

Lesson 9

Magnetism

Introduction: Connecting Your Learning

The previous lesson introduced electric forces, electric fields, and electric circuits. Electrostatic forces are associated with stationary electric charges. When the electric charges are confined to a conductor and energy is supplied, the electric charges form an electric current. This lesson introduces the concept of how moving electric charges generate a separate field referred to as a magnetic field. Magnetic fields can also be produced by magnetic materials such as lodestone or magnetite, but even this type of magnetic field can be traced back to the concept of moving charges.

This lesson discusses magnetism, in addition to the concept of electricity and magnetism combined together called electromagnetic induction. Magnetism is a force that acts at a distance and is caused by a magnetic field. The magnetic force strongly attracts an opposite pole of another magnet and repels a like pole. The magnetic field is similar to and different from an electric field.

Readings, Resources, and Assignments

Required
Textbook
Readings

Conceptual Physics
Chapter 6

Check Prior Knowledge

Check your prior knowledge by matching these terms. You can check your answers at the end of the lesson.

Term	Definition
Magnetic field	Induced voltage
Electric field	Earth's magnetic field
Two like magnetic poles	Electric field changing with time
Two unlike magnetic poles	Clusters of aligned atoms
Magnetic domains	Changes electrical energy to mechanical energy
Electromagnet	Increases or decreases voltages
Magnetosphere	Created by moving charges
Magnetic induction	Changes mechanical energy to electric energy
Generator	Attract each other
Motor	Generated by stationary charges
Transformer	Repel each other
Induced magnetic field	Current carrying coil of wire

Lesson Objectives

By the end of this lesson, you should be able to:

1. Compare and contrast the electric force and the magnetic force.
2. Differentiate between a magnetic field and an electric field.
3. Describe magnetic domains
4. Describe electromagnetic induction.
5. Explain Faraday's Law.
6. Distinguish between a generator and a motor.
7. Explain the operation of a transformer.
8. Describe Maxwell's counterpart to Faraday's Law.

Approaching the Objectives

This lesson is comprised of four sections:

Section 1: Magnetic Forces and Fields

Section 2: Electric Currents and Magnetic Fields

Section 3: Electromagnetic Induction

Section 4: Generators, Motors, and Transformers

Section 1: Magnetic Forces and Fields

Start this lesson by reading **Chapter 6, Section 6.1, pp. 113 to 117** in the *Conceptual Physics* textbook.

View the Kahn Academy videos on Introduction to [Magnetism \(Part 1\)](#) and [Magnetism \(Part 2\)](#).

When a stationary test charge is placed in the vicinity of a static point charge (creating an electric field), the test charge will experience a vector force on it. In the vicinity of a positive charge, the force will be repulsive. You may recall that like charges repel (test charges are positive by definition). In the vicinity of a negative charge, the test charge will be attracted to the negative charge. In the last lesson, you learned that the magnitude of the force is given by Coulomb's Law.

In the vicinity of a magnetic field, a moving test charge will experience a force, but the charge must be moving. The direction of the force is always at right angles to the plane formed by the velocity vector (v) and the magnetic field vector (B). A special vector product is defined for this application. This special vector product is called a vector cross product. The direction is given by the "right hand screw rule."

$$F_{\text{mag}} = q\mathbf{v} \times \mathbf{B}$$

Where q = the magnitude of the charge (C)

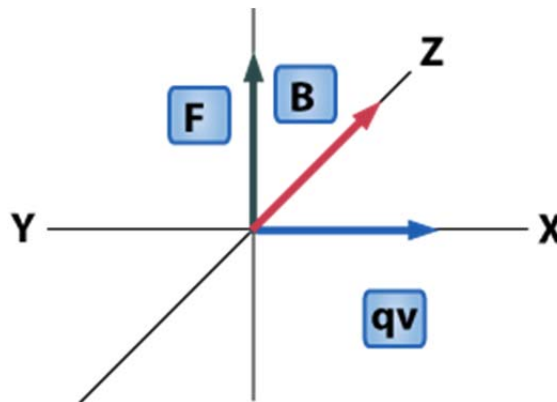
v = the velocity of the charge (m/s), and

$\mathbf{B}$ = the magnitude of the magnetic field (Tesla)

The force is then given in Newtons.

