Magnets have two ends – poles – called north and south. Like poles repel; unlike poles attract.

However, if you cut a magnet in half, you don’t get a north pole and a south pole – you get two smaller magnets.

- An unmagnetized piece of iron can be magnetized by stroking it with a magnet
  - Somewhat like stroking an object to charge an object
- 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, such as cobalt and nickel, are difficult to magnetize
  - They tend to retain their magnetism
Magnets and Magnetic Fields

Magnetic fields can be visualized using magnetic field lines, which are always closed loops.

Magnetic Fields

- A vector quantity
- Symbolized by $\mathbf{B}$
- 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
- 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

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 magnetic field produced by an electric dipole
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

Magnets and Magnetic Fields

The Earth’s magnetic field is similar to that of a bar magnet.

Note that the Earth’s “North Pole” is really a south magnetic pole, as the north ends of magnets are attracted to it.

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
  - 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°
- 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
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

Magnets and Magnetic Fields

The field between these two wide poles is nearly uniform.

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

During the 18th century Oersted found a connection between electricity and magnetism. He found that when a compass needle was placed near an electric wire, the needle deflected. He found that an electric current produces a magnetic field.
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

Magnetic Fields

- When moving through a magnetic field, a charged particle experiences a magnetic force
  - 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

Definition of “B”

The direction of the force is always perpendicular to the direction of the current and also perpendicular to the direction of the magnetic field \( B \).

The magnitude of the force is directly proportional to the current \( I \) in the wire, to the length \( L \) of the wire in the magnetic field, and to the magnetic field \( B \).

\[
F = IILB \sin \theta
\]

- The SI unit of magnetic field is the **Tesla (T)**
- **Weber**
- The cgs unit is a **Gauss (G)**
  - \( 1 \text{ T} = 10^4 \text{ G} \)

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 \( 5 \times 10^{-5} \text{ T} \)
Example 1: Magnetic force on a current-carrying wire.  
A wire carrying a 30-A current has a length $l = 12\, \text{cm}$ between the pole faces of a magnet at an angle $\theta = 60^\circ$. The magnetic field is approximately uniform at 0.90T. What is the force on the wire?

$$F = IlB \sin \theta$$

$$= (30\, \text{A})(0.12\, \text{m})(0.90\, \text{T})(0.866) = 2.8\, \text{N}$$

On a diagram, when we want to represent a magnetic field that is pointing out of the page (toward us) or into the page we use circles with a dot (a) to resemble the tip of an arrow pointing at you and the circle X (b) the tail pointing away.

Example 2: Measuring a magnetic field.  
A rectangular loop of wire hangs vertically. A magnetic field B is directed horizontally, perpendicular to the wire, and points out of the page. The length of the wire $ab$ is $l = 10\, \text{cm}$, which is near the center of a large magnet producing the field. The top portion of the wire loop is free of the field. The downward force of the loop is $F = 3.48 \times 10^{-2}\, \text{N}$. The wire carries a current $I = 0.245\, \text{A}$. What is the magnitude of the magnetic field $B$ at the center of the magnet?

$$B = \frac{F}{Il} = \frac{3.48 \times 10^{-2}\, \text{N}}{(0.245\, \text{A})(0.100\, \text{m})} = 1.42\, \text{T}$$
Finding the Direction of Magnetic Force

- Experiments show that the direction of the magnetic force is always perpendicular to both $\mathbf{v}$ and $\mathbf{B}$
- $F_{\text{max}}$ occurs when $\mathbf{v}$ is perpendicular to $\mathbf{B}$
- $F = 0$ when $\mathbf{v}$ is parallel to $\mathbf{B}$

Right Hand Rule #1

- Place your fingers in the direction of $\mathbf{v}$
- Curl the fingers in the direction of the magnetic field, $\mathbf{B}$
- Your thumb points in the direction of the force, $\mathbf{F}$, on a positive charge
  - If the charge is negative, the force is opposite that determined by the right hand rule

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
- One can define a magnetic field in terms of the magnetic force exerted on a test charge moving in the field with velocity $\mathbf{v}$
  - Similar to the way electric fields are defined

$$B \equiv \frac{F}{q\mathbf{v} \sin \theta}$$
The equation gives the magnitude of the force on a particle of charge q moving with a velocity v in a magnetic field of strength B, where the angle is between v and B. The force is greatest when the particle moves perpendicular to B. The force is zero if the particle moves parallel to the field lines. The direction of the force is perpendicular to the magnetic field B and to the velocity v of the particle. It is again by the right hand rule: you orient your right hand so that your outstretched fingers point along the direction of motion of the particle (v), and when you bend your fingers they must point along the direction of B; then your thumb will point in the direction of the force. This is true only for positively charged particles, and will be down for the diagram on the right.

