Chapter 14
Magnets and Electromagnetism
What is the Earth's magnetic field?
Is the magnetic force similar to the electrostatic force?

How do magnets work?
Magnets and the Magnetic Force

- We are generally more familiar with magnetic forces than with electrostatic forces.
  - Like the gravitational force and the electrostatic force, this force acts even when the objects are not touching one another.
- Is there a relationship between electrical effects and magnetism?
  - Maxwell discovered that the electrostatic force and the magnetic force are really just different aspects of one fundamental electromagnetic force.
- Our understanding of that relationship has led to numerous inventions such as electric motors, electric generators, transformers, etc.
As you probably already know, magnets attract metallic items made of iron or steel, but not silver, copper, aluminum, or most nonmetallic materials.

- The three most common magnetic elements are the metals iron, cobalt, and nickel.

Magnets also attract or repel each other depending on how they are aligned.

- The *north-seeking* end of a magnet wants to point north, and it is called the **north magnetic pole**.
- The *south-seeking* end wants to point south, and it is called the **south magnetic pole**.

*Like poles repel one another, and unlike poles attract one another.*
The force that two poles exert on one another varies with distance or pole strength.

- The magnetic force between two poles decreases with the square of the distance between the two poles, just as the electrostatic force does.
- Some magnets are stronger than others; the force is directly proportional to the pole strength of the magnets involved.
A magnet always has at least two poles: a **magnetic dipole**.

- Breaking a magnetic dipole in half results in two smaller magnetic dipoles.
- We cannot get just one magnetic north or south pole by itself: **magnetic monopoles** do not exist.
- **Magnetic field lines** produced by a magnetic dipole form a pattern similar to the electric field lines produced by an electric dipole.
  - Electric field lines originate on positive charges and terminate on negative charges.
  - Magnetic field lines form continuous loops: they emerge from the north pole and enter through the south pole, pointing from the north pole to the south pole outside the magnet.
  - Inside the magnet, they point from the south pole to the north pole.
A magnetic dipole tends to line up with an externally produced magnetic field just as an electric dipole tends to line up with an electric field.

- Both dipoles experience a torque due to the force from the externally produced field.
- This is why iron filings line up with the field lines around a magnet.
Is the Earth a magnet?

- The north *(north-seeking)* pole of a compass needle points toward the Earth’s “North Pole.”

  - The magnetic field produced by the Earth can be pictured by imagining a large bar magnet inside the Earth.

  - Since unlike poles attract, the south pole of the Earth’s magnet must point in a northerly direction.

  - The axis of the Earth’s magnetic field is not aligned exactly with the Earth’s axis of rotation.
Magnetic Effects of Electric Currents

- Oersted discovered that a compass needle was deflected by a current-carrying wire.
- With the wire oriented along a north-south line, the compass needle deflects away from this line when there is current flowing in the wire.
- The magnetic field produced by the current is perpendicular to the direction of the current.
- The magnetic field lines produced by a straight, current-carrying wire form circles centered on the wire.
  - The **right-hand rule** gives the direction of the field lines: with the thumb in the direction of the current, the fingers curl in the direction of the field lines produced by that current.
  - The effect gets weaker as the compass is moved away from the wire.
Two parallel current-carrying wires exert an **attractive** force on each other when the two currents are in the **same** direction.

- The force is proportional to the two currents \((I_1 \text{ and } I_2)\) and inversely proportional to the distance \(r\) between the two wires:

\[
\frac{F}{l} = \frac{2k'I_1I_2}{r}
\]

where \(k' = 1 \times 10^{-7} \text{ N/A}^2\)

- One ampere (A) is the amount of current flowing in each of two parallel wires separated by a distance of 1 meter that produces a force per unit length on each wire of \(2 \times 10^{-7} \text{ N/m}\).
Two long parallel wires carry currents of 5 A and 10 A in opposite directions as shown. What is the magnitude of the force per unit length exerted by one wire on the other?

a) $2.0 \times 10^{-6}$ N/m
b) $5.0 \times 10^{-6}$ N/m
c) $2.0 \times 10^{-4}$ N/m
d) 50 N/m
e) 1000 N/m

\[
F = \frac{2k' I_1 I_2}{r} = \frac{2 \left(1 \times 10^{-7} \text{ N/A}^2\right)(5 \text{ A})(10 \text{ A})}{(0.05 \text{ m})} = 2.0 \times 10^{-4} \text{ N/m}
\]
Two long parallel wires carry currents of 5 A and 10 A in **opposite** directions as shown. What are the directions of the forces on each wire?

a) The wires exert an attractive force on each other.
b) The wires exert a force repelling each other.
c) Each wire exerts a force on the other in the direction of the other wire's current (the red arrows shown).
d) Each wire exerts a force on the other in the direction opposite to the other one's current.
e) The wires exert no force on each other.

