SECTION 4

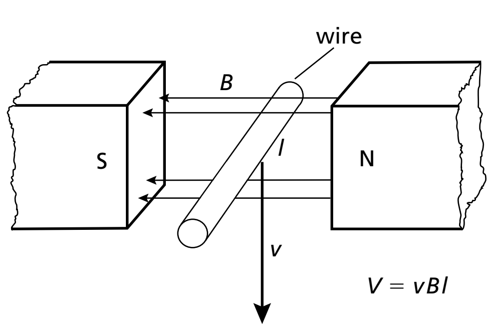
Detect and Induce Currents

Section Overview

Students investigate how a changing magnetic field near a wire induces a current in the wire. They use a galvanometer to measure currents induced in a coil of wire by moving a bar magnet and observe how the relative speed between a magnet and a coil of wire, its relative direction of motion, and the magnet's poles affect the induced current. Students then read how AC and DC electricity is generated and how accidental discoveries in the history of physics were made.

Background Information

The physics phenomenon discussed in *Section 4* is electromagnetic induction. The fact that electrons moving in a magnetic field experience a force and therefore a voltage or current can be induced is the basis for the "generator effect." Students will observe that an electromagnetic force, or voltage, is produced in a conductor when relative motion between the conductor and a magnetic field happens in a way that causes the conductor to cut magnetic field lines as shown below.



In the diagram, thrusting the wire downward so that it cuts across the magnetic field lines causes a force on the electrons in the wire. If the total charge in the wire is Q and the length of the wire within the magnetic field is l, then the force on the electrons is QvB, where v is the velocity of the wire and B is the strength of the magnetic field. By the left-hand rule, this force pushes negative charges to the front end of the wire (or out of the paper), leaving positive charge on the back end of the wire (or into the paper). The work done on these charges is the force times the distance, or $QvBl$, giving them this much potential energy. Electromotive force or voltage is potential energy per unit charge, so the voltage produced between the ends of the wire is $QvBl/Q = vBl$. Another way to relate the voltage produced in this situation is to imagine that the wire is part of a closed circuit. At any time, the circuit encloses a certain amount of magnetic flux (think magnetic field lines). The rate that this magnetic flux changes is equal to the voltage produced in the circuit. The equation describing this relationship is usually written as

$$V = -\Delta\Phi/\Delta t$$

where V is the voltage induced in the circuit, and $\Delta\Phi/\Delta t$ is the change in magnetic flux within the circuit per unit time. The negative sign indicates that the current that would flow in the wire if it were a complete circuit would produce a magnetic field that would tend to diminish the change in magnetic flux that caused the induced voltage. This phenomenon is often referred to as Lenz's law, and is an application of the principle of conservation of energy.

$V = -\Delta\Phi/\Delta t$ is equivalent to $V = vBl$.

The induced voltage, and current (if the wire is part of a circuit) happens only while the magnetic flux through the circuit is changing, and the amount of induced voltage at any instance depends directly on the rate at which the magnetic flux is changing. Also, the direction of the induced voltage depends on whether magnetic flux is increasing or decreasing. Alternatively, electrons in a wire moving in a magnetic field experience a force and therefore, an induced voltage is produced. The higher the velocity of the wire and the longer the section of wire in the magnetic field, the greater the induced voltage.

If in the diagram on the previous page, the wire had been thrust upward, the electrons would have moved in the opposite direction. This can be seen by using the left-hand rule for force on a moving charge or by realizing that the magnetic flux through a circuit closed from above would be decreasing. Finally, if a bundle of individual wires were used instead of a single wire, the effect of induction would be multiplied by the number of wires. Likewise, if the circuit is a coil with more than one turn, the same voltage is induced in each turn, so the total voltage in the circuit is multiplied by the number of turns.

There are many ways to create an induced voltage. The wire or circuit can move in and out of a magnetic field, the source of the magnetic field can move with respect to the wire or circuit, or the strength of the magnetic field can change (with no movement of the circuit or source of magnetic field). One way is to rotate a loop or coil of wire in a magnetic field, as in a generator. Another is used by students in this section—plunging a bar magnet in and out of a solenoid. In both cases, the principles involved are the ones described above; only the geometric configuration of the conductors and fields are different.

A generator basically is a motor in reverse. In a generator, work is done to move a conductor and the associated electric charges when cutting the field lines of a magnetic field. This sets up a current in the conductor, which does work in the external circuit (the part not in the magnetic field). The moving charges in the circuit then produce their own magnetic field, which opposes the force moving the conductor in the magnetic field (Lenz's law). In a motor, the external circuit does the work to move the charges in the magnetic field. If the charges move perpendicular to the lines of magnetic force (the flux), the associated magnetic field interacts with the stationary magnetic field of the motor to produce a force on the wire.

NOTES

Crucial Physics

- The force between a current-carrying wire and a magnetic field can be used to construct a galvanometer, which is a meter that detects small currents.
- Relative motion between the conductor and the magnetic field, so that the conductor cuts the magnetic field lines, produces a voltage. Increasing the strength of the magnetic field, the length of conductor in the field, or the speed of the relative motion between the field and the conductor increases the current induced in the wire.
- A generator is a device that transforms mechanical energy into electrical energy. It changes the energy of motion between a loop of wire and a magnetic field into electrical energy by inducing a current in the loop of wire.
- An alternating current (AC) is a current that changes direction periodically.
- An alternating current is created or induced when a loop of wire and a magnetic field move back and forth relative to each other.
- Accidental discoveries occur in science, but to be discovered, the observer has to be aware of background knowledge and must try to make sense of the observations.

Learning Outcomes	Location in the Section	Evidence of Understanding
Explain how a simple galvanometer works.	***Investigate*** Step 1 ***Physics Talk*** ***Physics to Go*** Question 1-3	After reading about galvanometers, students measure the current using a commercially made galvanometer, or one they have constructed. They explain how a galvanometer works and apply what they know to describe how a galvanometer can detect currents.
Induce current using a magnet and coil.	***Investigate*** Steps 3-6	Students induce a current in a coil solenoid by moving a permanent magnet and an electromagnet through its core.
Describe alternating current.	***Physics Talk*** ***Inquiring Further***	Students read and write about alternating currents and how they are generated.
Appreciate accidental discovery in physics.	***Physics Talk***	Students read about and discuss accidental discoveries in physics, such as those by Oersted, Faraday, and Gramme, who invented the electric motor.

NOTES

Section 4 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Magnet, large bar	1 per group	
Compass	1 per group	
Scissors	1 per group	
DC hand-operated generator	1 per group	
Alligator clip leads (singles)	2 per group	
Nail, 12d	1 per group	
Tube, cardboard, 1″ x 4″	1 per group	
Galvanometer, 0-500 ma	1 per group	
Sandpaper, 60 grit	1 per group	
Tape, masking		6 per class
Wire, #24, magnet, 60-ft roll		1 per class
Straw, drinking, transparent, pkg 100		1 per class

Time Requirement

- Allow one class period or 45 minutes for students to complete the *Investigate* portion of this section.

Teacher Preparation

- Assemble the required material. If the homemade galvanometer is used in place of the commercial version, cut the wire to the appropriate length and strip or sand the ends for good contact.
- A hollow tube is required. This can be a paper towel core, a section of a golf tube, or something similar that has a diameter large enough to allow a bar magnet to be inserted easily into the tube.
- If a power supply is used with the electromagnet rather than the hand generator, a normally open push-button switch should be included in the circuit to start and stop the current. Using this arrangement rather than the hand generator allows for larger current spikes than the generator, and a larger deflection of the galvanometer.

