17 Magnetism and Electromagnetic Induction

17-1 Magnetic Forces and Fields

Vocabulary

Magnetic Field: An area of influence around a moving charge. The size of the field is related to the amount of magnetic force experienced by the moving charge when it is at a given location in the field.

$$\textbf{magnetic field} = \frac{\textbf{force}}{\textbf{(charge)(speed)}} \quad \text{or} \quad B = \frac{F}{qv}$$

The SI unit for magnetic field is the **tesla (T)**, which equals one **netwon per amp·meter (N/A·m)**.

When solving for the magnetic force, rewrite this equation as $F = qvB$.

The magnitude of the magnetic force can also be written in terms of the current, I, flowing through a length of wire, L.

$$\textbf{force = (current)(length of wire)(magnetic field)} \quad \text{or} \quad F = ILB$$

Unlike gravitational force or electric force, magnetic force is perpendicular to the plane formed by the field and the moving charge, and is greatest when the magnetic field and the current are perpendicular to each other.

The easiest way to detect a magnetic field is with a compass.

Solved Examples

Example 1: A proton speeding through a synchrotron at 3.0×10^7 m/s experiences a magnetic field of 4.0 T that is produced by the steering magnets inside the synchrotron. What is the magnetic force pulling on the proton?

Solution: Remember, the charge of a proton or an electron is 1.60×10^{-19} C.

Given: $q = 1.60 \times 10^{-19}$ C
$v = 3.0 \times 10^7$ m/s
$B = 4.0$ T

Unknown: $F = ?$
Original equation: $F = qvB$

Solve: $F = qvB = (1.60 \times 10^{-19}\ \text{C})(3.0 \times 10^7\ \text{m/s})(4.0\ \text{T}) = \mathbf{1.9 \times 10^{-11}\ N}$

Example 2: A 10.0-m-long high-tension power line carries a current of 20.0 A perpendicular to Earth's magnetic field of 5.5×10^{-5} T. What is the magnetic force experienced by the power line?

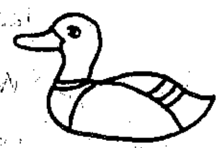
Given: $I = 20.0$ A
$L = 10.0$ m
$B = 5.5 \times 10^{-5}$ T

Unknown: $F = ?$
Original equation: $F = ILB$

Solve: $F = ILB = (20.0 \text{ A})(10.0 \text{ m})(5.5 \times 10^{-5} \text{ T}) = \mathbf{0.011\ N}$

Practice Exercises

Exercise 1: Dean is hunting in the Northwest Territories at a location where Earth's magnetic field is 7.0×10^{-5} T. He shoots by mistake at a duck decoy, and the rubber bullet he is using acquires a charge of 2.0×10^{-12} C as it leaves his gun at 300. m/s, perpendicular to Earth's magnetic field. What is the magnitude of the magnetic force acting on the bullet?



Answer: ____________________

Exercise 2: A wasp accumulates 1.0×10^{-12} C of charge while flying perpendicular to Earth's magnetic field of 5.0×10^{-5} T. How fast is the wasp flying if the magnetic force acting on it is 6.0×10^{-16} N?

Answer: ____________________

Exercise 3: Kron, the alien freedom fighter from the planet Krimbar, shoots his gun that fires protons at a speed of 3.0×10^{6} m/s. a) What is Krimbar's magnetic field if it creates a force of 2.88×10^{-15} N on the protons? b) How does this compare to Earth's magnetic field?

Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 4: The magnetic field in Boston, Massachusetts has a horizontal component to the north of 0.18×10^{-4} T and a vertical component of 0.52×10^{-4} T straight downward. a) What is the magnitude and direction of Earth's magnetic field in Boston? b) If a 2.0-m-long household wire is carrying a current of 15 A in a direction perpendicular to the field, what is the magnitude of the magnetic force experienced by the wire?

Answer: **a.** ____________________

Answer: **b.** ____________________

17-2 Electromagnetic Induction

Magnetic Flux and Induced Voltage

Vocabulary **Flux:** The number of magnetic field lines passing through a given area.

flux = (area)(perpendicular component of the magnetic field)

or $\phi = AB$

The unit for flux is the **weber (Wb)**, which equals one **tesla·meter squared ($T \cdot m^2$).**

Therefore, if a loop of wire lies perpendicular to a magnetic field, the maximum possible number of lines of flux will pass through the loop. If the loop of wire lies parallel to the field, the flux through the loop will be zero.

Vocabulary **Faraday's Law:** If the flux through a given area changes over time, a voltage will be induced in the wire and a current will momentarily flow. If the number of turns of wire is increased, the voltage will increase proportionally.

$$\textbf{potential difference} = \frac{\textbf{(number of turns)(change in flux)}}{\textbf{elapsed time}}$$

or $$V = \frac{N\Delta\phi}{\Delta t}$$

Note: This potential difference is also referred to as the **induced voltage.**

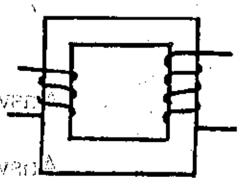
Vocabulary **Lenz's Law:** An induced voltage always produces a magnetic field that opposes the field that originally produced it.