Example 3: Magnetic force on a proton
A proton having a speed of $5.0 \times 10^6 \text{ m/s}$ in a magnetic field feels a force of $8 \times 10^{-14} \text{ N}$ toward the west when it moves vertically upward. When moving horizontally in a northerly direction, it feels zero force. What is the magnitude and direction of the magnetic field in this region?

$$B = \frac{F}{qv} = \frac{8 \times 10^{-14} \text{ N}}{(1.6 \times 10^{-19} \text{ C})(5.0 \times 10^6 \text{ m/s})} = 0.10 \text{T}$$

Since the proton feels no force when moving north, the field must be in a north-south direction. The right-hand rule tells us that B must point toward the north in order to produce a force to the west when the proton moves upward. (Your thumb points west and the outstretched fingers of your right hand point upward only when your bent fingers point north.)

Force on Electric Charge Moving in a Magnetic Field

If a charged particle is moving perpendicular to a uniform magnetic field, its path will be a circle.
**Example 4:** Electron’s path in a uniform magnetic field.

An electron travels at $2.0 \times 10^7 \text{ m/s}$ in a plane perpendicular to a 0.010-T magnetic field. Describe its path.

The electron moves at constant speed in a curved path whose radius of curvature is found using Newton’s second law, $F = ma$. We have a centripetal acceleration $a = v^2 / r^2$.

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

Since $F$ is perpendicular to $v$, the magnitude of $v$ doesn’t change. From this equation we see that if $B = \text{constant}$, then $r = \text{constant}$, and the curve must be a circle as stated previously.

$$ r = \frac{(9.1 \times 10^{-31} \text{ kg})(2.0 \times 10^7 \text{ m/s})}{(1.6 \times 10^{-19} \text{ C})(0.010 \text{T})} = 1.1 \times 10^{-2} \text{ m} $$

**Force on Electric Charge Moving in a Magnetic Field**

Problem solving: Magnetic fields – things to remember

1. The magnetic force is perpendicular to the magnetic field direction.
2. The right-hand rule is useful for determining directions.
3. Equations in this chapter give magnitudes only. The right-hand rule gives the direction.

**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

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

- $\mu_0 = 4\pi \times 10^{-7} \text{ T m/A}$
  - $\mu_0$ is called the **permeability of free space**
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:

\[
F = \frac{\mu_0 I_1 I_2}{2\pi d}
\]

**Force between Two Parallel Wires**

Parallel currents attract; antiparallel currents repel.

**Example 5:** Force between two current carrying wires.
The two wires of a 2.0-m long appliance cord are 3.0 mm apart and carry a current of 8.0 A dc. Calculate the force between these wires.

\[
F = \frac{\mu_0 I_1 I_2}{2\pi d} = \frac{(2.0 \times 10^{-7} \text{T} \cdot \text{m/A})(8.0 \text{A})^2(2.0 \text{m})}{(3.0 \times 10^{-3} \text{m})} = 8.5 \times 10^{-3} \text{N}
\]

where \( \mu_0 / 2\pi = 2.0 \times 10^{-7} \text{T} \cdot \text{m/A} \)

- 1775 – 1836
- Credited with the discovery of electromagnetism
  - Relationship between electric currents and magnetic fields
- Mathematical genius evident by age 12
**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 $2 \times 10^{-7}$ 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, $\Delta x$, contribute to the field, increasing its strength

**Solenoids and Electromagnets**

A solenoid is a long coil of wire. If it is tightly wrapped, the magnetic field in its interior is almost uniform:

$$B = \mu_0 I N / l$$
If a piece of iron is inserted in the solenoid, the magnetic field greatly increases. Such electromagnets have many practical applications.

**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.
- The field lines of the solenoid resemble those of a bar magnet.

**Magnetic Field in a Solenoid, Magnitude**

- The magnitude of the field inside a solenoid is constant at all points far from its ends.
- \( B = \mu_0 n I \)
  - \( n \) 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

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

Torque on a Current Loop; Magnetic Moment

The forces on opposite sides of a current loop will be equal and opposite (if the field is uniform and the loop is symmetric), but there may be a torque.