Safety Requirements

- If you are using a power supply or batteries to power the solenoid for *Step 6*, pay attention to possible heating of the solenoid and the galvanometer. Using the hand generator generally eliminates this problem.
- Caution students not to bring the magnets near any items that have magnetic strips that code information (for example, a credit card) or other magnetic media.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Magnet, large bar		1 per class
Compass		1 per class
Scissors		1 per class
DC hand-operated generator		1 per class
Alligator clip leads (singles)		2 per class
Nail, 12d		1 per class
Tube, cardboard, 1″ x 4″		1 per class
Galvanometer, 0-500 ma		1 per class
Sandpaper, 60 grit		1 per class
Tape, masking		6 per class
Wire, #24, magnet, 60-ft roll		1 per class
Straw, drinking, transparent, pkg 100		1 per class

Time Requirement

- Allow one class period or 45 minutes to complete the *Investigate* portion of this section as a whole-class demonstration, as well as discussing the *Physics Talk* and doing the other portions of the section from the *Pacing Guide*.

Teacher Preparation

- Assemble the required material for the circuit and test for proper operation before class. Set the circuit up in a place easily visible to all. A commercial galvanometer with a large dial is preferable for students to observe the results. If the homemade galvanometer is used in place of the commercial version, cut the wire to the appropriate length and strip or sand the ends for good contact.
- To increase the degree of deflection when pushing the magnet into the coil to make the effect more visible for students, try one of the following: Hold and use several magnets together with all the same poles facing in the same direction to increase the strength of the magnetic field. Alternatively, obtain a "rare-Earth" magnet, such as a neodymium magnet, which has a much stronger magnetic field and use that in place of the conventional magnets.
- A hollow tube is required. This can be a paper towel core, a section of a golf tube, or something similar that has a diameter large enough to allow a bar magnet to be inserted easily into the tube.
- If a power supply is used with the electromagnet rather than the hand generator, a normally open push-button switch should be included in the circuit to start and stop the current. Using this arrangement rather than the hand generator allows for larger current spikes than the generator, and a larger deflection of the galvanometer.

Safety Requirements

- If you are using a power supply or batteries to power the solenoid for *Step 6*, pay attention to possible heating of the solenoid and the galvanometer. Using the hand generator generally eliminates this problem.
- Do not to bring the magnets near any items that have magnetic strips that code information (for example, a credit card) or other magnetic media. This is particularly important if you are using a neodymium or other powerful magnet.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Imagining invisible threads made of wax to represent a magnetic field	***Physics Talk***	**Augmentation** • For students who are visual learners, the analogy with the wax threads and the diagrams in this section may help students understand how some movements of the magnet and solenoid created a current while other movements did not. However, for students who are auditory and/or concrete learners, visualizing the analogy and understanding the diagrams may be more difficult and not aid in their understanding. Model the movement of a wire within a magnetic field to bring each of the diagrams to life. Use a galvanometer to allow students to see if a current is induced in the wire. • To help students better understand the magnetic field and moving-wire diagrams, use different colors to represent the magnetic field and the wires. Review the symbols students should use to represent magnetic fields, wires, direction of movements and so on as they continue to build upon their understanding for the *Chapter Challenge*. • Use actual threads between two magnets and use a marker to represent the wire. As the marker moves past the threads, it will leave a mark on each thread it "cuts" through. If any threads are left untouched, the direction the wire moved will not induce a current. Students should be able to conclude that the wire must be moved perpendicular to the magnetic field.
Reading comprehension	***Physics Talk*** Accidental Discoveries and the History of Physics	**Augmentation** • In this section, students are asked to read about the discoveries of three different men, understand the connection among their discoveries, and appreciate the accidental nature of the discoveries. • Ask students to work with a partner to read this section and write one statement about each scientist and his discovery. Then ask them to write one concluding statement about a connection among their discoveries. • Ask for volunteers to read this section aloud. Develop a group timeline on the board or chart paper as students are reading. Students can add to the timeline as they learn more about electromagnetism and the scientists who have discovered ways to use it. **Accommodation** • Provide a copy of this section of the text to allow students to underline or highlight key points as they read. Provide a limit for the number of sentences a student may highlight to force them to think carefully about which statements they choose. • Provide a graphic organizer that includes the scientists' names, a brief description of their discoveries, and a picture. Leave a blank column for students to record the importance of each scientist's discovery based on their reading and background knowledge.
Understanding the factors that affect the strength of an induced current	***Active Physics Plus***	**Augmentation** • In order to complete the *Chapter Challenge*, students need to understand different ways to manipulate magnets and wires to generate currents. Students who struggle to generalize academic knowledge to real-life tasks will benefit from exploring these factors through a hands-on approach as described in this section. However, designing three experiments may be too time-consuming for some students as compared to the actual learning payoff. • Ask six small groups of students to design an experiment setup to test one of the three factors (number of turns in the coil, strength of the magnet, or orientation of the magnet). Then each lab setup will become a station at which other groups of students can explore a new factor. As students rotate through the stations, they will have two opportunities to explore each factor. Ask students to record their observations at each of the stations and write a concluding statement about how the factor affects the induced current based on their observations.

Learning Issue	Reference	Augmentation and Accommodations
Describing energy transformations	***Physics to Go*** Questions 1 and 4	**Augmentation** • As students are completing the investigation, ask them to decide and record what kind of energy they are using and what kind of energy is being produced. It may be helpful to brainstorm a list of different kinds of energy before they begin. • Point out the paragraph at the end of the *Physics Talk* that describes the basic energy transformation in a motor and a generator. **Accommodation** • Provide an energy-flow-diagram graphic organizer that has a blank space for each step in the energy transfer. Include a picture for each step if possible. Include a word bank if necessary.
Using concepts learned in previous chapters	***Physics to Go*** ***Preparing for the Chapter Challenge***	**Augmentation** • Students may not remember what factors affect voltage. Refer students to their experience with the *Electron Shuffle* to review the factors that affect voltage.

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Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Pronunciation Vocabulary comprehension	***Investigate*** Step 1	Like many scientific words, galvanometer has many syllables and can be intimidating. Model its pronunciation, and point out to students that they already know three of its five syllables—"ometer"—from "thermometer," for example. Reassure students that this big word has a simple meaning: a tool used to measure electric current.
Higher-order thinking	***Physics Talk*** Accidental Discoveries and the History of Physics	"Thomas Jefferson said that he believed in luck and that he noticed that the harder he worked the more luck he had." Here you have a variant of "chance favors the prepared mind." Hold a class discussion about these two statements. What do they mean? Then invite ELL students to share similar sayings from their native language and explain them to the class. Sometimes, such sayings have a cultural basis. Talking about sayings from their native culture may give ELL students a chance to broaden their classmates' views of other cultures.
Understanding concepts	***Active Physics Plus*** Lenz's law	Challenge students to remember and state the law of conservation of energy. Then ask them to state Lenz's law in their own words and explain how it holds true to the law of conservation of energy.

For the *Chapter Challenge*, students will have to write instructions and design a toy that will be fun and accessible or understandable to younger children. Remind students that Michael Faraday was known for demonstrating science to children at the Royal Academy. Have ELL students set up experiments from this section and put on a demonstration for younger students. (Perhaps you can invite children from an elementary school in your district to come to your classroom, or hold a Saturday demonstration for siblings and children in the neighborhood.) It has been said that the best way to understand something is to teach it. By performing a demonstration, your students will solidify their understanding of the scientific concepts in this section. Also, they will gain insight into how to talk to and interact with curious young scientific minds, skills they will be able to apply when they design, and write instructions for the use of the toy they develop for the *Chapter Challenge*.

