Magnetism

The magnetic force is yet another force that exists in nature. It is closely tied to the electrostatic force in what is commonly known as the electromagnetic force. This force is ultimately responsible for the operation of motors, generators, speakers, and much of our modern technology.

**Basic facts about magnets:**
1) All magnets have North and South poles. These poles cannot exist independently (i.e., there are no magnetic monopoles)
2) Opposite poles attract.
3) Like poles repel.
4) Both poles attract certain materials that are not magnets.
5) Invisible magnetic fields exist around magnets.

**Magnetic Fields (B):** Magnetic Fields exist in the space around magnets and are represented by magnetic field lines.
- The direction of the magnetic field outside a magnet is determined by the deflection of the north needle of a compass. Within the magnet, the lines point from S to N.
- Magnetic field lines form complete loops.
- Magnetic field lines do not cross.
- The density of magnetic field lines corresponds to the strength of the magnetic fields.

**Magnetic Field Patterns:**

**Magnetic Forces (F_m):** Magnetic forces occur when charges move at angles with respect to the magnetic field. Thus, these forces only occur when charges are moving perpendicular to the magnetic field.
What does the magnetic force depends on?
1) the magnitude of the charge
2) the strength of the field
3) the speed, v, or the object
4) the sine of the angle between the velocity and the magnetic field

\[ \vec{F}_m = q\vec{v} \times \vec{B} \quad |F_m| = qBv \sin \theta \]

Solving for the field, \( B = \frac{F_m}{qv \sin \theta} \) unit: \( \frac{N}{C m s} = \text{tesla}(T) \)

Determining direction of the Magnetic Field: The magnetic force is perpendicular to the plane defined by the velocity and magnetic field vectors:

To determine the direction of the field, use Right Hand Rule #1 (Flat hand rule):
1) Point the thumb of your right hand along the direction of velocity
2) Point the fingers (of flat right hand) along the direction of the magnetic field
3) If the charge is positive, the magnetic force is in the direction your palm points. The direction for negative charges is opposite, i.e., in the direction the back of your hand points.

Example: Determine the magnetic force for each figure below if the speed is 10m/s, the charge is +/- 5\( \mu \text{C} \), and the field is 2T.

1) [Diagram of figure 1]
2) [Diagram of figure 2]
3) [Diagram of figure 3]
Practice using RHR#1
Determine the direction of the net magnetic force in each case.

1. \( \overrightarrow{B} \)

2. \( \overrightarrow{B} \) (out of page)

3. \( \overrightarrow{A} \)

4. \( \overrightarrow{B} \) (into page)

5. \( \overrightarrow{B} \)

6. \( I_A \) \( \overrightarrow{B} \)
   \( I_B \) \( \overrightarrow{B} \)
The motion of charges in magnetic fields:

Fact: Magnetic forces cannot change the speed of a charge, but they may change its direction of motion.

Why?

Conclusion: Magnetic forces can do no work to change the kinetic energy of a charge.

Analogy: For a planet in circular orbit, the gravitational force is perpendicular to the velocity of the planet. This centripetal force turns the planet in a circle, but does not change the speed.

In uniform magnetic fields, magnetic forces cause moving charges to move in circular (or helical) paths.

\[
\begin{align*}
F_{\text{net}} &= ma \\
F_c &= ma_c \\
F_m &= m \frac{v^2}{r} \\
qBv \sin 90^\circ &= m \frac{v^2}{r} \\
r &= \frac{mv}{qB}
\end{align*}
\]

Example: A beam of protons moves with a radius of 0.250m perpendicular to a 0.300 T magnetic field.

a) Determine the speed of the protons.

\[
v = \frac{rqB}{m} = \frac{(0.250m)(1.6\times10^{-19}C)(0.300T)}{1.67\times10^{-27}kg} = 7.19\times10^6 m/s
\]

b) Practice: Calculate the magnetic force (centripetal force) on the protons.
Determining Forces on Current-Carrying wires: Wires carrying current will experience a magnetic force if they are in a plane that has a component perpendicular to a magnetic field:

\[ |F_m| = qB(v)\sin\theta = qB(\frac{L}{\Delta t})\sin\theta = \left(\frac{q}{\Delta t}\right)BL\sin\theta \]

\[ |F_m| = IBL\sin\theta = ILB\sin\theta \]

Practice: Use right-hand rule #1 to find the direction of the magnetic force in the wire shown above.