In order to find the direction of the force, it is convenient to use a three-dimensional sketch or right hand diagram. The convention for a vector pointed into the plane of the paper is "X." For a vector coming out of the paper, a "•" is used. One way to remember this is to visualize an arrow going into the paper and the X represents the feathers on the arrow. Coming out of the paper, the dot represents the tip of the arrow. Consider the following example:

In this diagram, the x and y axes are in the plane of the paper. The z axis is in and out of the paper.



Example: A charge of 1 Microcoulomb (μC) is moving along the x axis at 100 m/s. The magnetic field ($\mathbf{B}$) has a magnitude of 5 Tesla. The direction of the magnetic field is into the paper.

Find the magnitude and direction of the force on the moving charge.

Answer: The magnitude is given by $qvB = (1 \times 10^{-6} \mu\text{C}) (100 \text{ m/s}) (5 \text{ Tesla}) = 5 \times 10^{-4} \text{ N}$.

If the qv vector was turned toward the $\mathbf{B}$ vector (think of unscrewing the lid on a jar), the lid would loosen or come up. So the force vector points up in the positive "y" direction.

Note: If the angle between the qv vector and the $\mathbf{B}$ vector decreases, the direction of the $\mathbf{F}$ vector remains the same, but the magnitude decreases. The general equation is:

$\mathbf{F} = q\mathbf{v} \times \mathbf{B} = qvB \sin \Theta$ where Θ is the angle between the $q\mathbf{v}$ and $\mathbf{B}$ vectors.

So the maximum force occurs when the angle is 90 degrees and the force is zero when the $q\mathbf{v}$ and $\mathbf{B}$ vectors are in the same (or opposite) direction.

The next section discusses the relationship between electric currents in a wire and the magnetic field that results from this current flow.

Section 2: Electric Currents and Magnetic Fields

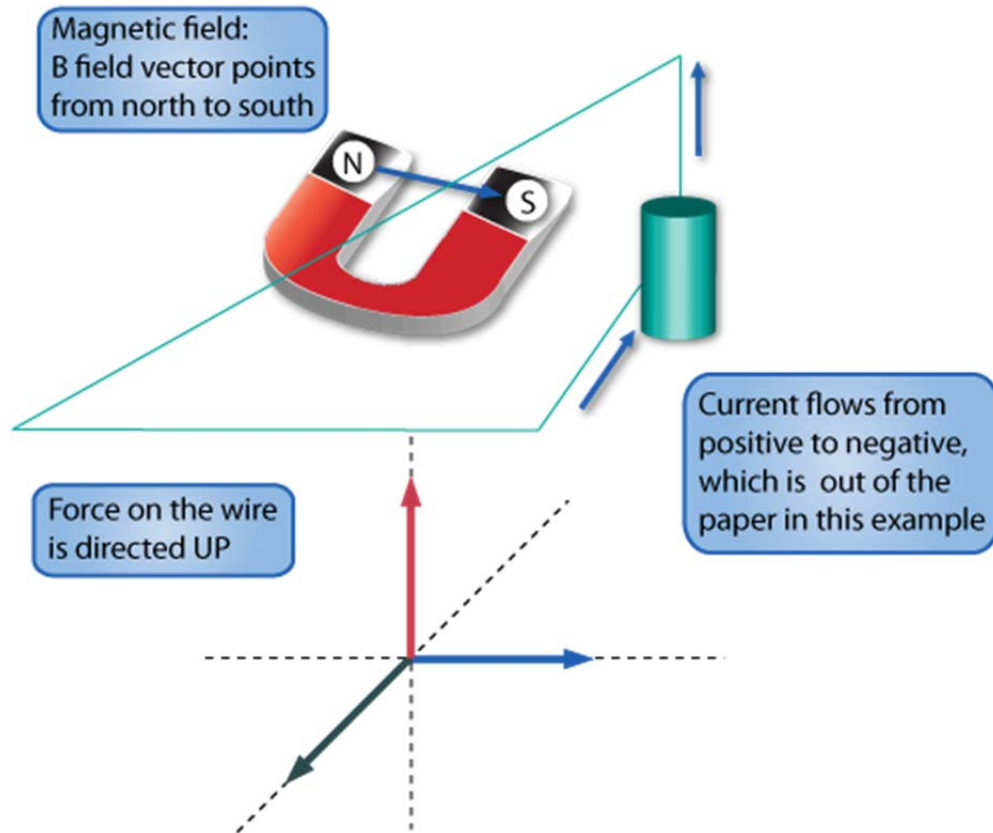
Start this section by reading **Chapter 6, Section 6.2, pp. 117 to 124** in the *Conceptual Physics* textbook.