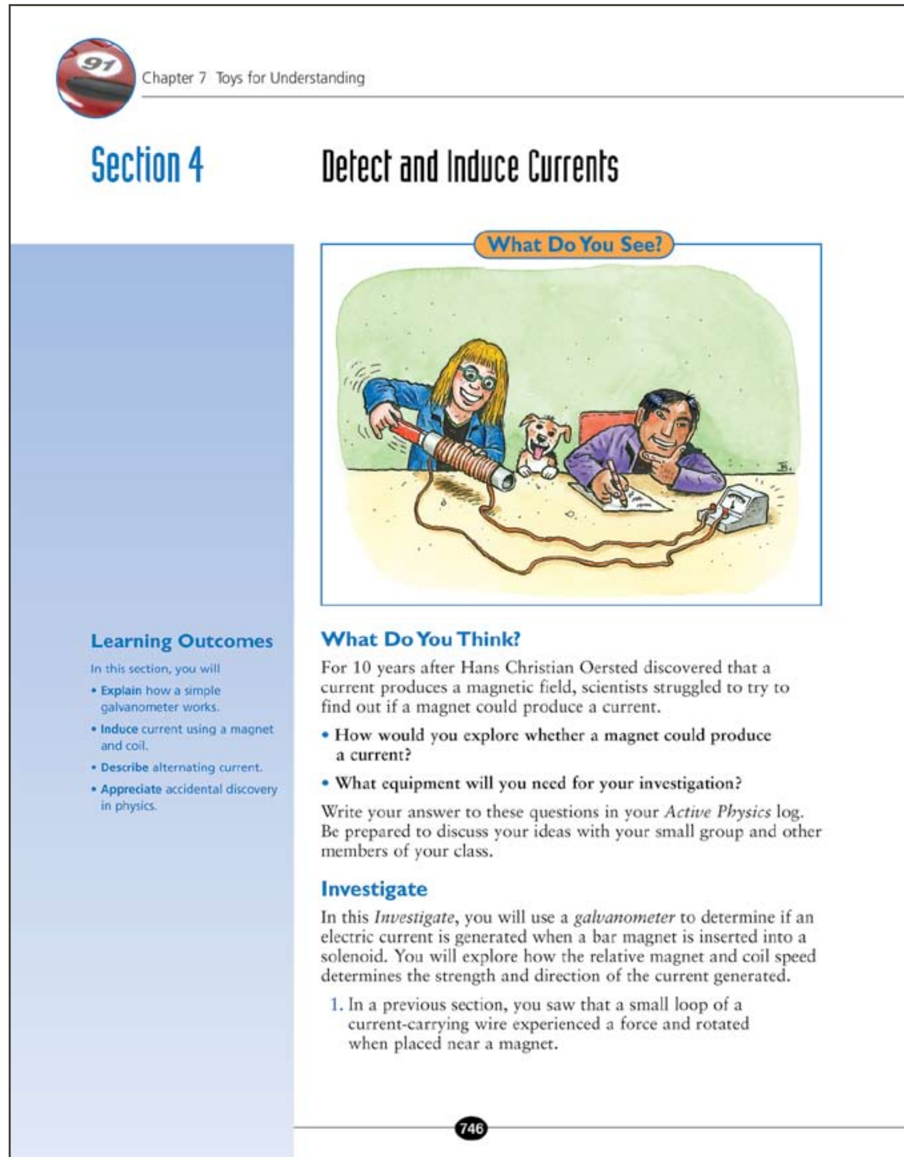
If you have students who could benefit from some extra credit work, you may wish to have them research and report on serendipitous discoveries in science (which led to the development of the microwave oven, the smallpox vaccine, and countless other advancements in science and technology). In keeping with the spirit of the *Chapter Challenge*, you may suggest they focus on toys that were developed accidentally.

SECTION 4

Teaching Suggestions and Sample Answers

What Do You See?

Ask your class what they think the students in the illustration are doing. Use an overhead to trace the path of the wire leading to the electronic meter. Ask students how the illustration connects to the title of the section. Then ask them what they think the image depicts and ask them to record their responses. Point out that the illustration provides important clues to physics concepts that are investigated in this section. Remind them to revisit the illustration as their understanding of how currents are induced progresses.



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Section 4 Detect and Induce Currents

What Do You See?

Learning Outcomes

In this section, you will

- **Explain** how a simple galvanometer works.
- **Induce** current using a magnet and coil.
- **Describe** alternating current.
- **Appreciate** accidental discovery in physics.

What Do You Think?

For 10 years after Hans Christian Oersted discovered that a current produces a magnetic field, scientists struggled to try to find out if a magnet could produce a current.

- How would you explore whether a magnet could produce a current?
- What equipment will you need for your investigation?

Write your answer to these questions in your *Active Physics* log. Be prepared to discuss your ideas with your small group and other members of your class.

Investigate

In this *Investigate*, you will use a *galvanometer* to determine if an electric current is generated when a bar magnet is inserted into a solenoid. You will explore how the relative magnet and coil speed determines the strength and direction of the current generated.

1. In a previous section, you saw that a small loop of a current-carrying wire experienced a force and rotated when placed near a magnet.

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Students' Prior Conceptions

Generally, students know that pushing or moving something faster increases the velocity of this object and that this velocity is related to the mechanical motion and force of the hand pushing the object. In this section, it is important for you to address the relationship between mechanical energy and electromagnetic energy as applied to induced current.

1. **A bar magnet placed inside of the coil carries a charge.** Firstly, students must understand that a bar magnet itself is electrically neutral; its molecular composition and alignment of molecules create a number of poles which occur in combined pairs of opposites, denoted by north-south, but there is no "free charge" on the magnet. It is the relative motion between the magnet and the coil that induces a current due to the force exerted upon the electrons in the wire. This can be further highlighted as students observe the changes produced in the current when the motion of the bar magnet is changed. If the bar magnet is stationary, there is no current.
2. **Students confound the relationships between mechanical energy and other forms of energy; they do not recognize that mechanical work input into a system can result in a corresponding output of electrical energy.** Connecting the hand-cranking of the generator to produce a current and electrical energy can be applied to inducing a current with mechanical energy by moving the magnet through the coil. The change in motion and the change in the mechanical energy, also produce a change in the induced electrical energy. The advent of extremely powerful magnets (for

CHAPTER 7

What Do You Think?

These preliminary questions are designed to elicit students' prior knowledge and to focus on the physics concepts that they will be exploring. Have them discuss their answers with their group members to allow them to improve their responses. Emphasize that previous investigations should help in answering these *What Do You Think?* questions. In a class discussion, record students' ideas that you can refer to later during the study of this section. The answers generated at this stage will give you an idea of how you can address preconceptions for students to gain a clearer understanding of concepts.

What Do You Think?

A Physicist's Response

To explore whether a magnet could produce a current, you should consider how a current produces a magnetic field. Moving charges produce magnetic fields. For an analogy consider this: If you were sitting on a charge in a magnetic field and there was motion between the charge and the field you would not know if the charge were moving through the field or if the field were moving past the charge. Hence, a field moving past a conductor could cause an interaction, which results in pushing the charge in the conductor and producing a current.

To test this concept you would need a conducting wire (coiled to increase the effect), a permanent magnet, and a way to detect if a current is induced in the wire; for example, by placing a compass needle near the wire. If the compass needle gets deflected then a current exists, as was observed in earlier sections. However, the compass needle needs to be far away from the bar magnet to be unaffected by it, but close enough to the loop of wire being used to be able to detect a current. For example, one might wrap a few coils of wire around a compass needle and place it at a distance from a solenoid with which a bar magnet interacts. Then one could move the bar magnet by the solenoid in various ways.

example, neodymium magnets) allows students to directly experience this if they try to slide one of these magnets across a strip of copper or aluminum. Although the metals are not magnetic, they resist the sliding motion since they are generating a current in the metal strip.

3. **Students believe energy can be changed completely from one form to another with no loss of useful energy.** While students encounter hurdles when thinking of energy as changing from mechanical to electrical to a new form of mechanical energy, they believe in the literal definition of the conservation of energy so strongly that they resist the concept that energy transformations are not 100% efficient. They believe conservation of energy means energy should be conserved. Students should consider this transformation of energy and evaluate the efficiency of the creation and release of energy because they are required to design a motor and/or generator for the *Chapter Challenge.*

4. **If students do not believe that energy is lost, they believe that energy is exhausted in bringing about an effect.** You may intervene with student thinking on this energy corollary as they evaluate the notes and explanations presented by their class members about their observations.

