TOPIC 3.2: ELECTROMAGNETIC INDUCTION

S4P-3-7 Define magnetic flux ($\Phi = B_{\perp}A$).

S4P-3-8 Demonstrate how a change in magnetic flux induces voltage.

S4P-3-9 Calculate the magnitude of the induced voltage in coils using $V = \frac{N\Delta\Phi}{\Delta t}$.

S4P-3-10 Outline Lenz's Law and apply to related problems.

S4P-3-11 Describe the operation of an AC generator.

S4P-3-12 Graph voltage versus angle for the AC cycle.

S4P-3-13 Describe the operation of transformers.

S4P-3-14 Solve problems using the transformer ratio of $\frac{V_p}{V_s} = \frac{N_p}{N_s}$.

S4P-3-15 Describe the generation, transmission, and distribution of electricity in Manitoba.
Include: step-up and step-down transformers, power transfer, High Voltage Direct Current

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

SPECIFIC LEARNING OUTCOME

S4P-3-7: Define magnetic flux ($\Phi = B_{\perp}A$).

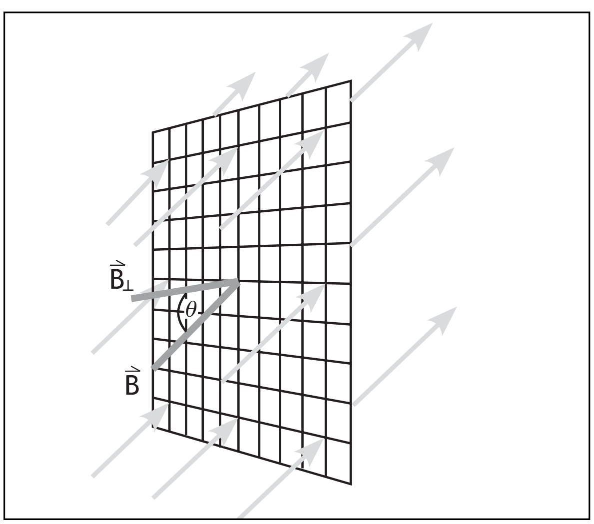
SUGGESTIONS FOR INSTRUCTION

Entry Level Knowledge

Students diagrammed magnetic fields using lines of force in Senior 3 Physics.

Notes to the Teacher

Magnetic flux, Φ, represents a quantity of magnetic force lines passing through a given area. The number of magnetic force lines increases if we have a stronger field or if the area enclosed is larger. Therefore, $\Phi = B_{\perp}A$. In SI units, flux is measured in webers (Wb) and is calculated from $\Phi = B_{\perp}A$ with B measured in Tesla and A in metres squared. It is important to note that only the component of the magnetic field perpendicular to the area is used in the calculation. Thus, in general, $\Phi = BA\cos\theta$ where θ is the angle between the magnetic field and the normal to the area.



Example

A magnetic induction of 4.5×10^{-5} T passes through a circular coil of diameter 16.4 cm at an angle of 41°.

The perpendicular component of the magnetic field, $B_{\perp}$, is equal to:

$$B\cos\theta = \left(4.5 \times 10^{-5}\ T\right)\cos 41^{\circ} = 3.40 \times 10^{-5}\ T$$

$$A = \pi r^2 = \pi\left(\frac{0.164\ \text{m}}{2}\right)^2 = 2.11 \times 10^{-2}\ \text{m}^2$$

$$\Phi = B_{\perp}A = \left(3.40 \times 10^{-5}\ T\right)\left(2.11 \times 10^{-2}\ \text{m}^2\right) = 7.2 \times 10^{-7}\ Wb$$

Demonstration

Students perform a two-dimensional simulation of flux lines entering a coil by using a sheet of lined paper and a strip of construction paper 15 cm by 0.5 cm. The strip of construction paper represents the end view of a coil, and the blue lines on the lined paper represent magnetic flux lines. Hold the strip at 90° to the lines on the paper and count the number of lines the strip covers. The normal to the coil is parallel to the lines in this position and $\theta = 0°$.

SKILLS AND ATTITUDES OUTCOMES

S4P-0-1e: Differentiate between how scientific theories explain natural phenomena and how scientific laws identify regularities and patterns in nature.

