. What are the magnitude and direction of the minimum magnetic field needed to suspend the wire—that is, to balance the gravitational force on it?

The linear density (mass per unit length) of the wire is 46.6 g/m.



$$F_B = I\,L\,B\sin\theta \qquad F_g = -mg$$

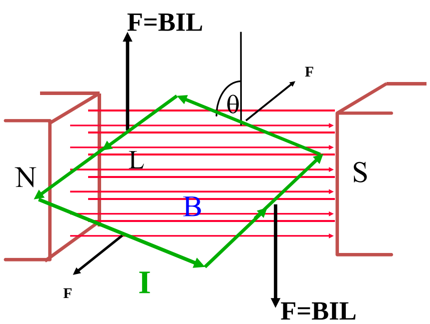
$$\mathbf{F_B + F_g = 0} \qquad \mathbf{m = \rho L}$$

$$\mathbf{I\,L\,B = \rho\,L\,g} \qquad \mathbf{\sin\theta = 1}$$

$$B = \frac{\rho g}{I} = \frac{0.0466\,\mathrm{kg/m}\;\;9.81\,\mathrm{m/s^2}}{28\mathrm{A}} = 0.0163\,\frac{\mathrm{N}}{\mathrm{Am}} = 16.3\,\mathrm{mT}$$

26

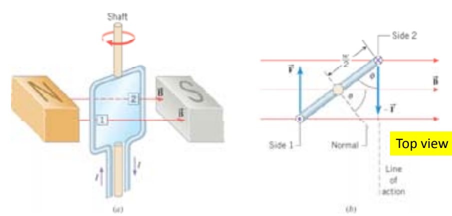
21.6 The torque on a current-carrying Coil



27

21.6 The Torque on a Current-Carrying Coil

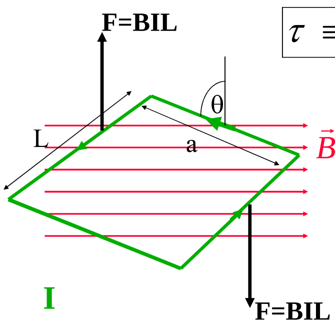
$$\text{Net torque} = \tau = ILB\left(\tfrac{1}{2}w\sin\phi\right) + ILB\left(\tfrac{1}{2}w\sin\phi\right) = IAB\sin\phi$$



$$\tau = \overbrace{NIA}^{\text{magnetic moment}}\,B\sin\phi$$

number of turns of wire

Magnetic Force on a Current Loop
Torque & Electric Motor



$$\tau \equiv IA\;B\sin\theta$$

current I

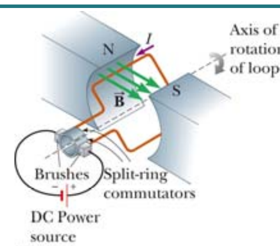
$$\vec{\tau} = I\vec{A} \times \vec{B}$$

$\vec{A}$ Normal to the current loop with area A

29

Electric Motor

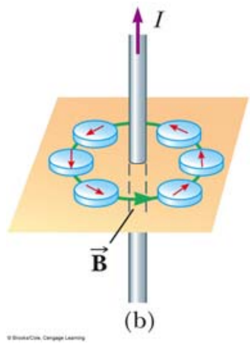
- An electric motor converts electrical energy to mechanical energy
  - The mechanical energy is in the form of rotational kinetic energy
- An electric motor consists of a rigid current-carrying loop that rotates when placed in a magnetic field



- 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

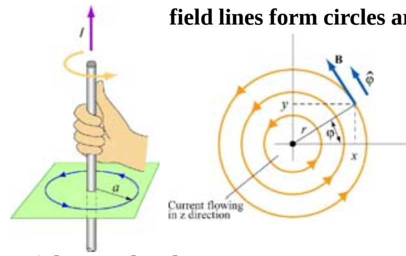
21.7 Magnetic fields produced by currents

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



Direction of Magnetic Field of a Long, Straight Wire

field lines form circles around the wire



'Right-Hand Rule # 2'

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

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

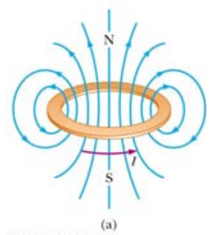
permeability of free space

32

Magnetic Field of a Current Loop

- **The magnitude of the magnetic field at the center of a circular loop with a radius R and carrying current I is**

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



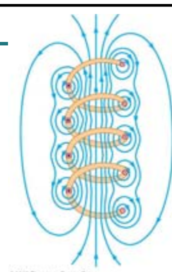
- **With N loops in the coil, this becomes**