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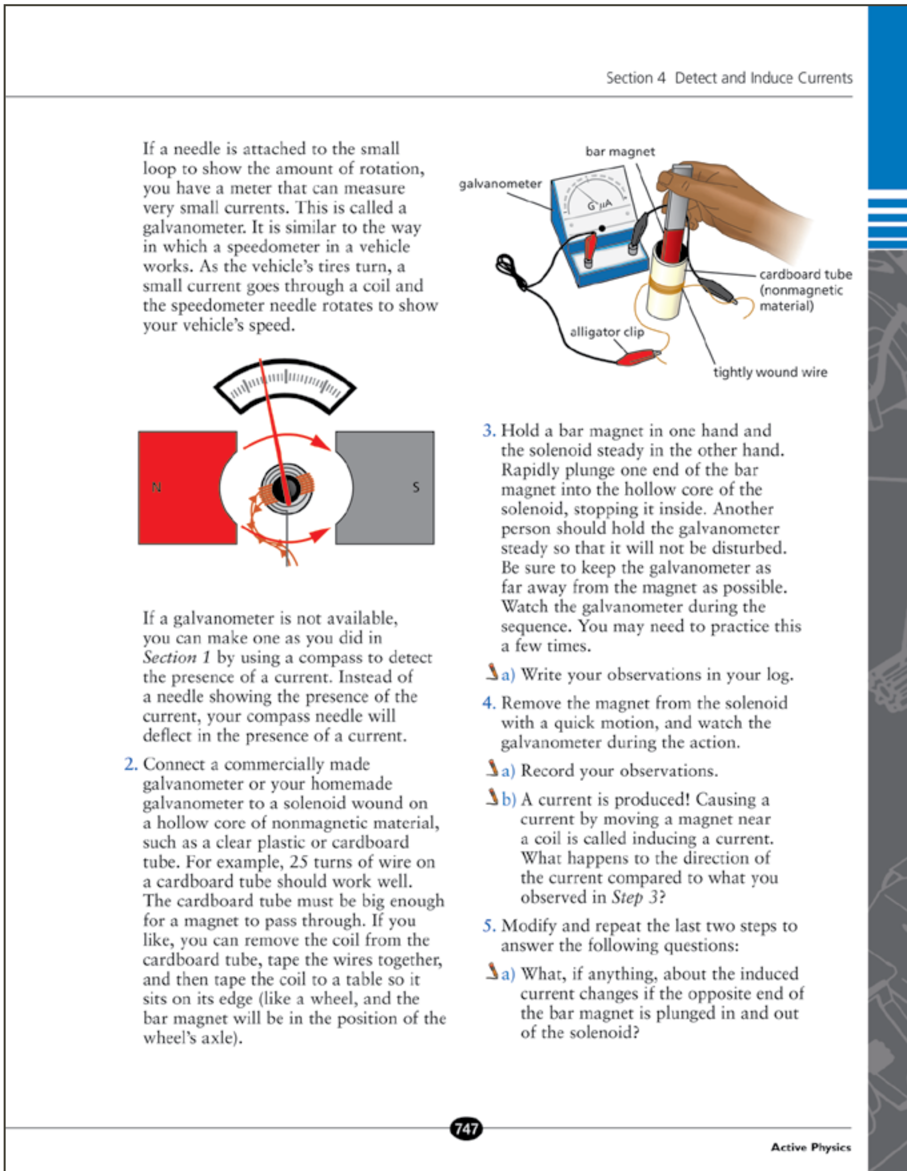

If a needle is attached to the small loop to show the amount of rotation, you have a meter that can measure very small currents. This is called a galvanometer. It is similar to the way in which a speedometer in a vehicle works. As the vehicle's tires turn, a small current goes through a coil and the speedometer needle rotates to show your vehicle's speed.

If a galvanometer is not available, you can make one as you did in *Section 1* by using a compass to detect the presence of a current. Instead of a needle showing the presence of the current, your compass needle will deflect in the presence of a current.

2. Connect a commercially made galvanometer or your homemade galvanometer to a solenoid wound on a hollow core of nonmagnetic material, such as a clear plastic or cardboard tube. For example, 25 turns of wire on a cardboard tube should work well. The cardboard tube must be big enough for a magnet to pass through. If you like, you can remove the coil from the cardboard tube, tape the wires together, and then tape the coil to a table so it sits on its edge (like a wheel, and the bar magnet will be in the position of the wheel's axle).

3. Hold a bar magnet in one hand and the solenoid steady in the other hand. Rapidly plunge one end of the bar magnet into the hollow core of the solenoid, stopping it inside. Another person should hold the galvanometer steady so that it will not be disturbed. Be sure to keep the galvanometer as far away from the magnet as possible. Watch the galvanometer during the sequence. You may need to practice this a few times.

a) Write your observations in your log.

4. Remove the magnet from the solenoid with a quick motion, and watch the galvanometer during the action.

a) Record your observations.

b) A current is produced! Causing a current by moving a magnet near a coil is called inducing a current. What happens to the direction of the current compared to what you observed in *Step 3*?

5. Modify and repeat the last two steps to answer the following questions:

a) What, if anything, about the induced current changes if the opposite end of the bar magnet is plunged in and out of the solenoid?

Investigate

1.

For this investigation, wrapping a compass with a coil of wire works as well as a commercial galvanometer. The commercial meter movement of the galvanometer is the basic meter movement for all analog meters, such as ammeters and voltmeters.

2.

Students assemble their galvanometer. Coils close together work better than coils far apart.

3.a)

With a commercial galvanometer, when the magnet is pushed rapidly into the coil, students will see a slight movement of the galvanometer needle to one side. The compass wound with several coils of wire will also show a deflection.

Teaching Tip

If the deflection caused by the magnet moving into the coil is very small, a larger deflection can be seen if two magnets are used. The magnets need to be held with like poles together (north pole to north pole) to double the field strength.

4.a)

Students should see an approximately equal deflection to the opposite side when the magnet is removed.

4.b)

Students should note the reversed direction of the deflection of the needle.

5.a)

Reversing the magnetic polarity reverses the direction of the needle deflection.

5.b)

The faster the magnet moves, the greater the needle deflection.

5.c)

When the magnet is stationary relative to the coil, no current is induced.

5.d)

When the solenoid is moved and the magnet held stationary, a current is produced, which causes the needle to deflect.

5.e)

Moving the magnet and solenoid in opposite directions induces a current, possibly larger than previously observed because of a greater relative velocity.

5.f)

Moving the solenoid and magnet together in the same direction produces no relative motion, so no current is induced.

Teaching Tip

If a power supply is available, using it to power the electromagnet will increase the deflection observed when the current is turned off and on if a higher voltage is used. Rapidly turning the power supply off and on will make the needle move back and forth, similar to the AC current discussed in the *Physics Talk* of this section.

6.a)

When the electromagnet is stationary inside the solenoid, no current is induced.

6.b)

When the current in the electromagnet is stopped, a brief deflection of the galvanometer

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b) How does the induced current change if the speed of the magnet is changed?

c) When the magnet is not moving (stopped), what is the amount of induced current?

d) When the magnet is held stationary and the solenoid is moved back and forth over and around it, what is the effect on the induced current?

e) What is the effect of moving both the magnet and the solenoid simultaneously in opposite directions?

f) What is the effect of holding the magnet firmly inside the solenoid and moving both of them back and forth together?

6. Substitute an electromagnet for the permanent magnet. Place the electromagnet into the solenoid.

a) When the electromagnet is not moving, what is the amount of the induced current?

b) The current in the electromagnet is maintained by the battery or the rotation of the hand generator crank. While carefully watching the galvanometer, stop the current. Did you observe an induced current?

c) While carefully watching the galvanometer, create a current. Did you observe an induced current?

d) A current has a magnetic field associated with it. As the current is created, the magnetic field lines move out from the electromagnet to fill the space surrounding it. These magnetic field lines move past the wires in the solenoid. Even though there is no movement of the electromagnet, there is a movement of the field lines past the wires of the solenoid. Draw a series of sketches showing how field lines move past the wires.

Physics Talk

PRODUCING A CURRENT USING A MAGNET

Generating Electricity

In this *Investigate*, you were able to produce electricity by moving a magnet within a coil of wire. You created electrical energy by physically moving the bar magnet through the coil. When neither the magnet nor the coil moved relative to each other, no electricity was generated. A device that produces electricity is called a **generator**. When you produced electricity, you used the **galvanometer** as a detector.