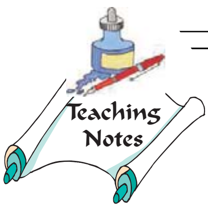
S4P-9-2c: Formulate operational definitions of major variables or concepts.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

SUGGESTIONS FOR INSTRUCTION



SUGGESTIONS FOR ASSESSMENT

Paper-and-Pencil Tasks

Students solve problems using the definition of flux.

General Learning Outcome Connection

Students will…

Understand how stability, motion, forces, and energy transfers and transformations play a role in a wide range of natural and constructed contexts (GLO D4)

Specific Learning Outcome

S4P-3-8: Demonstrate how a change in magnetic flux induces voltage.

Suggestions for Instruction

Entry Level Knowledge

Students have studied that a charge moving through a magnetic field experiences a deflecting force.

Notes to the Teacher

A changing magnetic field exerts a deflecting force on a charge. This results in a charge separation that produces a voltage.

Demonstration

Induced voltage can be demonstrated by connecting a solenoid to a galvanometer and moving a bar magnet in and out of the solenoid. The induced voltages result in currents that can be detected by the galvanometer. Note the results of different actions of the magnet. When the magnet is pushed into or pulled out of the solenoid, a current is induced. When the magnet is moved one way (e.g., into the coil), the needle deflects one way; when the magnet is moved the other way (out of the coil), the needle deflects the other way. Not only can a moving magnet cause a current to flow in the coil, the direction of the current depends on how the magnet is moved. However, if the magnet is at rest inside the solenoid, no current is produced in the coil. Consequently, only changing magnetic fields will induce currents.

Class Discussion

You can conclude from these observations that a changing magnetic field will induce a voltage in the coil, causing a current to flow. It follows that if the magnetic flux through a coil is changed, a voltage will be produced. This voltage is commonly referred to as the **induced voltage**. The term **voltage**, although common, is an historical term, and students say that a voltage is induced.

There are three possible ways to change magnetic flux (remember that magnetic flux is defined as $\Phi = BA\cos\theta$):

1. change the magnetic field
2. change the area of the loop
3. change the angle between the field and the loop

SKILLS AND ATTITUDES OUTCOME

S4P-0-1d: Describe how scientific knowledge changes as new evidence emerges and/or new ideas and interpretations are advanced.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand how stability, motion, forces, and energy transfers and transformations play a role in a wide range of natural and constructed contexts (GLO D4)

SUGGESTIONS FOR INSTRUCTION

Teaching Notes

SUGGESTIONS FOR ASSESSMENT

Observation

Students demonstrate the ability to induce a current in a coil with a moving magnet.

General Learning Outcome Connection

Students will…

Recognize that scientific knowledge is based on evidence, models, and explanations, and evolves as new evidence appears and new conceptualizations develop (GLO A2)

Specific Learning Outcomes

S4P-3-9: Calculate the magnitude of the induced voltage in coils using $V = \frac{N\Delta\Phi}{\Delta t}$.

S4P-3-10: Outline Lenz's Law and apply to related problems.

Suggestions for Instruction

Entry Level Knowledge

Students have been introduced to basic magnetic fields, and the interaction of magnetic fields and a current carrying conductor, in Senior 3 Physics.

Notes to the Teacher

Faraday's Law is a fundamental relationship that states that the induced voltage in a coil is proportional to the rate of change of magnetic flux. For a single loop,

$$V = \frac{\Delta\Phi}{\Delta t},$$

it follows that if a coil contains N loops, then

$$V = \frac{N\Delta\Phi}{\Delta t}.$$

If the rate of change of flux is in webers/second, then the voltage will be in volts.

The induced current in a circuit is such that the direction of the magnetic field it produces always opposes the original change in flux. This is a consequence of the Law of Conservation of Energy and basically means that external work must be done in order to produce electrical energy in the circuit. Thus, Faraday's Law requires a minus sign to account for the direction of the induced voltage

$$\left(V = \frac{N\Delta\Phi}{\Delta t}\right).$$

Normally, the minus sign is ignored and the direction of the induced voltage is found by the right-hand rule (or in some texts, the left-hand rule). For a coil, the right-hand rule is:

> "If the thumb points in the direction of the magnetic field, the fingers will curl in the direction of the induced current."