In other words, if the original magnetic field, and thus the flux, is going toward the north, the induced voltage will produce an opposing field and flux that goes toward the south.

Transformers

Vocabulary **Transformer:** A device that produces a change in voltage in an alternating current circuit.

A transformer consists of an iron core wound with a primary coil and a secondary coil. An alternating current placed through the primary coil induces a changing magnetic field through the core, which, in turn, induces a voltage in the secondary coil.



$$\frac{\textbf{voltage in primary coil}}{\textbf{voltage in secondary coil}} = \frac{\textbf{turns in primary coil}}{\textbf{turns in secondary coil}} \quad \text{or} \quad \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

If the primary coil has more turns than the secondary coil, the transformer will step down, or decrease, the incoming voltage. If the primary coil has fewer turns than the secondary coil, the transformer will step up, or increase, the incoming voltage.

Solved Examples

Example 3: Tyrone is pedaling his bike down the street perpendicular to Earth's magnetic field of 5.5×10^{-5} T. What is the flux through the metal rim of his bicycle wheel, if the wheel has an area of $1.13\ m^2$?

Given: $A = 1.13\ m^2$
$B = 5.5 \times 10^{-5}$ T

Unknown: $\phi = ?$
Original equation: $\phi = AB$

Solve: $\phi = AB = (1.13\ m^2)(5.5 \times 10^{-5}\ T) = \mathbf{6.2 \times 10^{-5}\ Wb}$

Example 4: If the bicycle in Example 3 takes 2.0 s to make a 90° turn onto a northbound street, what is the induced voltage in one metal rim of the bicycle?

Given: $N = 1$ turn
$\phi = 6.2 \times 10^{-5}$ Wb
$\Delta t = 2.0$ s

Unknown: $V = ?$
Original equation: $V = \dfrac{N\Delta\phi}{\Delta t}$

Solve: $V = \dfrac{N\Delta\phi}{\Delta t} = \dfrac{(1\ \text{turn})(6.2 \times 10^{-5}\ \text{Wb})}{2.0\ \text{s}} = \mathbf{3.1 \times 10^{-5}\ V}$

Example 5: While out for a walk with his mother, Lance notices a large, cylindrical gray box high atop a telephone pole. His mother explains that it is a transformer. This transformer takes 6000. V from the power company and steps it down to the 240 V supplied to each of the houses on the street, with the use of a secondary coil containing 100. turns. How many turns are there in the primary coil?

Given: $V_p = 6000.\text{ V}$

$V_s = 240\text{ V}$

$N_s = 100.\text{ turns}$

Unknown: $N_p = ?$

Original equation: $\dfrac{V_p}{V_s} = \dfrac{N_p}{N_s}$

Solve: $N_p = \dfrac{V_p N_s}{V_s} = \dfrac{(6000.\ V)(100.\text{ turns})}{240\text{ V}} = \mathbf{2500\ turns}$

Practice Exercises

Exercise 5: Patty is driving down the expressway on her way to the office in a town where the horizontal component of Earth's magnetic field is 3.5×10^{-5} T to the north. The driver's side window of Patty's car has an area of 0.40 m^2.
a) What is the magnitude of the flux through the window if the car is moving south? b) How does it differ if the car is moving west?

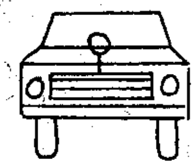
Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 6: A medical process called *magnetic resonance imaging* (MRI) replaces X-rays in some instances where pictures are required to study internal organs. Eleanor is undergoing an MRI procedure and is placed inside a chamber housing the coil of a large electromagnet that has a radius of 25.0 cm. A flux of 0.290 Wb passes through the coil opening. What is the magnetic field inside the coil?

Answer: ____________________

Exercise 7: The hood ornament on Abe's sedan is shaped like a ring 8.00 cm in diameter. Abe is driving toward the west so that Earth's 5.00×10^{-5} T field provides no flux through the hood ornament. What is the induced voltage in the metal ring as Abe turns from this street onto one where he is traveling north, if he takes 3.0 s to make the turn?



Answer: ____________________

Exercise 8: Becky wears glasses whose wire frames are shaped like two circles, each with an area of 2.0×10^{-3} m^2. The horizontal component of Earth's magnetic field in Becky's hometown is 1.9×10^{-5} T. If Becky turns her head back and forth, rotating it through 90° every 0.50 s, what is the induced voltage in the wire frame of one eyepiece?