Previously you have used a hand-cranked generator to produce electricity. A closer inspection of the hand-cranked generator shows that inside the generator, you either move a magnet through a coil or move the coil past the magnet. Inducing a current shows the conversion of mechanical energy to electrical energy to mechanical energy. The movement of the generator handle or magnet is an example of mechanical energy.

Physics Words

generator (electric): a device that produces electricity.

galvanometer: an instrument used to detect and measure an electric current.

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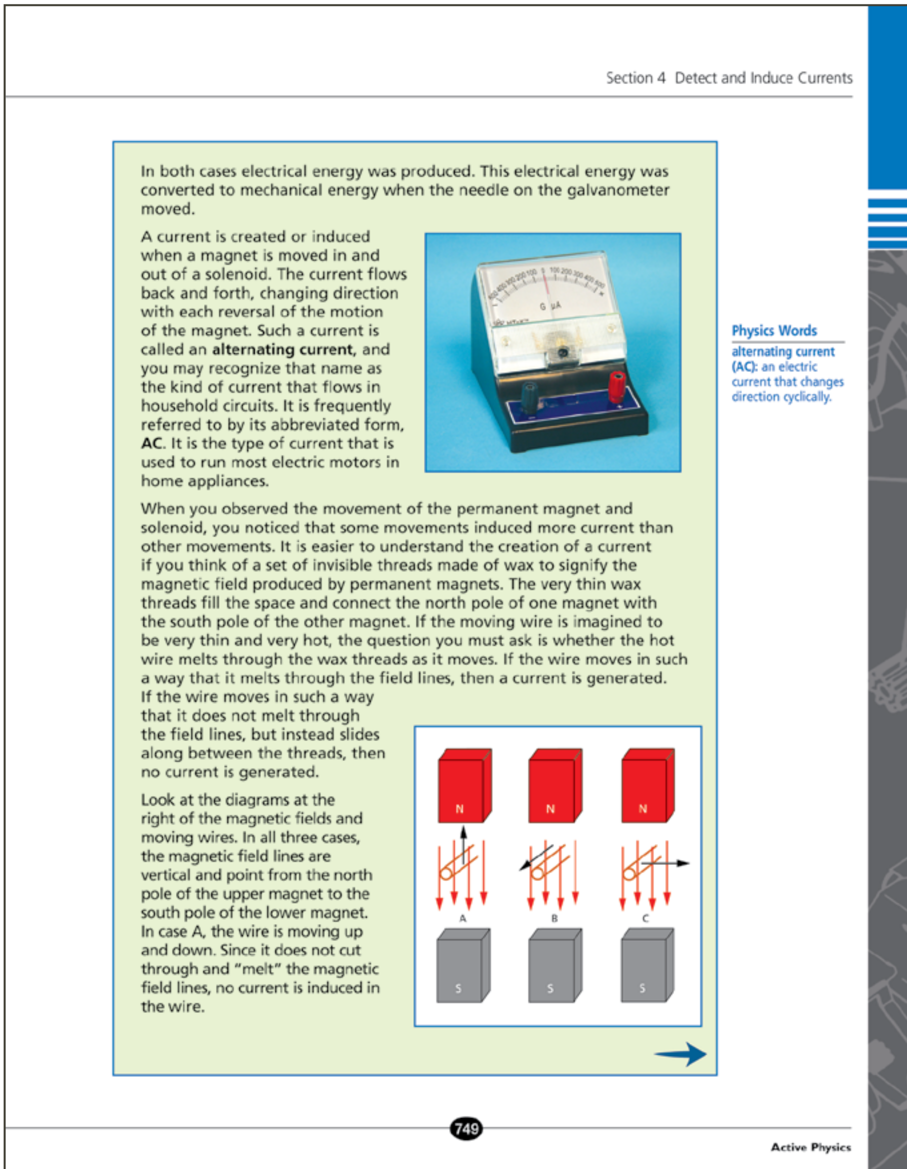
needle should be observed. This indicates that a short-lived current was induced.

6.c)

When the current is started again, a brief deflection of the galvanometer needle is observed, indicating that a short-lived current was induced. The galvanometer needle will deflect in the opposite direction this time, indicating the current induced was in the opposite direction.

6.d)

Students' sketches should show something similar to a small magnetic field around the electromagnet in the solenoid when the current is first turned on. After a while, the students' sketches should show a larger magnetic field around the electromagnet to show that the field has moved outward and passed through the solenoid as it expanded.



In both cases electrical energy was produced. This electrical energy was converted to mechanical energy when the needle on the galvanometer moved.

A current is created or induced when a magnet is moved in and out of a solenoid. The current flows back and forth, changing direction with each reversal of the motion of the magnet. Such a current is called an **alternating current**, and you may recognize that name as the kind of current that flows in household circuits. It is frequently referred to by its abbreviated form, **AC**. It is the type of current that is used to run most electric motors in home appliances.

Physics Words

alternating current (AC): an electric current that changes direction cyclically.

When you observed the movement of the permanent magnet and solenoid, you noticed that some movements induced more current than other movements. It is easier to understand the creation of a current if you think of a set of invisible threads made of wax to signify the magnetic field produced by permanent magnets. The very thin wax threads fill the space and connect the north pole of one magnet with the south pole of the other magnet. If the moving wire is imagined to be very thin and very hot, the question you must ask is whether the hot wire melts through the wax threads as it moves. If the wire moves in such a way that it melts through the field lines, then a current is generated. If the wire moves in such a way that it does not melt through the field lines, but instead slides along between the threads, then no current is generated.

Look at the diagrams at the right of the magnetic fields and moving wires. In all three cases, the magnetic field lines are vertical and point from the north pole of the upper magnet to the south pole of the lower magnet. In case A, the wire is moving up and down. Since it does not cut through and "melt" the magnetic field lines, no current is induced in the wire.

Physics Talk

This *Physics Talk* discusses how electricity is generated by moving a magnet within a coil of wire and how an alternating current is created. The discussion is supported by students' observations in the *Investigate*. Students also read about the accidental discoveries in physics; for example, Oersted's discovery of a current inducing a magnetic field in 1820, Faraday's discovery of electromagnetic induction in 1831, and Gramme's invention of the electric motor in 1873.

Review what students executed in the *Investigate* and let them know that a device that generates electricity is called a generator and a device to measure or detect it is a galvanometer. Discuss the hand-cranked generators that were used in the past to generate electricity, and consider passing them out to allow students to inspect them. Point out that with the hand-cranked generators, turning the handle causes either a coil to be moved near a magnet or a magnet to be moved near a coil, producing electrical energy.

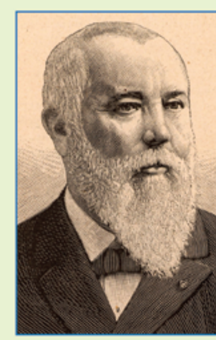
Emphasize that whenever there is relative motion between a magnet and a conductor, where the conductor goes through a changing magnetic field that has some component perpendicular to the relative motion, a current is set up in the conductor. Let students know that a rotating coil induces a current that changes direction and goes back and forth, producing an alternating current. This is the most common type of current used in buildings. Describe the analogy of the conductor cutting through field lines that are made of thin wax threads to assist students' understanding. Use the overhead projector for this discussion. Review the accidental discoveries in the history of physics focusing on Oersted's discovery in 1820, Faraday's discovery in 1831, and Gramme's discover of the electric motor in 1873. Consider asking students what these stories teach them about the pursuit of knowledge.

In case B, the wire is moving in and out along the direction of the wire itself. Again, since it does not cut through and "melt" the magnetic field lines, no current is induced in the wire. In case C, the wire is moving horizontally. When it does this, it cuts through and "melts" the magnetic field lines, so current is induced in the wire. There's one more detail that is very important. If the wire is moving to the right as in case C, the negative current flows along the wire out of the page. If the wire is moving to the left in case C, the negative current flows along into the page. In other words, when the wire moves so as to cut through or "melt" the magnetic field lines, the direction of the induced current in the wire reverses if the direction the wire is moving reverses.