To apply the hand rules, a diagram is required.

Demonstration

Allow a moving magnet to induce a current in a coil of wire. Connect the coil to a galvanometer and move a bar magnet in and out of the centre of the coil. Note the deflection of the galvanometer needle. Describe what happens when you move the magnet more or less quickly, and when you put the North or South pole into the coil first. Then, try other relative motions and positions, including some where the axes of the magnet and the coil are perpendicular. Does it make a difference if you move the coil, rather than the magnet, in the same relative motion?

SKILLS AND ATTITUDES OUTCOMES

S4P-0-1e: Differentiate between how scientific theories explain natural phenomena and how scientific laws identify regularities and patterns in nature.

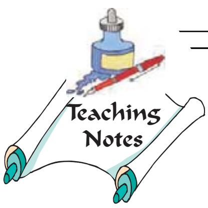
S4P-0-2c: Formulate operational definitions of major variables or concepts.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

SUGGESTIONS FOR INSTRUCTION



SUGGESTIONS FOR ASSESSMENT

Laboratory Report

In their reports, students describe the motions they used, what flux changes they should produce, and how the observed current can be explained by using Faraday's Law and/or Lenz's Law. Some sketches will probably help their explanation.

Visual Display

Students prepare diagrams of different scenarios for induced currents and the application of right-hand rules to determine the direction of the current.

Pencil-and-Paper Tasks

Students solve problems using the laws of Faraday and Lenz together.

General Learning Outcome Connection

Students will…

Describe scientific and technological developments, past and present, and appreciate their impact on individuals, societies, and the environment, both locally and globally (GLO B1)

Specific Learning Outcomes

S4P-3-11: Describe the operation of an AC generator.

S4P-3-12: Graph voltage versus angle for the AC cycle.

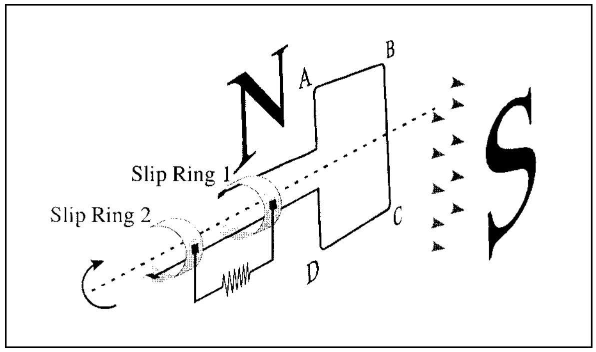
Suggestions for Instruction

Entry Level Knowledge

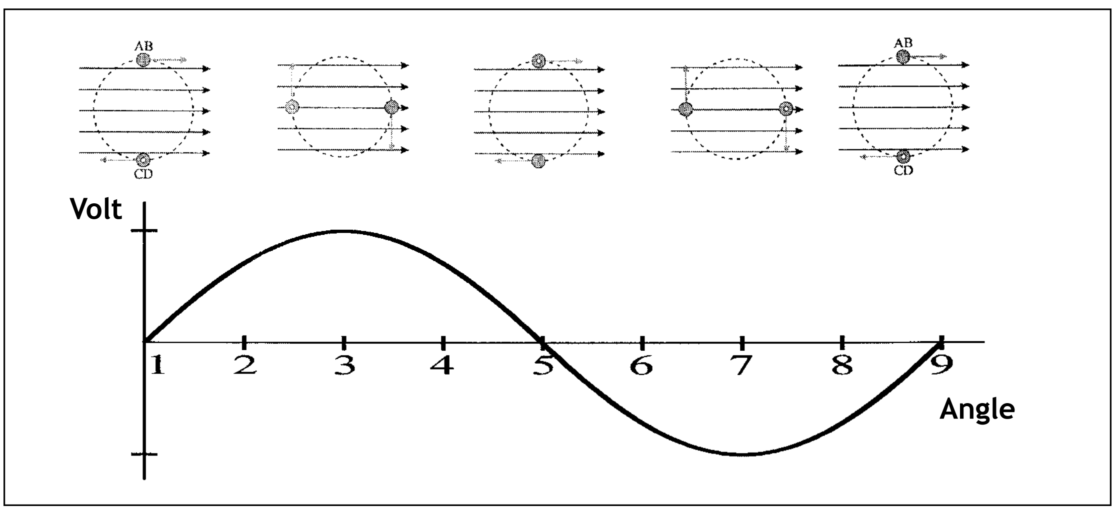
The definition of flux, $\Phi = BA\cos\theta$, was covered in a previous learning outcome.