View this video from the Kahn Academy on [Magnetism \(Part 3\)](#).

When an electric current flows near the vicinity of a magnetic field, a force will be exerted on the wire. The equation given in the last section, $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$, can be written in terms of current (I) and the length of the section of wire (l). Recall that current equals charge divided by time, and velocity equals displacement (length) divided by time. Looking at the units helps you see this.

$$(q)(v) = (I)(l)$$

$$(\text{coulombs})(\text{meters/second}) = (\text{coulombs/second})(\text{meters})$$



The next section discusses the opposite effect of generating a force when a current flows in the vicinity of a magnetic field. When mechanical energy is used to create relative motion between a magnetic field and a length of current carrying conductor (i.e., a wire), a voltage (difference of potential) can be created across the wire. This is the beginning concept in explaining how a generator functions.

Section 3: Electromagnetic Induction

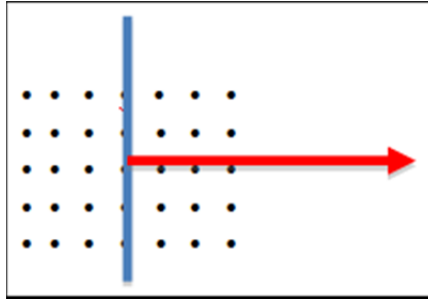
Start this section by reading **Chapter 6, Section 6.3, pp. 124 to 129** in the *Conceptual Physics* textbook.

View this video from the Kahn Academy on [Magnetism](#).

There are three basic requirements to induce a voltage in a conductor: (1) a magnetic field, (2) a conductor, and (3) relative motion between the magnetic field and the conductor. In simple terms, a wire can be waved in the vicinity of the magnetic field or a magnetic field can be waved in the vicinity of a conductor. Another possible scenario is that both the magnetic field and the conductor are moving relative to a fixed observer. The voltage that is induced is sometimes referred to as electromotive force (EMF). It is instructive to point out that EMF is not really a "force" so it does not have units of Newtons, but rather, it has units of volts.

Example: An airplane travels at 1,000 km/hr in a region where the magnetic field is $5 \times 10^{-5} \text{ T}$ and nearly vertical. What is the potential difference induced between the wing tips that are 70 m apart?

Step 1. Draw a picture:



Step 2. Formulate an equation:

Faraday's Law is based on a quantity referred to as magnetic flux (Φ_B), which equals the magnetic field strength (B) multiplied by the area that represents the loop of wire passing through the magnetic field. If the field is perpendicular to the plane formed by the loop of wire, then $\Phi_B = BA$.