The wires repel each other.
Two long parallel wires carry currents of 5 A and 10 A in opposite directions as shown. What is the total force exerted on a 30-cm length of the 10-A wire?

(a) $2.0 \times 10^{-6}$ N  
(b) $3.0 \times 10^{-6}$ N  
(c) $2.0 \times 10^{-5}$ N  
(d) $6.0 \times 10^{-5}$ N  
(e) $2.0 \times 10^{-4}$ N

\[ F = \frac{2kI_1I_2}{l} = \frac{2 \times 10^{-4} \text{ N/m}}{0.30 \text{ m}} = 2.0 \times 10^{-5} \text{ N} \]

\[ F = \left( \frac{F}{l} \right) l = \left( 2.0 \times 10^{-4} \text{ N/m} \right) (0.30 \text{ m}) = 6 \times 10^{-5} \text{ N} \]
Magnetic forces are exerted by magnets on other magnets, by magnets on current-carrying wires, and by current-carrying wires on each other.

- The force exerted by one wire on the other is attractive when the currents are flowing in the same direction and repulsive when the currents are flowing in opposite directions.
- The magnetic force exerted on a moving charge of an electric current is perpendicular to both the velocity of the charges and to the magnetic field.
- This force is proportional to the quantity of the charge and the velocity of the moving charge and to the strength of the magnetic field:

\[ F = qvB \]

\[ F = II'B \]
Two long parallel wires carry currents of 5 A and 10 A in opposite directions as shown. What is the strength of the magnetic field produced by the 5-A wire at the position of the 10-A wire? 

- a) $2.4 \times 10^{-6}$ T
- b) $2.0 \times 10^{-5}$ T
- c) $1.2 \times 10^{-5}$ T
- d) $1.2 \times 10^{-4}$ T
- e) $2.4 \times 10^{-4}$ T

The force $F$ on the wire is given by $F = 6 \times 10^{-5}$ N = $IlB$.

- $l = 0.30$ m is the length of the 10A wire,
- $B$ is due to the 5A current,
- and $I$ is the 10A current.

$$B = \frac{F}{Il} = \frac{(6 \times 10^{-5} \text{ N})}{(10 \text{ A})(0.30 \text{ m})}$$

$$= 0.00002 \text{ N/A} \cdot \text{m}$$

$$= 2 \times 10^{-5} \text{ T}$$
- For this relationship to be valid, the velocity must be perpendicular to the field.
- This actually defines the **magnetic field** as the force per unit charge and unit of velocity:
  \[
  B = \frac{F}{qv_{\perp}}
  \]
  units: 1 tesla (T) = 1 N/A·m

  - If the index finger of the right hand points in the direction of the velocity of the charge, and the middle finger in the direction of the magnetic field, then the thumb indicates the direction of the magnetic force acting on a **positive** charge.
The force on a moving positively charged particle is perpendicular to the particle’s motion and to the magnetic field, just as the force on a current is perpendicular to the current and to the field.

- The force on a negative charge is in the opposite direction of the force on a positive charge: \( q \rightarrow -q \).

Because the force is perpendicular to the velocity of the particle, the force does no work on the particle.

- It cannot increase the particle’s kinetic energy; it only serves to change the direction of the particle’s motion.
- It provides a centripetal acceleration.
- If the charge is moving perpendicular to a uniform magnetic field, the particle will follow a circular path.
Two long parallel wires carry currents of 5 A and 10 A in opposite directions as shown. What is the direction of the magnetic field produced by the 5-A wire at the position of the 10-A wire?

a) Perpendicular to the plane of the page and into the page
b) Perpendicular to the plane of the page and out of the page
c) Upward
d) Downward
e) Inward toward the other wire
f) Outward away from the other wire

Perpendicular to plane of page and into page
A straight wire with a length of 15 cm carries a current of 4 A. The wire is oriented perpendicularly to a magnetic field of 0.5 T. What is the size of the magnetic force exerted on the wire?

a) 0.3 N  
b) 0.48 N  
c) 0.6 N  
d) 1.0 N  
e) 2.0 N

The direction of this force will be perpendicular to both the current in the wire and to the magnetic field, as described by the right-hand rule.

\[
l = 15 \text{ cm} = 0.15 \text{ m} \\
I = 4 \text{ A} \\
B = 0.5 \text{ T} \\
F = ILB \\
= (4 \text{ A})(0.15 \text{ m})(0.5 \text{ T}) \\
= 0.3 \text{ N}
\]
Magnetic Effects of Current Loops

- When a current-carrying wire is bent into a circular loop, the magnetic fields produced by different segments of the wire add to produce a strong field near the center of the loop.
The magnetic field produced by a current loop is identical to one produced by a short bar magnet (a magnetic dipole).