Application: A current vibrating back and forth at a particular frequency is sent through a coil in speakers. The magnetic forces on the coil force the cone of the speaker to vibrate at the same frequency.

Example: Find an expression for the magnetic force (magnitude and direction) on each segment of the coil shown below.

Question: What is the net force on the coil?

The net torque on the coil: \( \tau_{net} = \text{Force} \times \text{Lever arm} = 2(Fm)(\frac{w}{2}) \)
The coil below has a total of "N" windings that are able to pivot. When subjected to a magnetic field it will start to twist around due to the magnetic torque (see previous example).

If the rotating stem of the twisting coil is attached to a torsional spring, the rotation angle will depend on the current. A needle can be attached and the instrument calibrated to measure, for example, amperes of current. This device is called a "galvanometer."

Motors: When the normal line to the loop becomes parallel with magnetic field ($\phi=0$) the torque momentarily goes zero and then reverses direction, this making the galvanometer oscillate back and forth. To make it continue to rotate in the same direction, a "commutator" is required to reverse the current at the appropriate times such that the net torque continues to be in the same direction.
Magnetic Fields Produced by Moving Charges:
Moving charges produce magnetic fields!

In 1820, Hans Christian Oersted made an observation that marked the beginning of the field of electromagnetism. When current flowed through a wire, he noticed that a nearby compass needle moved. This indicates that moving charges produce magnetic fields. This highlights the intimate connection between electricity and magnetism.

Application #1: Magnetic field in the vicinity of long, straight wires. The magnetic field depends directly on the current in the wire and inversely with the radial distance from the wire.

\[ |B| = \frac{\mu_0 \cdot I}{2\pi \cdot r} = (2 \times 10^{-7} \frac{Tm}{A}) \cdot \frac{I}{r} \]

where \( \mu_0 = \text{permeability of free space} \)

\[ \mu_0 = 4\pi \times 10^{-7} \frac{Tm}{A} \]

The direction of the magnetic field is determined by Right Hand Rule #2:
1) Anchor the thumb of the right hand on the wire in the direction of \( I \)
2) Point your fingers toward the region where you wish to find \( B \)
3) Your fingers will curl 90° in the direction of \( B \)

Example: An electron is moving at a speed \( v \) at a distance \( d \) from the current-carrying wire shown.

a) Determine the magnetic field (magnitude and direction) at the location of the wire.

b) Determine the magnetic force (magnitude and direction) on the wire.

c) Question: Does the electron exert a force on the wire? Explain.
Practice using RHR#2
Determine the direction of the net magnetic field at each point.
Forces between current carrying wires: The moving electron in the electron example (example in application #1) may be thought of as a current-carrying wire, except the conventional current would be considered as flowing in the opposite direction as the electron. Use the right-hand rules to determine whether the following 2 pairs of wires will attract or repel.

Application #2: Magnetic field at the very center of a circular loop (radius \( R \)) of current.

\[
|B| = \frac{N \mu_0 I}{2R}
\]

Use the right-hand rule #2 to find the direction of the field in the middle of the loop shown above.

Application #3: Magnetic field within a long, thin coil of wire (solenoid). An electromagnet consists of a cylindrical coil of current-carrying wire.

