Chapter 29

1

Magnetic Fields

Magnetic Poles

2

- Every magnet, regardless of its shape, has two poles.
  - Called North and South poles
  - A single magnetic pole has never been isolated.
  - The poles received their names due to the way a magnet behaves in the Earth's magnetic field.
  - Poles exert forces on one another
    - Like poles repel each other
      - N-N or S-S
    - Unlike poles attract each other
      - N-S

Magnetic Fields

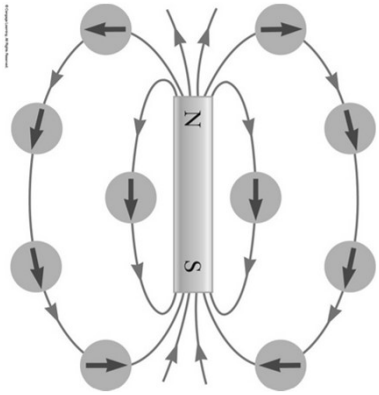
3

- Reminder: an electric field surrounds any electric charge
- The region of space surrounding any moving electric charge also contains a magnetic field.
- A magnetic field also surrounds a magnetic substance making up a permanent magnet.

Magnetic Fields, cont.

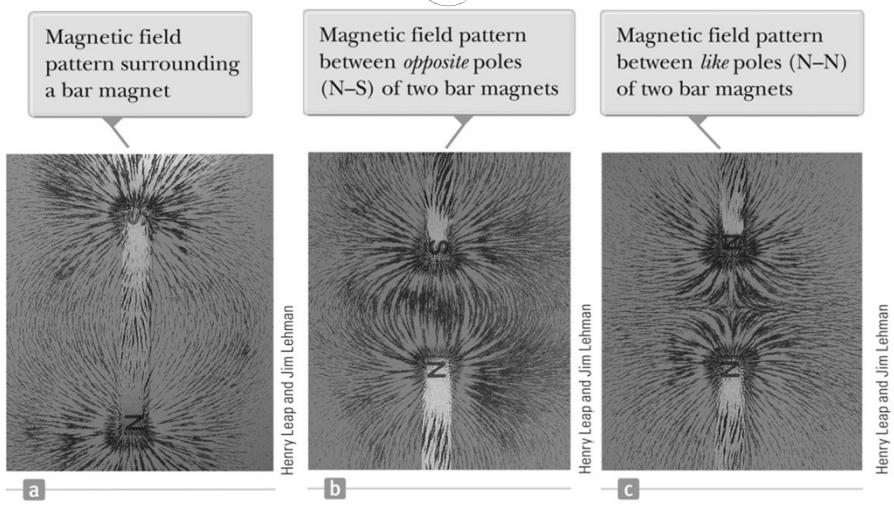
4

- A vector quantity
- Symbolized by $\vec{B}$
- The lines outside the magnet point from the North pole to the South pole.



Magnetic Field Lines, Like Poles

5



Definition of Magnetic Field

6

- The magnetic field at some point in space can be defined in terms of the magnetic force, $\vec{F}_B$.
- The magnetic force will be exerted on a charged particle moving with a velocity, $\vec{v}$.

Properties of a Force on a Charge Moving in a Magnetic Field

7

- The magnitude F_B of the magnetic force exerted on the particle is proportional to the charge, q, and to the speed, v, of the particle.
- When a charged particle moves parallel to the magnetic field vector, the magnetic force acting on the particle is zero.

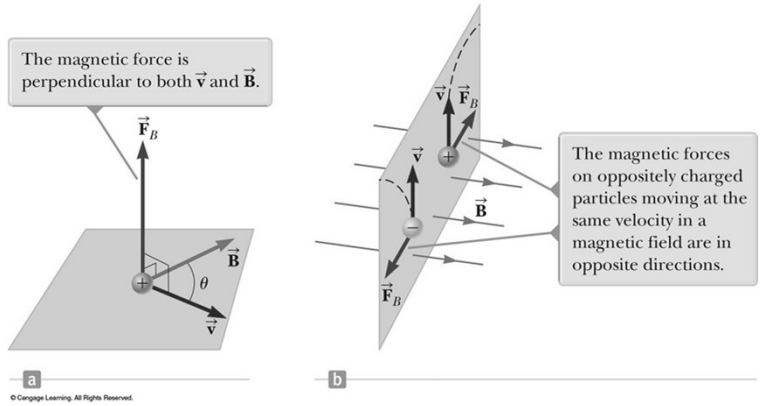
Properties of a Force on a Charge Moving in a Magnetic Field