Notes to the Teacher

Generally, as a loop rotates in a constant magnetic field, it "cuts" the field lines at different angles and experiences a changing flux. Since the coil is rotating, the circular motion of the coil will result in an induced voltage. In the following diagram, the armature of an AC generator is represented by a rectangular loop ABCD, with side AB connected to slip ring 1 and side CD connected to slip ring 2. The slip rings make contact with brushes. The external circuit is connected to the brushes. The generation of the AC waveform can be explained in terms of the motion of the sides of the loop as it is rotated through the magnetic field.



Voltage induced in the loop produces a current that passes from one slip ring, through its brush, through the external circuit, and back to the other brush and to its slip ring. A complete circuit exists.



SKILLS AND ATTITUDES OUTCOME

S4P-0-3b: Describe examples of how technology has evolved in response to scientific advances, and how scientific knowledge has evolved as the result of new innovations in technology.

GENERAL LEARNING OUTCOMES CONNECTION

Students will…

Describe and appreciate how the natural and constructed worlds are made up of systems and how interactions take place within and among these systems (GLO E2)

Recognize that characteristics of materials and systems can remain constant or change over time, and describe the conditions and processes involved (GLO E3)

SUGGESTIONS FOR INSTRUCTION

As the loop rotates, segments AB and CD cut the magnetic field lines and a voltage is induced in the loop. Since the angle at which the segments interact with the field lines changes, so does the induced voltage. In other words, it is not constant and changes direction every half rotation. The previous diagrams are cross-sections of the rotating loop as it corresponds to the changing voltage. Initially, AB and CD are moving parallel to the field lines and the induced voltage is zero (recall that flux is proportional to the sine of the angle that the field lines are "cut"). The induced voltage will be proportional to the sine of the angle and will reach a maximum at 90°. The voltage then decreases to zero and reverses direction in the second half of the rotation.

See Appendix 3.4 for a template to make an overhead of the above graphic.

SUGGESTIONS FOR ASSESSMENT

Pencil-and-Paper Tasks

Students are given a series of angles for a rotating loop (e.g., 0°, 30°, 90°, 225°). The student marks on the sine curve the value of the induced voltage.

General Learning Outcome Connection

Students will…

Recognize that science and technology interact with and advance one another (GLO A5)

Specific Learning Outcomes

S4P-3-13: Describe the operation of transformers.

S4P-3-14: Solve problems using the transformer ratio of

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}.$$

Suggestions for Instruction

Entry Level Knowledge

In Senior 3 Physics, students diagrammed and described qualitatively the magnetic field around a current-carrying wire. Students also qualitatively described the magnetic field produced in a current-carrying solenoid.

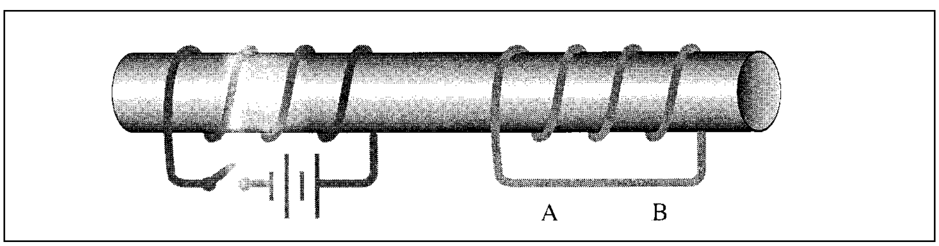
Notes to the Teacher

A current in a wire creates a magnetic field around the wire. If this wire is wrapped into a coil, the magnetic field in the centre of the coil will arrange itself such that the field is parallel with the axis of the loop. The direction of the magnetic field in the centre can be found using your right hand. Place your thumb in the direction of conventional current and wrap your fingers around the coil. The direction the fingers point is the direction of the magnetic field. The intensity of the magnetic field in the centre can be varied by either varying the current in the coil or increasing the number of turns in the coil. This principle is used in creating transformers.