- In fact, in an external magnetic field, a current loop will experience a torque just as a bar magnet would.
Consider a rectangular loop:

- Each segment of the rectangular loop is a straight wire.
- The force on each segment is given by \( F = IIL \).
- Using the right-hand rule, you can verify that the loop will tend to rotate in the direction indicated.
- The forces on the two ends of the loop produce no torque about center of the loop, because their lines of action pass through the center of the loop.
- The forces on the other two sides combine to produce a torque that tends to line up the plane of the loop perpendicular to the magnetic field.
A current-carrying rectangular loop of wire is placed in an external magnetic field as shown. In what direction will this loop tend to rotate as a result of the magnetic torque exerted on it?

The loop will rotate counterclockwise. The forces on the long arms are outward and because they do not share a common line of action, impart a counterclockwise torque on the loop.
Since the magnetic forces on the loop segments are proportional to the electric current flowing around the loop, the magnitude of the torque is also proportional to the current.

Thus, the torque on a current-carrying coil can be used for measuring electric current.

An electric meter consists of a coil of wire, a permanent magnet, and a restoring spring to return the needle to zero when there is no current flowing through the coil.
This torque is also the basis of operation for electric motors.

- The current must reverse directions every half turn to keep the coil turning.
- This can be achieved by using alternating current, or by using a reversing direction of dc current with a **split ring commutator**.

One design for a simple dc motor consists of a wire-wound rotor mounted on an axle between the pole faces of a permanent magnet.

The split ring causes the current to reverse directions every half turn, thus keeping the coil turning the same direction.
The magnetic field produced by a coil of wire will be stronger than one produced by a single loop carrying the same current.

- The magnetic field produced by each loop all add together.
- The resulting field strength is proportional to the number of turns \( N \) that are wound on the coil.
- The torque on the coil, when placed in an external magnetic field, is also proportional to both the current and the number of turns in the coil.
Can we utilize the similarities between a current-carrying coil of wire and a magnet?

• By winding a coil around a steel needle or nail, the magnetic field produced is enhanced.
• The nail then behaves like a magnet that is stronger than most natural magnets.
• This is an electromagnet.
Faraday’s Law: 
Electromagnetic Induction

- We have seen that an electric current produces a magnetic field.
  - *Can magnetic fields produce electric currents?*

- **Faraday** tried, at first unsuccessfully, to detect a current in a coil as a result of a current in a nearby coil.
  - The *primary coil* was connected to a battery to produce a current.
  - The *secondary coil* was connected to a *galvanometer*, a device to detect magnitude and direction of current.
With coils of about 200 feet of copper wire, Faraday noticed a very brief deflection of a galvanometer when the current in the primary coil was first started or when it was interrupted.

- The galvanometer deflected one way when the primary was first connected to the battery and the opposite direction when the contact was broken.
- No current was detected in the secondary coil when there was a secondary current in the primary coil.

An electric current is only induced in the secondary coil when there is a changing current in the primary.
The changing current in the primary coil implies a changing magnetic field.
The electric current in the secondary coil implies that there is an electric field being induced.
Faraday also detected a current in a coil of wire when a magnet was moved into or out of the center of the coil.
- The galvanometer deflected one way when the magnet was being inserted and the opposite direction when it was being withdrawn.
- No current was detected when the magnet was not moving.

An electric field is produced when there is a changing magnetic field.
**Magnetic flux** ($\Phi$) is a measure of how much magnetic field is passing through a loop of wire.

- It is at a maximum when the field lines are perpendicular to the plane of the loop, and it is zero when the field lines are parallel to the plane of the loop.