8

- When the particle's velocity vector makes any angle $\theta \neq 0^{\circ}$ with the field, the force acts in a direction perpendicular to the plane formed by the velocity and the field.
- The magnetic force exerted on a positive charge is in the direction opposite the direction of the magnetic force exerted on a negative charge moving in the same direction.
- The magnitude of the magnetic force is proportional to $sin\theta$, where θ is the angle the particle's velocity makes with the direction of the magnetic field.

More About Direction

9



Force on a Charge Moving in a Magnetic Field, Formula

10

- The properties can be summarized in a vector equation:

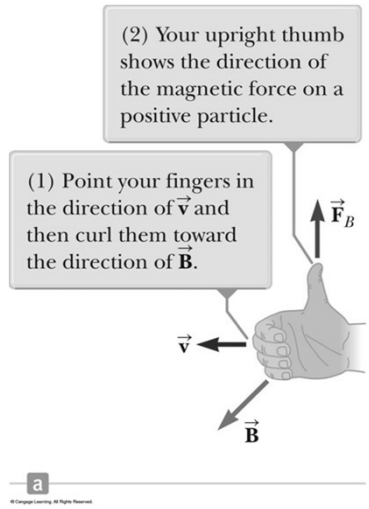
$$\vec{F}_B = q\vec{v} \times \vec{B}$$

- $\vec{F}_B$ is the magnetic force
- q is the charge
- $\vec{v}$ is the velocity of the moving charge
- $\vec{B}$ is the magnetic field

Direction: Right-Hand Rule #1

11

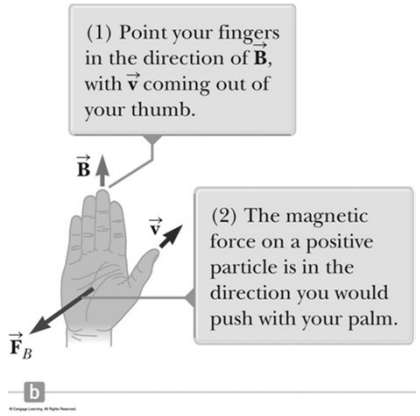
- This rule is based on the right-hand rule for the cross product.
- Your thumb is in the direction of the force if q is positive.
- The force is in the opposite direction of your thumb if q is negative.



Direction: Right-Hand Rule #2

12

- Alternative to Rule #1
- The force on a positive charge extends outward from the palm.
- The advantage of this rule is that the force on the charge is in the direction you would push on something with your hand.
- The force on a negative charge is in the opposite direction.



More About Magnitude of F

13

- The magnitude of the magnetic force on a charged particle is

$$F_B = |q|vBsin\theta$$

θ is the smaller angle between v and B

- F_B is zero when the field and velocity are parallel or antiparallel
  - $\theta = 0^\circ$ or 180°
- F_B is a maximum when the field and velocity are perpendicular
  - $\theta = 90^\circ$

Differences Between Electric and Magnetic Fields

14

- **Direction of force**
  - The electric force acts along the direction of the electric field.
  - The magnetic force acts perpendicular to the magnetic field.
- **Motion**
  - The electric force acts on a charged particle regardless of whether the particle is moving.
  - The magnetic force acts on a charged particle only when the particle is in motion.
- **Work**
  - The electric force does work in displacing a charged particle.
  - The magnetic force associated with a steady magnetic field does no work when a particle is displaced.
    - This is because the force is perpendicular to the displacement of its point of application.

Work in Fields, cont.

15

- The kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone.
- When a charged particle moves with a given velocity through a magnetic field, the field can alter the direction of the velocity, but not the speed or the kinetic energy.