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

33

Magnetic Field of a Solenoid

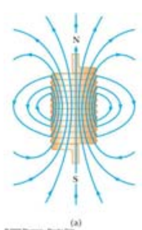
- If a long straight wire is bent into a coil of several closely spaced loops, the resulting device is called a *solenoid*
- It is also known as an electromagnet since it acts like a magnet only when it carries a current

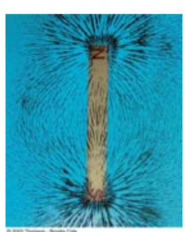


- The field lines inside the solenoid are nearly parallel, uniformly spaced, and close together
  - This indicates that the field inside the solenoid is nearly uniform and strong
- The exterior field is nonuniform, much weaker, and in the opposite direction to the field inside the solenoid

Magnetic Field of a Solenoid

- The field lines of a closely spaced solenoid resemble those of a bar magnet





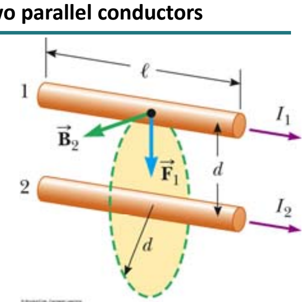
- The magnitude of the field inside a solenoid is constant at all points far from its ends

- **$B = \mu_0 n I$**
  - n is the number of turns per unit length
  - n = N / L

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:

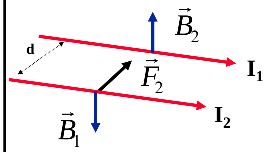
$$\frac{F_2}{\ell} = \frac{\mu_o I_1 I_2}{2\pi d}$$



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

36

Magnetic Force Between Two Parralel Conductors



Current 1 produces a magnetic field $B_1 = \mu_0 I / (2\pi d)$ at the position of wire 2.

This produces a force on current 2:

$$|\vec{F}_2| = I_2 |\vec{L}| |\vec{B}_1|$$

For parallel wires the force on a length L of wire 2 is:

$$F_2 = I_2 L B_1 = \frac{\mu_0 I_1 I_2 L}{2\pi d} \quad \text{or} \quad \frac{F_2}{L} = \frac{\mu_0 I_1 I_2}{2\pi d}$$

Direction: towards 1, if the currents are in the same direction.

What is the force on wire 1?

What happens if one current is reversed?

37

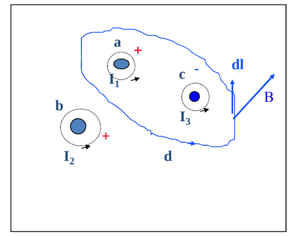
21.8 Ampere's Law

Draw an "Amperian loop" around the sources of current.

The sum of the tangential component of $\vec{B}$ around this loop is equal to $\mu_0 I$:

$$\sum B_{||} \Delta s = \mu_0 I_{enc}$$

blue - into figure (−)
red - out of figure (+)



38

Ampere's Law - a sum along a line

Different Loops: a, b, c, d

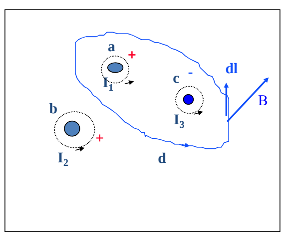
$$\sum B_{||} \Delta s = \mu_0 I_1$$

$$\sum B_{||} \Delta s = \mu_0 I_2$$

$$\sum B_{||} \Delta s = \mu_0 (-I_3)$$

$$\sum B_{||} \Delta s = \mu_0 (I_1 - I_3)$$

blue - into figure (−)
red - out of figure (+)



39

Ampere's Law to find B for a long straight wire

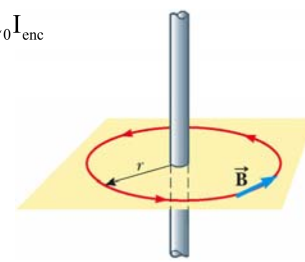
- Use a closed circular path
- The circumference of the circle is 2 π r

$$\sum B_{||} \Delta s = \mu_0 I_{enc}$$

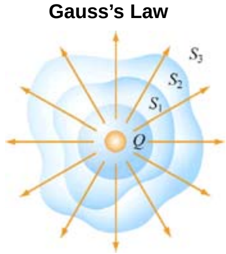
$$\sum B_{||} \Delta s = B \sum \Delta s = \mu_0 I_{enc}$$

$$B\, 2\pi r = \mu_0 I_{enc}$$

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

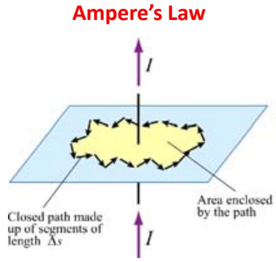


Gauss's Law



The total "flux" of E-field lines depends only on the amount of charge inside

Ampere's Law



The total "curl" of B-field lines depends only on the current punching through the loop

41