Accidental Discoveries and the History of Physics

The history of science is filled with discoveries that have led to leaps of progress in knowledge and applications. This is certainly true of physics and, in particular, electricity and magnetism. These discoveries "favor" the prepared mind. Oersted's discovery in 1820 of the magnetic field surrounding a current-carrying wire already has been mentioned. Similarly, Michael Faraday discovered electromagnetic induction in 1831. Faraday was seeking a way to induce electricity using currents and magnets. He noticed that a brief induced current happened in one circuit when a nearby circuit was switched on and off. This is similar to your investigation of the current induced when you turned the electromagnet on and off. One story is that Faraday turned the circuit on expecting a continuous effect. Instead there was a very short current in the second circuit that stopped almost immediately. After waiting for some time while nothing happened, he disappointedly turned the main circuit off only to be surprised by another brief flow of current in the second circuit. After a flash of thought he excitedly turned the switch on and off repeatedly and found that as long as he kept switching the main circuit, then the second circuit's current continued to flow. Both Oersted and Faraday are credited for taking advantage of the events that happened before their eyes, and pursuing them.

About one-half century after Faraday's discovery of electromagnetic induction, which immediately led to the development of the generator, another event occurred. In 1873, a Belgian engineer, Zénobe Gramme, set up a demonstration of DC generators at an exposition (a forerunner of a world's fair) in Vienna, Austria.



Zénobe Gramme (1826 – 1901) was a Belgian engineer.

Steam engines were to be used to power the generators, and the electrical output of the generators would be demonstrated. While one DC generator was operating, Gramme connected its output to the output of another generator that was not operating. The shaft of the inactive generator began to rotate—because it was acting as an electric motor! Although Michael Faraday had shown as early as 1821 that rotary motion could be produced using currents and magnets, in other words a "motor effect," nothing useful resulted from it. Gramme's discovery, however, immediately showed that electric motors could be useful. In fact, the electric motor was demonstrated at the same Vienna exposition where Gramme's discovery was made. A fake waterfall was set up to drive a DC generator using a paddle wheel arrangement, and the electrical output of the generator was fed to a "motor" (a generator running "backward"). The motor was shown to be capable of doing useful work.

Zénobe Gramme invented the first useful electrical motor.

A motor converts electrical energy into mechanical energy. You used an electric current (electrical energy) to turn a loop of wire (mechanical energy). A generator converts mechanical energy into electrical energy. You pushed a magnet (mechanical energy) through a coil and produced an electric current (electrical energy.)

Checking Up

1. When a magnet is moved into and out of a coil of wire, what happens to the direction of the electric current produced?
2. In order to generate an electric current by moving a wire through a magnetic field, which way must the wire be moved?
3. What did Zenobe Gramme do to make the first practical DC motor start working?

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
	••	••	••

Investigating Factors that Affect the Strength of the Current Induced

In your investigation, you examined the current induced in a coil from a moving magnet. Two aspects of the motion varied: the direction and speed of the magnet.

It is interesting to examine how other factors affect the induced current.

a) Design an experiment that keeps all factors the same except the number of turns in the coil. It is best to test coils with a very different number of turns.

Checking Up

1.

The current produced alternates between a positive and negative direction as the magnet is moved into and out of a coil of wire.

2.

The wire must be moved such that it cuts across field lines in order to produce a current in the wire.

3.

To make the first practical DC motor start working, Zenobe Gramme set up a DC generator using a paddle wheel arrangement. The electrical output of the generator was fed to a motor (a generator running backward) that was shown to be capable of doing useful work.

CHAPTER 7

Active Physics Plus

This *Active Physics Plus* provides students with the opportunity to explore the concepts that connect electricity and magnetism and the factors that affect the strength of an induced current through experimentation. Consider having all groups conduct each experiment or split the class up so that a set of two groups complete one experiment and all groups report their observations and results to the class. Lenz's law and the left-hand rule are discussed and students apply these to determine the directions of induced currents.

a.

Students should design and carry out an experiment to determine how changing the number of turns in the coils affects the amount of the induced current when a magnet is moved relative to the coil. Observations should show that increasing the number of turns in the coils increases the strength of the induced current.

b.

Students should design and carry out an experiment to determine how changing the strength of the magnet affects the amount of the induced current when a magnet is moved relative to the coil. Observations should show that increasing the strength of the magnet increases the strength of the induced current.

c.

Students should design and carry out an experiment to determine how changing the orientation of the magnet affects the amount of the induced current when a magnet is moved relative to the coil. Observations should show that the strength of the induced current depends on the orientation of the magnet, and that the induced current is greatest when the field lines are cut at a 90° angle.

Chapter 7 Toys for Understanding

The goal is to find a quantitative relationship between the size of the induced current and the number of turns in the coil.

b) Design an experiment that keeps all factors the same except the strength of the magnet. It might be difficult to know how the strengths of magnets compare, but you might use the number of staples or paper clips it can pick up as a guide.

c) Design an experiment that keeps all factors the same expect the orientation of the magnet relative to the coil. You have already examined what happens when the positions of the poles of the magnet are reversed. In this experiment, examine what happens when the magnet is oriented at several different angles.

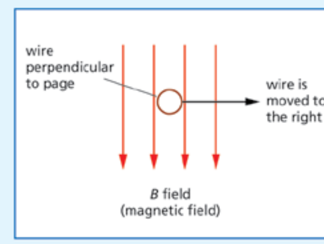
Lenz's Law

A current-carrying wire in a magnetic field experiences a force that moves the wire. This is the basis of the electric motor. A moving wire cutting across magnetic field lines induces a current. This is the basis of the electric generator. It seems that it may be possible to give a wire a tiny push and have the wire move. The wire's movement would then cause a current. The current would then make the wire move some more. More movement induces more current and then more movement and more current forever.

Conservation of energy implies that this cannot happen. You cannot get more and more energy out of a system without putting more and more energy into it.

The dilemma is solved by considering the directions of the force and the direction of the induced current. The left-hand rule for determining the direction of the force is to place your thumb in the direction of the electron current and your outstretched fingers in the direction of the magnetic field. The force on the wire is perpendicular to your palm.

As the wire in the diagram is moved to the right, a current is created. For the sake of argument, imagine that the current could be into the page or out of the page. If the current were into the page, the force on the wire would be to the right. This would then move the wire more to the right and produce more current into the page. This is the "lots of energy for nothing" scenario described earlier.



The alternative is what really happens. As the wire in the diagram is moved to the right, a current is created. This current is out of the page. If the current is out of the page, the force on the wire would be to the left. This would then stop the wire's movement and no more current would be created. If you did want to create more current, you would have to push harder to the right to overcome the force due to the current in the magnetic field.
More current requires more force and more electrical energy requires more mechanical energy. This is consistent with the principle of conservation of energy.