The basic transformer consists of two separate (not connected) coils of wire, each wrapped around one side of a rectangular iron core.

As current passes through the primary (input side) coil, it creates a magnetic field inside the iron core. The iron core allows the magnetic field to flow through the secondary coil. This change of magnetic field in the secondary coil induces a voltage across it, which results in a temporary secondary voltage and current in the output coil. If the current in the primary coil is now reversed, the magnetic field it creates will also reverse. The magnetic field though the secondary coil is now reversed, which again induces a temporary secondary voltage and resulting output current. In order to achieve a continuous output voltage in the secondary coil, a continuously changing current in the primary coil is required. Thus, transformers require alternating current to be operational. The output current will be alternating as well.

In order to obtain a voltage in the secondary coil that is different from the voltage in the primary coil, the number of turns for each coil can be varied. A small number of turns in the primary coil will result in a weak magnetic field being produced. However, if this weak magnetic field links a secondary coil with a large number of turns, the voltage induced will be large. Thus, the output



SKILLS AND ATTITUDES OUTCOMES

S4P-0-2i: Select and integrate information obtained from a variety of sources.

Include: print, electronic, specialists, or other resource people

S4P-0-3b: Describe examples of how technology has evolved in response to scientific advances, and how scientific knowledge has evolved as the result of new innovations in technology.

S4P-0-4e: Demonstrate a continuing and more informed interest in science and science-related issues.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

SUGGESTIONS FOR INSTRUCTION

voltage will be larger than the input voltage. A transformer of this nature is called a **step-up transformer**. The same principle is also used when the primary coil has a large number of turns and the secondary coil has a small number of turns. This is called a **step-down transformer** and results in the output voltage being smaller than the input voltage. Transformers are classified in terms of the relative sizes of output (secondary) and input (primary) voltages.

In summary, transformers utilize alternating current to raise or lower voltages of a source by linking magnetic field through two non-connected wires.

It can be reasoned that the voltage induced in the secondary coil is proportional to the number of turns in the coil. As well, the flux created in the primary coil is directly proportional to the number of turns in the primary coil and directly proportional to the voltage of the coil. As a result,

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}.$$

SUGGESTIONS FOR ASSESSMENT

Student Research/Report

Students research the use of transformers by Manitoba Hydro. The research should include the concept of how the transformers work, the actual physical layout of transformers built by Manitoba Hydro, and the varying points at which transformers are positioned by Manitoba Hydro.

Students can locate “broken” 12 V (or any voltage) adapters that can be taken apart and examined. They can submit a report that explains the details of each component in the adapter. Before disassembling any electrical equipment, it is necessary to remove wires so that the apparatus can never be plugged in.

Student Demonstration

Students can build transformers using a large nail and wire. Have them try to create a transformer of a specified output, given the value of the input source.

Pencil-and-Paper Tasks

Students solve questions using the transformer relation.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Recognize that science and technology interact with and advance one another (GLO A5)

SPECIFIC LEARNING OUTCOMES

S4P-3-13: Describe the operation of transformers.

S4P-3-14: Solve problems using the transformer ratio of

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}.$$

SUGGESTIONS FOR INSTRUCTION

Students may be tempted to think that since the voltage output of a transformer can be higher than the voltage input, the transformer can increase the amount of power output. This would be like obtaining energy from nothing. However, since energy is always conserved, the power output cannot exceed the power input. In fact, since a transformer will warm up, it is evident that the power output will be less than the power input. Assuming the ideal:

Power into primary = Power out of secondary

$$P_p = P_s$$
$$V_p I_p = V_s I_s$$
$$\frac{V_p}{V_s} = \frac{I_s}{I_p}$$

Note from the above relation that a coil with a high voltage will have a low current (and a high effective resistance), and a coil with a low voltage will have a high current (and a low effective resistance).

Illustrative Example

What is the ratio of turns for a transformer that requires a 4-volt output from a 120-volt input source?

Solution:

Utilizing $\frac{V_p}{V_s} = \frac{N_p}{N_s}$, $\frac{120\,V}{4\,V} = 30.$

Thus, the ratio of turns for N_p to N_s is 30. An example of a transformer like this might have 300 turns in the primary coil and 10 turns in the secondary coil.