For a coil of $N$ loops, the flux through the coil is equal to the flux through one loop, multiplied by the number of loops:

$$\Phi = NBA$$
Suppose that the magnetic flux through a coil of wire varies with time as shown. Where does the induced voltage have its largest magnitude?

a) From 0 s to 1 s
b) At 1 s
c) From 1 s to 3 s
d) At 3 s
e) From 3 s to 5 s

From 0 to 1s the flux is changing the most rapidly and during this time the induced voltage will be the largest.
Faraday’s Law

- A voltage (electromotive force) is induced in a circuit when there is a changing magnetic flux passing through the circuit.
- The induced voltage is equal to the rate of change of the magnetic flux:

\[ \mathcal{E} = \frac{\Delta \Phi}{t} \]

- This process is called *electromagnetic inductance*. 
Lenz’s Law

- The *direction of the induced current* generated by a changing magnetic flux produces a magnetic field that opposes the change in the original magnetic flux.
A coil of wire with 50 turns has a uniform magnetic field of 0.4 T passing through the coil perpendicular to its plane. The coil encloses an area of 0.03 m². If the flux through the coil is reduced to zero by removing it from the field in a time of 0.25 s, what is the induced voltage in the coil?

a) 0.012 V  b) 0.12 V  c) 0.60 V  d) 1.5 V  e) 2.4 V

\[ N = 50 \text{ turns} \]
\[ B = 0.4 \text{ T} \]
\[ A = 0.03 \text{ m}^2 \]
\[ t = 0.25 \text{ s} \]

\[ \Phi = NBA \]
\[ = (50 \text{ turns})(0.4 \text{ T})(0.03 \text{ m}^2) \]
\[ = 0.60 \text{ T} \cdot \text{m}^2 \]

\[ \mathcal{E} = \frac{\Delta \Phi}{t} \]
\[ = \frac{(0.60 \text{ T} \cdot \text{m}^2 - 0)}{0.25 \text{ s}} \]
\[ = 2.4 \text{ V} \]
Joseph Henry noticed that the spark or shock obtained when an electromagnet was connected to a battery was larger than one obtained by touching the terminals of the battery with an uncoiled wire.

- The changing magnetic flux through a coil of wire produced when the coil is connected or disconnected from the battery produces an induced voltage in the same coil.
- The induced current in the coil opposes the changing magnetic flux.
- This phenomenon is called self-inductance.
Generators and Transformers

- A generator converts mechanical energy to electrical energy by electromagnetic induction and produces an alternating current.

- A simple generator consists of a coil of wire that generates an electric current when turned between the pole faces of permanent magnets.

- The coil’s rotation causes the magnetic flux through the coil to change continuously.

- It is this changing flux that produces a current in the coil.
The flux changes continuously from a maximum value in one direction, to zero, to a maximum value in the opposite direction.

The induced voltage depends on the rate of change of the flux.

When the flux is increasing the fastest, the voltage is a maximum; when the flux is decreasing the fastest, the voltage is a maximum in the other direction (negative).
A **transformer** adjusts the voltage of an ac circuit up or down as needed for a particular application.

- Transformers are seen on utility poles, at electrical substations, and as voltage adapters for electrical devices.
- The ability to use generators and transformers mean that alternating current is convenient for large-scale power production and distribution.
The ratio of the number of turns in the primary coil to the voltage on the primary coil is equal to the ratio of the number of turns on the secondary coil to the induced voltage in the secondary coil:

\[ \frac{N_1}{\Delta V_1} = \frac{N_2}{\Delta V_2} \]

\[ \Delta V_2 = \Delta V_1 \left( \frac{N_2}{N_1} \right) \]
If you need 12 volts to run an appliance, using the power provided at the wall socket with 120 volts, you need a step-down transformer with ten times as many turns in the primary coil as in the secondary coil.

If you need higher voltages than the 120 volts provided, you use a step-up transformer with more turns on the secondary than on the primary.

\[ \frac{N_1}{\Delta V_1} = \frac{N_2}{\Delta V_2} \]

\[ \Delta V_2 = \Delta V_1 \left( \frac{N_2}{N_1} \right) \]
Can a transformer be used, as shown in the diagram below, to step up the voltage of a battery?

a) Yes  
b) No  
c) Impossible to tell from this figure

No, it will not work as shown in the diagram. If one contact of the battery and the primary were to be continuously opened and closed, this would produce a variable flux and then the transformer would work.
High voltages are desirable for long-distance transmission of electrical power.

- The higher the voltage, the lower the current needed to transmit a given amount of power.
- Minimizing the current minimizes the heat lost to resistive heating ($P=I^2R$).
- Transmission voltages as high as $230 \text{ kV} = 230,000 \text{ V}$ are not unusual.
- Transformers at electrical substations reduce the voltage to $7200$ volts for in-town distribution.
- Transformers on utility poles or underground lower this voltage from $220$ to $240$ volts for entry into buildings.
- This can be used as is for stoves, dryers, etc., or lowered to $110$ volts for common household circuits.

Direct current is occasionally used to transmit power over long distances, as it does not lose energy by radiation of electromagnetic waves like alternating current does.