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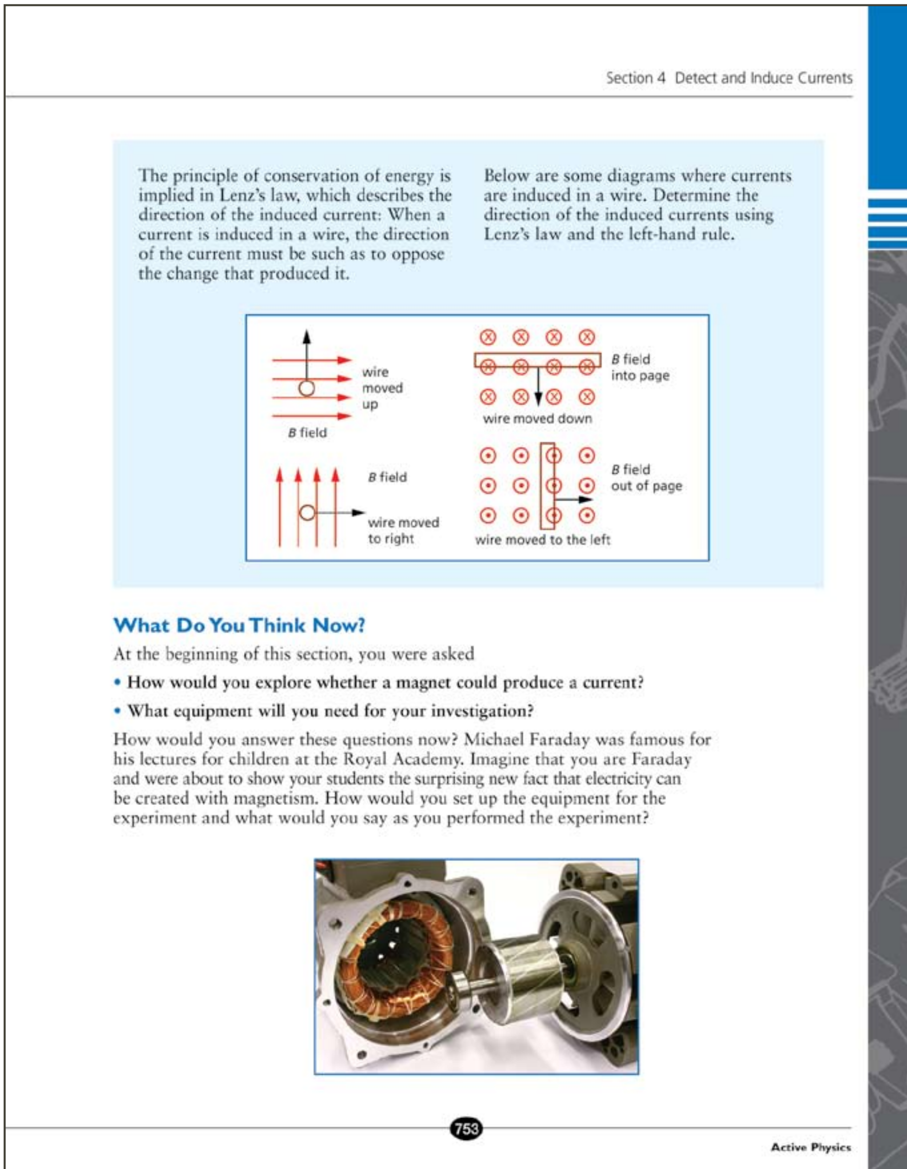
Active Physics

Lenz's Law

Discuss with the class the forces involved in a situation where a current is induced using the left-hand rule. Emphasize that the left thumb is placed in the direction of the electron current, the outstretched fingers are in the direction of the magnetic field, and the force is perpendicular to the palm. Use this rule to show the induced current created in the example of the wire cutting through a field and to explain how energy is conserved in this system. Emphasize that the induced current is in a direction such that it opposes the change that produced it.


Section 4 Detect and Induce Currents

The principle of conservation of energy is implied in Lenz's law, which describes the direction of the induced current: When a current is induced in a wire, the direction of the current must be such as to oppose the change that produced it.

Below are some diagrams where currents are induced in a wire. Determine the direction of the induced currents using Lenz's law and the left-hand rule.

What Do You Think Now?

At the beginning of this section, you were asked

- **How would you explore whether a magnet could produce a current?**
- **What equipment will you need for your investigation?**

How would you answer these questions now? Michael Faraday was famous for his lectures for children at the Royal Academy. Imagine that you are Faraday and were about to show your students the surprising new fact that electricity can be created with magnetism. How would you set up the equipment for the experiment and what would you say as you performed the experiment?

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Active Physics

The directions of induced current are the following:

If the magnetic field were to the right and the wire moved up toward the top of the page, the induced electron current would be out of the page.

If the wire were moved to the right of the page and the field pointed toward the top of the page, the current induced would be into the page.

If the wire were moving down the page across a field that points into the page, the induced current would be to the left of the page.

If the wire were moved to the right of the page across a magnetic field coming out of the page, the induced current would be toward the top of the page.

What Do You Think Now?

Revisit the *What Do You Think* questions and review students' initial ideas. Ask them how they would answer these questions now based on their observations and what they know about induced currents. After discussing how students would revise their answers, share *A Physicist's Response* so that they can update their original responses. Consider having student groups present their equipment setup on how magnets can produce electricity.

CHAPTER 7

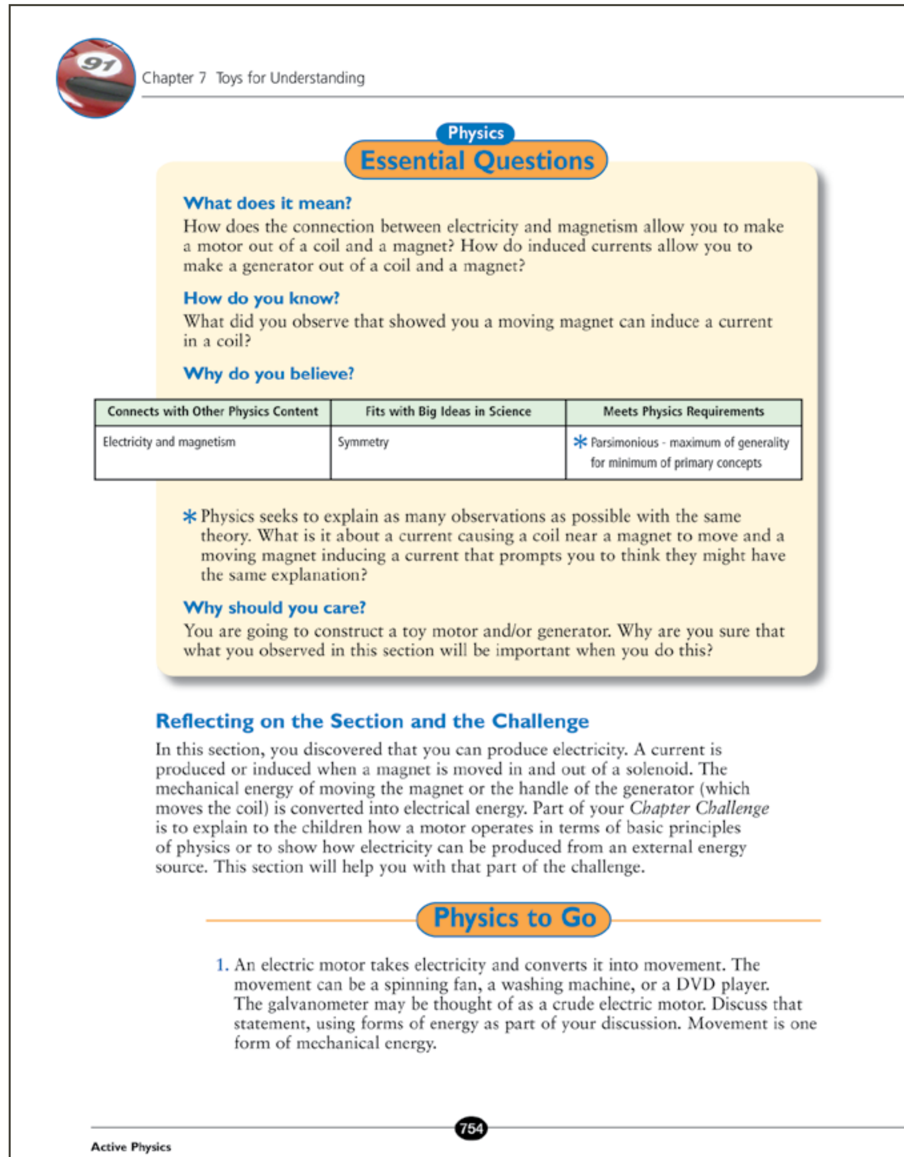
Reflecting on the Section and the Challenge

This section provides further opportunity for students to reflect on the connection between electricity and magnetism. Consider asking students to give you specific examples of how electric motors convert electrical energy to mechanical energy. Have a class discussion on how the relative motion between a wire and a magnet will help them prepare for the *Chapter Challenge*.

Physics to Go

1.

A galvanometer is a measuring tool that has a needle that moves when a current is present. This is an example of converting electrical energy into mechanical energy, which is what a motor does.