The magnitude of the torque is given by: \[ \tau = NIA \sin \theta \]

The quantity \( NIA \) is called the magnetic dipole moment, \( M = NIA \) \( M \):

Example 6: Torque on a coil
A circular coil of wire has a diameter of 20.0 cm and contains 10 loops. The current in each loop is 3.00 A, and the coil is placed in a 2.00-T magnetic field. Determine the maximum and minimum torque exerted on the coil by the field.

\[ A = \pi r^2 = \pi (0.100m)^2 = 3.14 \times 10^{-2} m^2 \]

\[ \tau = NIA \sin \theta = (10)(3.00A)(3.14 \times 10^{-2} m^2)(2.00T)(1) = 1.88 N \cdot m \]

The minimum torque occurs if \( \sin \theta = 0 \), for which \( \theta = 0^\circ \), and then \( \tau = 0 \).
Applications: Galvanometers, Motors, Loudspeakers

A galvanometer takes advantage of the torque on a current loop to measure current.

An electric motor also takes advantage of the torque on a current loop, to change electrical energy to mechanical energy.

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 $\theta$ until the torque becomes 0 at $\theta = 0^\circ$
- 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
- 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
- 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
Applications: Galvanometers, Motors, Loudspeakers

Loudspeakers use the principle that a magnet exerts a force on a current-carrying wire to convert electrical signals into mechanical vibrations, producing sound.

Mass Spectrometer

A mass spectrometer measures the masses of atoms. If a charged particle is moving through perpendicular electric and magnetic fields, there is a particular speed at which it will not be deflected:

\[ v = \frac{E}{B} \]

All the atoms reaching the second magnetic field will have the same speed; their radius of curvature will depend on their mass.

Ferromagnetism: Domains and Hysteresis

Ferromagnetic materials are those that can become strongly magnetized, such as iron and nickel. These materials are made up of tiny regions called domains; the magnetic field in each domain is in a single direction.
When the material is unmagnetized, the domains are randomly oriented. They can be partially or fully aligned by placing the material in an external magnetic field.

A magnet, if undisturbed, will tend to retain its magnetism. It can be demagnetized by shock or heat. The relationship between the external magnetic field and the internal field in a ferromagnet is not simple, as the magnetization can vary.

Starting with unmagnetized material and no magnetic field, the magnetic field can be increased, decreased, reversed, and the cycle repeated. The resulting plot of the total magnetic field within the ferromagnet is called a hysteresis curve.

**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
- 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
- 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
1. A magnetic field will be produced by moving electrons.

2. The equation \( \mathbf{E} = \frac{\mathbf{F}}{q} \) contains vector quantities.

3. The diagram on the right that best represents a magnetic field between two magnetic poles is C.

4. The diagram on the right that best represents the magnetic field near a bar magnet is B.

5. The diagram on the right shows a compass placed near the north pole, N, of a bar magnet. The diagram below that best represents the position of the needle of the compass as it responds to the magnetic field of the bar magnet is A.

6. Electrons are moving to the right in the conductor represented in the diagram. The direction of the magnetic field above the wire at point P is into the page.

7. The arrows in the diagram below indicate the direction of the electron flow. The south pole of the electromagnet is located closest to point A.
8. The diagram on the right represents the magnetic field around point P, at the center-carrying wire. The direction of the electron flow in the wire is from B to A.

9. Magnetic flux density may be measured in Wb/m².

10. The diagram on the right shows a coil of wire connected to a battery. The N-pole of this coil is closest to C.

11. An electron traveling at a speed (v) in the plane of this paper enters a uniform magnetic field. The diagram that best represents the condition under which the electron will experience the greatest magnetic force as it enters the magnetic field is A.

12. A magnetic force is experienced by an electron moving through a magnetic field. If the electron were replaced by a proton traveling at the same velocity, the magnitude of the magnetic force experienced by the proton would be the same.

13. If a charged particle moving through a magnetic field experiences a magnetic force, the angle between the magnetic field and the force exerted on the particle is 90°.

14. A wire carrying an electron current (e⁻) is placed between the poles of a magnet, as shown to the right. The arrow represents a conductor carrying a current in which the electron flow is from left to right. The conductor is located in a magnetic field which is directed into the page. The direction of the magnetic force on the conductor will be toward the bottom of the page.

15. The diagram to the right represents a conductor carrying a current in which the electron flow is from left to right. The conductor is located in a magnetic field which is directed into the page. The direction of the magnetic force on the conductor will be toward the bottom of the page.

16. An electromagnet would have the greatest strength if its wire were wrapped around a core made of iron.
17. Electromagnetic radiation can be generated by an accelerating electron.

18. When electrical charges are accelerated in a vacuum, they may generate light waves.

19. Radiations such as radio, light, and gamma are propagated by the interchange of energy between electric and magnetic fields.

20. An accelerating particle that does not generate electromagnetic waves could be a neutron.