Units of Magnetic Field

16

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

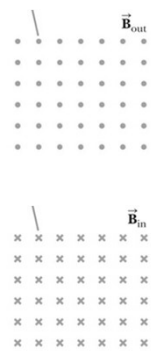
$$T = \frac{Wb}{m^2} = \frac{N}{C.(m/s)} = \frac{N}{A.m}$$

  - Wb is a weber
- A non-SI commonly used unit is a Gauss (G).
  - $1\,T = 10^4\,G$

Notation Notes

17

- When vectors are perpendicular to the page, dots and crosses are used.
  - The dots represent the arrows coming out of the page.
  - The crosses represent the arrows going into the page.
- The same notation applies to other vectors.



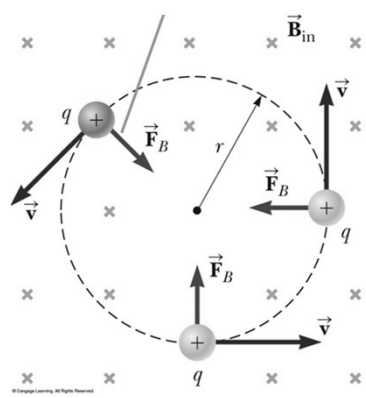
Charged Particle in a Magnetic Field

18

Consider a particle moving in an external magnetic field with its velocity 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

19

•Use the particle under a net force and a particle in uniform circular motion models.

•Equating the magnetic and centripetal forces:

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

•Solving for r:

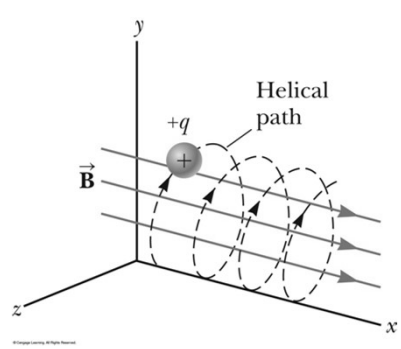
$$\boxed{r = \frac{mv}{qB}}$$

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

Motion of a Particle, General

20

•If a charged particle moves in a magnetic field at some arbitrary angle with respect to the field, its path is a helix.



Charged Particles Moving in Electric and Magnetic Fields

21

In many applications, charged particles will move in the presence of both magnetic and electric fields.

In that case, the total force is the sum of the forces due to the individual fields.

The total force is called the lorentz force.

In general:

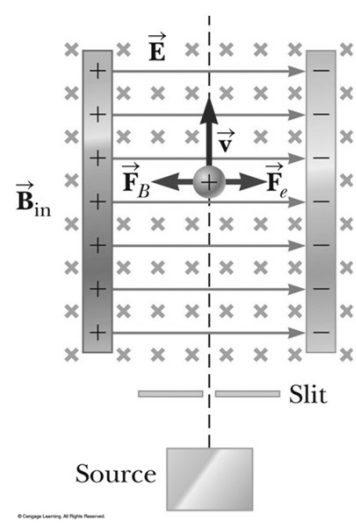
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

Velocity Selector

22

- Used when all the particles need to move with the same velocity.
- A uniform electric field is perpendicular to a uniform magnetic field.
- When the force due to the electric field is equal but opposite to the force due to the magnetic field, the particle moves in a straight line.
- This occurs for velocities of value.

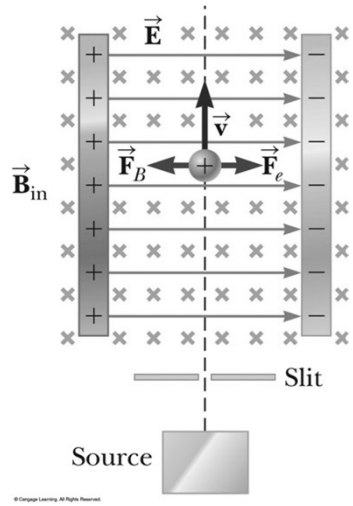
$$v = \frac{E}{B}$$



Velocity Selector, cont.

23

- Only those particles with the given speed will pass through the two fields undeflected.
- The magnetic force exerted on particles moving at a speed greater than this is stronger than the electric force and the particles will be deflected to the left.
- Those moving more slowly will be deflected to the right.



Magnetic Force on a Current Carrying Conductor

24

A force is exerted on a current-carrying wire placed in a magnetic field.