Answer: ____________________

Exercise 9: Audrey disassembles the control box of her electric train and finds a small transformer inside. Its primary coil is made up of 600. turns and the secondary coil is made up of 60. turns. a) If the household voltage supplied to the train is 120 V, what voltage is required to make the train run? b) Is this a step-up or a step-down transformer?

Answer: a. ____________________

Answer: b. ____________________

Exercise 10: A hydroelectric plant in Niagara Falls sends 3000 V to the transformer in a substation that steps it up to 120 000 V for transmission to homes in New York City. If the primary coil contains 2000 turns, how many turns are there in the secondary coil of the step-up transformer?

Answer: ____________________

Additional Exercises

A-1: In the giant CERN particle accelerator in Switzerland, protons are accelerated to speeds of 2.0×10^8 m/s through a magnetic field of 3.5 T and then collided with a fixed target. What is the magnitude of the magnetic force experienced by the protons as they are accelerated around the giant ring?

A-2: In Fred's color TV, electrons are shot toward the screen through a 1.0×10^{-3}-T magnetic field set up in the picture tube. a) If each electron experiences a magnetic force of 2.9×10^{-15} N, at what speed is it propelled through the picture tube? b) How does this speed compare to the speed of light?

A-3: A proton shot out of the sun at a speed of 6.0×10^6 m/s during a "sunspot maximum" travels through the strong magnetic field of the sun. What is the maximum magnetic force experienced by the proton at a point where the sun's magnetic field is 0.090 T?

A-4: A 0.90-m-long straight wire on board the *Voyager* spacecraft carries a current of 0.10 A perpendicular to Jupiter's strong magnetic field of 5.0×10^{-4} T. What is the magnitude of the magnetic force experienced by the wire?

A-5: While vacuuming the living room rug, Buster pulls the 4.0-m vacuum cleaner cord so that it is lying perpendicular to Earth's magnetic field of 5.3×10^{-5} T. a) If the cord is carrying a current of 6.0 A, how large a magnetic force is created on the cord by Earth's magnetic field? b) If Buster then pulls the cord so that it lies parallel to Earth's magnetic field, how large is the magnetic force now experienced by the cord?

A-6: At the equator, where Earth's 3.0×10^{-5}-T magnetic field is parallel to the surface of Earth, Donna is spinning her wedding ring (which has a diameter of 2.0 cm) on top of the table. Find the change in flux through the ring if Donna a) slides it horizontally across the table, b) rolls it across the table, c) spins it on its edge.

A-7: Amanda's little brother spins a bar magnet whose magnetic field is 3.0×10^{-2} T over the face of Amanda's electric watch, perpendicular to a circular loop of wire of radius 0.60 cm inside the watch. a) What is the induced voltage in the wire if the magnet is spun over the watch in 0.30 s? b) Why is it a bad idea to put an electric watch too close to a strong magnetic field?

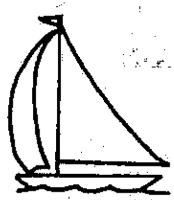
A-8: While Hiroshi sits in his living room, the newspaper carrier rings his doorbell. If a voltage of 120 V passes through the 200-turn primary coil of the transformer, how many turns are needed in the secondary coil to reduce the voltage to the 6.0 V needed to run the doorbell?

A-9: A bug zapper in the Snyders' back yard runs off a 120-V household line through a transformer whose primary coil contains 50. turns while the secondary coil contains 2000. turns. a) What is the output voltage of the transformer? b) Is this a step-up or a step-down transformer?

Challenge Exercises for Further Study

B-1: When Helen turns on the TV set, electrons are accelerated through a 20 000.-V potential difference and deflected by a 1.0×10^{-2}-T magnetic field. What is the average magnetic force experienced by an electron? ($m_e = 9.11 \times 10^{-31}$ kg)

B-2: Captain Kittredge is sailing due north, as indicated by his compass needle, in a location where Earth's magnetic field is 2.0×10^{-5} T. The captain inadvertently places his radio near the compass, allowing the wire from his radio to align in a north-south direction. The 0.80-m-long wire carries a current of 5.0 A and produces a magnetic force on the compass needle of 2.8×10^{-4} N. To what angle will the compass needle turn while the wire is over it?



B-3: A velocity selector is a device that measures the speed of a charged particle by shooting the particle through oppositely charged plates enclosed in a tube. Inside the tube is a constant magnetic field, B. If a particle is to travel, undeflected, down the center of the tube, the magnetic force must equal the electric force. If the magnetic field of 0.630 T is perpendicular to the electric field of 5.00×10^4 N/C, find the speed of an electron sent through the velocity selector.

B-4: An alpha particle (He nucleus) is shot at 5.0×10^6 m/s into a magnetic field of 0.20 T in a device known as a mass spectrometer. What is the radius of the path followed by the alpha particle? (Hint: He nuclei contain 2 protons and 2 neutrons, each with a mass of 1.67×10^{-27} kg.)