SKILLS AND ATTITUDES OUTCOMES

S4P-0-2i: Select and integrate information obtained from a variety of sources.

Include: print, electronic, specialists, or other resource people

S4P-0-3b: Describe examples of how technology has evolved in response to scientific advances, and how scientific knowledge has evolved as the result of new innovations in technology.

S4P-0-4e: Demonstrate a continuing and more informed interest in science and science-related issues.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

SUGGESTIONS FOR INSTRUCTION

Teaching Notes

SUGGESTIONS FOR ASSESSMENT

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Distinguish critically between science and technology in terms of their respective contexts, goals, methods, products, and values (GLO A3)

SPECIFIC LEARNING OUTCOME

S4P-3-15: Describe the generation, transmission, and distribution of electricity in Manitoba.

Include: step-up and step-down transformers, power transfer, High Voltage Direct Current

SKILLS AND ATTITUDES OUTCOMES

S3P-0-1c: Relate the historical development of scientific ideas and technology to the form and function of scientific knowledge today.

SUGGESTIONS FOR INSTRUCTION

Entry Level Knowledge

Students were introduced to the generation and transmission of hydroelectric power in Senior 1 Science.

Notes to the Teacher

Manitoba holds tremendous resource potential to supply electricity from a renewable energy source: hydroelectric power. Several generating stations are located throughout the province, with more being considered in northern regions. To transmit the power efficiently, the output from a generating station is stepped up to high-voltage levels (500 kV). This reduces the current, which results in less heat developed in the wires. The heat is wasted energy so it is far more economical to transmit at higher voltage and lower current.

As well, the high-voltage/low-current lines can be produced lighter, since the magnitude of current for the same power distribution is smaller. However, due to arcing, the wires must be very high off the ground and the insulators used are very large. To distribute electricity to major regions, the voltage is stepped down to 115 kV. This allows the towers and insulators to be smaller. Each region then distributes the power to communities at an even lower voltage (66 kV or 33 kV), and again the towers and insulators can be made smaller. The community then distributes the power to neighbourhood substations, where it is reduced again by five to ten times.

At this stage, the power is distributed by the familiar hydro poles and is finally reduced at pole-top transformers to 220 V, which is then distributed to three or four of the neighbouring houses. The lower voltage is much safer within a community and requires smaller poles.

Although alternating current is preferred due to the ease in transforming it to various voltages and currents, Manitoba Hydro is also a pioneer in the development of High Voltage Direct Current (HVDC). It is more economical to transmit power from long distances (over 300 km) as direct current rather than alternating current. DC requires only two conductors per circuit, whereas the AC lines use three conductors (3-phase AC). The AC towers must be structurally stronger to support the extra cable. The costs associated with the materials, and their construction, are much lower for long-distance DC lines than for AC lines. To transmit the power as DC, the AC from the generating station is rectified to DC in a converter station. Once transmitted to southern areas, the DC is changed back to AC in an inverter station. All remaining lines carry alternating current and simply use step-down transformers.

SKILLS AND ATTITUDES OUTCOMES

S4P-0-3a: Analyze, from a variety of perspectives, the risks and benefits to society and the environment when applying scientific knowledge or introducing technology.

S4P-0-3c: Identify social issues related to science and technology, taking into account human and environmental needs and ethical considerations.

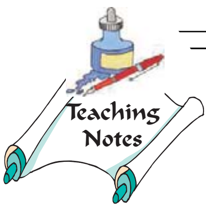
S4P-0-4d: Develop a sense of personal and shared responsibility for the impact of humans on the environment, and demonstrate concern for social and environmental consequences of proposed actions.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Identify and demonstrate actions that promote a sustainable environment, society, and economy, both locally and globally (GLO B5)

SUGGESTIONS FOR INSTRUCTION



SUGGESTIONS FOR ASSESSMENT

Research/Report

Students research the development of the Manitoba Hydro network.

Debate

Students research and debate the works of Thomas Edison and Nicola Tesla in the battle of alternating current versus direct current.

SUGGESTED LEARNING RESOURCES

Energy and economic development website of the government of Manitoba:

<http://www.gov.mb.ca/est/energy/power/statistics.html>

Notes