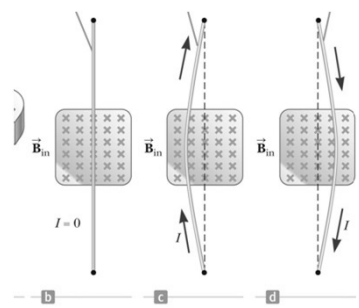
The current is a collection of many charged particles in motion.

The direction of the force is given by the right-hand rule.

Force on a Wire

25

- In case (b):
  - There is no current, so there is no force.
  - Therefore, the wire remains vertical.
- In case (c):
  - The magnetic field is into the page
  - The current is up the page
  - The force is to the left
  - The wire deflects to the left
- In case (d):
  - The magnetic field is into the page
  - The current is down the page
  - The force is to the right
  - The wire deflects to the right



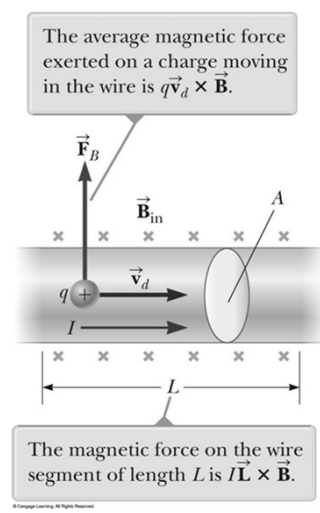
Force on a Wire, Equation.

26

- The magnetic force exerted on the wire is:

$$\vec{F}_B = I\vec{L} \times \vec{B}$$

  - I is the current.
  - $\vec{L}$ is a vector that points in the direction of the current.
    - Its magnitude is the length L of the segment.
  - $\vec{B}$ is the magnetic field.



Torque on a Current Loop

27

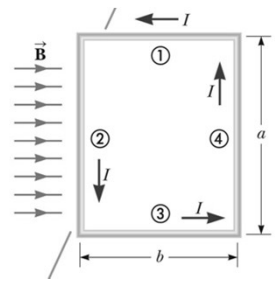
The rectangular loop carries a current I in a uniform magnetic field.

No magnetic force acts on sides 1 & 3.

There is a force on sides 2 & 4 since they are perpendicular to the field.

The direction of F_2 is out of the page.

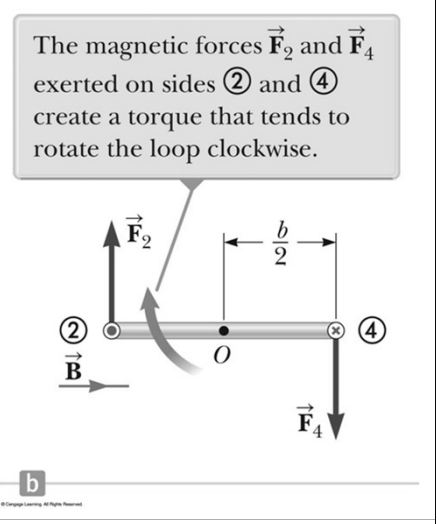
The direction of F_4 is into the page.



Torque on a Current Loop, 3

28

- The forces are equal and in opposite directions, but not along the same line of action.
- The forces produce a torque around point O.



Torque on a Current Loop

29

•The torque has a maximum value when the field is perpendicular to the normal to the plane of the loop.

•The torque is zero when the field is parallel to the normal to the plane of the loop.

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

- $\vec{A}$ is perpendicular to the plane of the loop and has a magnitude equal to the area of the loop.

Magnetic Dipole Moment

30

•The product $I\vec{A}$ is defined as the magnetic dipole moment, $\vec{\mu}$, of the loop:

$$\vec{\mu} = I\vec{A}$$

•SI units: $A.m^2$

•It has the same direction as the normal to the plane of the loop.

•Torque in terms of magnetic moment:

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

Potential Energy

31

•The potential energy of the system of a magnetic dipole in a magnetic field depends on the orientation of the dipole in the magnetic field given by

$$U = -\vec{\mu} \,.\, \vec{B}$$

- The minimum potential energy is ($U_{min.} = -\mu B$) and occurs when the dipole moment (the normal to the plane of the loop) is in the same direction as the field.
- The maximum potential energy is ($U_{max.} = +\mu B$) and occurs when the dipole moment (the normal to the plane of the loop) is in the direction opposite the field.