Faraday's Law states that the voltage induced is directly proportional to the rate that the flux changes with respect to time. In other words, the induced voltage is related to the speed of the conductor as it travels through the magnetic field. The equation that results from these experiments is below.

$$EMF = -N(\Delta\Phi_B/\Delta t)$$

N represents the number of loops of the conductor and the negative sign is a reminder that the direction of the induced voltage can produce a current whose magnetic field opposes the original change in magnetic flux. Remember (Δ) can be read as (the change in).

This equation can be rearranged into more measurable terms. Ignoring N and the $(-)$,

$$EMF = (\Delta\Phi_B/\Delta t) = (B\Delta A)/\Delta t = (B l v \Delta t)/\Delta t = B l v$$

$$EMF = Blv \text{ (If the field is perpendicular to the plane of the conductor.)}$$

Convert 1,000 km/hr to m/s. $v = 280$ m/s. $B = 5 \times 10^{-5}$ T and $l = 70$ m

Step 3. Substitute the numbers and do the math.

EMF = ?

Check your answer at the end of the lesson.

The next section discusses the difference between motors and generators and introduces the electrical transformer.

Section 4: Generators, Motors, and Transformers

View these videos from the Kahn Academy on Electrical Motors, Magnetism [9](#), [10](#) and [11](#).

The basic difference between a motor and a generator is that a motor converts electrical energy to mechanical energy, and a generator does just the opposite. A generator converts mechanical energy to electrical energy. Surface ships and submarines have large pieces of machinery referred to as ship's service motor-generators (SSMGs). The same piece of machinery can act as either a motor (taking electrical energy from the batteries to drive a propulsion motor) or a generator (drawing mechanical energy from the rotating shaft to produce electricity to charge the batteries).

A device that has not been mentioned yet is the transformer. A transformer acts to either step up a voltage or step down a voltage. Transformers are primarily used with alternating current (AC), similar to the wall voltage in normal households. When electrical power has to be transferred long distances, it is more economical to transfer very high voltages (small currents). Voltages in high-tension lines can exceed 100,000 v in order to minimize the power lost to heat in the wires. (Remember, $P = I^2R$, where I is the current and R is the resistance in the wire.) When the voltage arrives at the house, it has to be stepped down to a much lower voltage (i.e., 120 volts), and a much higher current has to be available to operate appliances like stoves, dryers, toasters, etc.

Math Challenge:

An average of 120 kW of electrical power is sent to a small town from a power plant 10 km away. The transmission lines have a total resistance of 0.40Ω. Find the power loss if the power is transmitted at 240 volts compared to 24,000 volts.

Check your answer at the end of the lesson.

Summarizing Your Learning

This lesson compared the electric field with the magnetic field. These forces and fields are related but exhibit important differences. One key difference between electric and magnetic fields involves the relative motion of the charged particles involved. Both types of fields are vector quantities, but the direction of the forces follows different rules. Practical applications of magnetic fields are seen in generators, motors, and transformers, to name a few. Electricity and magnetism have become an integral part of human society and continued improvement in the efficiency for electromagnetic devices will play an important role in the sustainability of this planet.

Practice Answers

Check Prior Knowledge

Term	Definition
Magnetic field	Created by moving charges
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Two unlike magnetic poles	Attract each other
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Electromagnet	Current carrying coil of wire
Magnetosphere	Earth's magnetic field
Magnetic induction	Induced voltage
Generator	Changes mechanical energy to electric energy
Motor	Changes electrical energy to mechanical energy
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Induced magnetic field	Electric field changing with time

Section 3: Electromagnetic Induction

Step 3. Substitute the numbers and do the math.

$$\text{EMF} = \underline{\quad 1.0 \text{ v} \quad}$$

Section 4: Generators, Motors, and Transformers

An average of 120 kW of electrical power is sent to a small town from a power plant 10 km away. The transmission lines have a total resistance of 0.40Ω . Find the power loss if the power is transmitted at 240 volts compared to 24,000 volts.

240 v ... power loss is 100kW (over 80% of the power would be wasted)

24,000 v... power loss is 10 w (less than 1/100 of 1%)