Use RHR #2 to show the direction of the B-lines in the solenoid above.
Calculation of magnetic field inside a long thin solenoid (Length >> diameter): The field inside depends only on the value of the current and the number of turns per unit length (n)

\[ B = \mu_0 n I \]

where \( n = \frac{\text{# turns}}{\text{Length}} = \frac{N}{L} \)

\[ \mu_0 = 4\pi \times 10^{-7} \frac{Tm}{A} \]

The equation above applies for a vacuum or air core solenoid. When a core such as iron is placed within the windings, B will strengthen significantly.

Example: Assume the solenoid pictured above has length = 10.0 cm, radius = 0.500 cm, # turns = 200, and current=2.00 Amps.

a) What is the magnetic field (magnitude and direction) in the solenoid?

b) Determine the magnetic force (magnitude and direction) on a +20.0\( \mu \)C charge projected at a velocity 40.0 m/s vertically upward through the central region of the solenoid (perpendicular to the axis of the solenoid).

c) Determine the magnetic force on the +20.0\( \mu \)C charge projected at a velocity 40.0 m/s to the right (parallel to the axis of the solenoid).

Sources of magnetism—We have already studied electromagnetism, which refers to magnetic fields produced by moving charges in electrical wires and solenoids. There are 4 other sources of magnetism that we will discuss: ferromagnetism, geomagnetism, diamagnetism, and paramagnetism. Magnetic fields may be produced by charges that are moving through space, from atom to atom in a wire, or circulating within the atom itself.
Ferromagnetism: Some materials like iron, cobalt, and nickel are classified as ferromagnetic. These materials have tiny regions in them called "magnetic domains" that can be visualized as miniature magnets. These tiny domains are approximately a 0.1-0.01 mm in length and consist of $10^{16}-10^{19}$ neighboring atoms. The atoms in each magnetic domain have their electron spins aligned along a common axis. In a bar of iron that is not permanent magnet, the arrows below represent the fact that the domains point in random directions (note that this is only a representation; there are so many domains in the bar and they are so small that it is impossible to draw them all).

![Non-magnetized bar of iron](image)

Permanent magnets, on the other hand, have domains that generally point in the same direction as shown below:

![Permanent magnet](image)

Why are paper clips and other non-magnetized ferromagnetic materials attracted to magnets? The magnetic domains within these materials temporarily align themselves in the direction of an external magnetic field through a process known as induced magnetism. Induced magnetism is demonstrated in the following diagram:

![Induced magnet](image)

When the permanent magnet is removed, the domains in the material usually snap back to their original positions.
Under certain conditions, the domains of an induced magnet may continue to point in the direction of the external magnetic field even after that field is removed. This phenomenon is known as **magnetic remanence**, a phenomenon used to create permanent magnets. There are 4 common ways that magnetic remanence may be obtained:

1) Exposing the ferromagnetic material to a very large external magnetic field.
2) Heating and then cooling the ferromagnetic material in the presence of an external magnetic field.
3) Striking the material in the direction of the external magnetic field.
4) Exposing the material to the external magnetic field for a long period of time.

**Geomagnetism:** There are moving charges within the molten core of the earth that are responsible for the fact that earth itself behaves like a magnet. **Geomagnetism** is the study of magnetic behavior of the earth.

The magnetic poles of the earth have drifted over time and are not located exactly at the geographic north and south poles. This means that a compass needle will not point truly north and adjustments must be made to any reading. Compass measurements in the continental United States may be off by as much as 25 degrees, depending on a location’s magnetic declination.

Evidence from geological rock samples indicates that the earth’s magnetic field has changed significantly over time. Rocks that were formed recently have magnetic domains that point north. Rocks that were formed at other periods in the earth’s history, however, may point south or even in random directions depending on when they were formed.

**Diamagnetism:** A generally weak magnetic effect that exists in some materials (e.g., benzene and silicon) that actually results in repulsion between a material and a magnet.

**Paramagnetism:** A generally weak magnetic effect that exists in some materials (e.g., aluminum) that results in an attraction between a material and a magnet.