Physics

Essential Questions

What does it mean?

How does the connection between electricity and magnetism allow you to make a motor out of a coil and a magnet? How do induced currents allow you to make a generator out of a coil and a magnet?

How do you know?

What did you observe that showed you a moving magnet can induce a current in a coil?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	Symmetry	* Parsimonious - maximum of generality for minimum of primary concepts

* Physics seeks to explain as many observations as possible with the same theory. What is it about a current causing a coil near a magnet to move and a moving magnet inducing a current that prompts you to think they might have the same explanation?

Why should you care?

You are going to construct a toy motor and/or generator. Why are you sure that what you observed in this section will be important when you do this?

Reflecting on the Section and the Challenge

In this section, you discovered that you can produce electricity. A current is produced or induced when a magnet is moved in and out of a solenoid. The mechanical energy of moving the magnet or the handle of the generator (which moves the coil) is converted into electrical energy. Part of your *Chapter Challenge* is to explain to the children how a motor operates in terms of basic principles of physics or to show how electricity can be produced from an external energy source. This section will help you with that part of the challenge.

Physics to Go

1. An electric motor takes electricity and converts it into movement. The movement can be a spinning fan, a washing machine, or a DVD player. The galvanometer may be thought of as a crude electric motor. Discuss that statement, using forms of energy as part of your discussion. Movement is one form of mechanical energy.

Physics Essential Questions

What does it mean?

A current-carrying wire produces a magnetic field. The magnetic field of the wire can interact with the magnet, causing the wire to move, which allows you to make a motor. A magnet moving past a wire can induce a current in that wire, which allows you to make a generator.

How do you know?

The wire was placed near a compass. When the current was induced, you observed a movement of the compass needle.

Why do you believe?

They both show a relationship between electricity and magnetism.

Why should you care?

This section demonstrated the physics behind generating a current. Using mechanical energy to produce electrical energy is a generator. Almost all the electricity you use every day comes from generators. Without this electricity, life would be much more difficult.

Section 4 Detect and Induce Currents

2. The galvanometer detects the amount and direction of the electric current. Explain how the galvanometer works.
3. How could the galvanometer be made more sensitive, so that it could detect very weak currents?
4. An electric generator takes motion and turns it into electricity. The electricity can then be used for many purposes. The solenoid and the bar magnet in this section could be thought of as a crude electric generator. Explain the truth of this last statement, referring to specific forms of energy in your explanation.
5. Imagine repeating the investigation in such a way that you would be able to see only the galvanometer and not the solenoid, the magnet, and the person moving the equipment. Would you be able to tell from the galvanometer whether the magnet is being moved, or the solenoid is being moved, or both are being moved? Explain your answer.
6. In generating electricity in this section, you moved the magnet or the coil. How can you use each of the following resources to move the magnet?
   a) wind
   b) water
   c) steam
7. *Preparing for the Chapter Challenge*

   If the toy you are going to have the child assemble has a generator as part of the design, it should not develop more than 10 V (volts) for safety reasons. Make a list of the things you should consider in the design of the generator that will determine the amount of voltage the generator can put out. What should you include in the kit list to allow the student to test the generator to see if it is working properly when it is assembled?

Inquiring Further

Household Currents

Find out about the 120 V (volt) AC used in United States home circuits. If household current alternates, at what rate does it surge back and forth? Write down any information about AC that you can find and bring it to class.

2.

The galvanometer is essentially an electromagnet. It is composed of a loop of wire and a magnetic needle that is free to rotate. When a current is present, it induces a magnetic field, which pushes or deflects a magnetic needle.

3.

You can increase the number of loops of wire, increase the strength of the magnetic needle, and/or make the magnetic needle longer so a smaller deflection could be more readily observed.

4.

A solenoid and a bar magnet as used in the *Investigate* could be a crude electric generator because it converts motion energy (the relative motion between the magnet and the coil caused by someone moving them) to the electrical energy of the induced current.

5.

You would not be able to tell if the magnet, solenoid, or both were being moved. You could only say that relative motion between the two objects existed if the galvanometer was being deflected.

6.a)

The kinetic energy of wind (air particles) could be used to move a magnet, especially if it was hanging on a string or if the panels of a windmill were made of magnetic materials.

6.b)

The kinetic energy of water (for example, moving down a stream or a waterfall) could be used to rotate magnets if a water wheel was used to rotate a magnet about a fixed coil. You might even consider making parts of the water wheel magnetic.

6.c)

Steam could be used as in a steam engine to push pistons or other objects. These objects could be magnetic or attached to a magnet, causing it to move.

7.

Preparing for the Chapter Challenge

Students should make a list of things they need to consider in the design of a generator and how they could determine the voltage to be sure that it is not greater than 10 V (for safety reasons). Students might mention use of an ammeter or voltmeter to determine the maximum voltage or induced current produced by the generator. Students might mention the use of Ohm's law

CHAPTER 7

to determine the current drawn from a given voltage source and/or the use of a fuse to assure that a certain current is not exceeded provided they know the resistance and assume the maximum voltage. They also should develop a kit list to allow the children testing the generator to see if it is working properly after it is assembled.

Inquiring Further

Household Currents

Students should research and report on the 120 V alternating current used in the United States. The rate at which currents surge back and forth is at 60 Hertz. 240 V at 60 Hz is also available for larger appliances, such as air conditioners, stoves, and clothes dryers. Power plants generally transmit electrical power along three cables in three phases offset by 120° to ensure that one of the signals is reaching its peak value.

NOTES

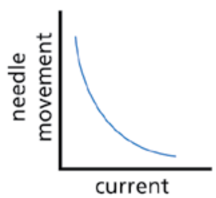
CHAPTER 7

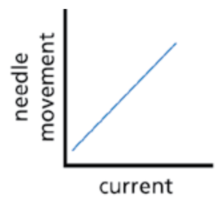
NOTES

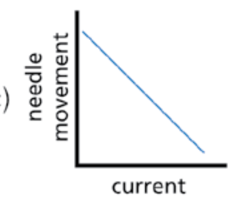
SECTION 4 QUIZ

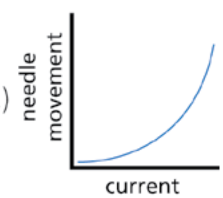
7-4a **Blackline Master**

1. Which graph below best represents the degree of deflection of a galvanometer needle and the current passing through the galvanometer?

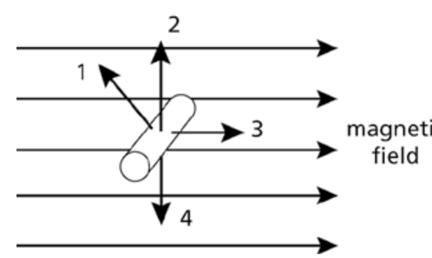
a) 

b) 

c) 

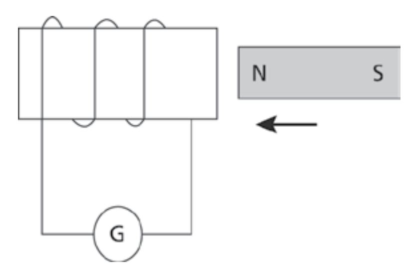
d) 

2. The diagram at right shows a magnetic field with a wire located in the field. No voltage will be generated in the wire when it is moved in direction



a) 1.
b) 2.
c) 3.
d) 4.

3. The north pole of a magnet is pushed into a coil of wire connected to a galvanometer as shown in the diagram. If the galvanometer needle moves to the right when the north pole of the magnet is pushed into the coil, which of the following will make the needle move to the left?



a) Pulling the north pole away from the coil to the right.

b) Turning the magnet over and pushing the south pole into the coil.

c) Moving the coil toward the south pole.

d) All of the above.

4. Which of the following will increase the reading on the galvanometer in the diagram in *Question 3*?

a) Increasing the size of the galvanometer.

b) Increasing the number of turns in the coil.

c) Moving the magnet more slowly.

d) Increasing the radius of the coil.

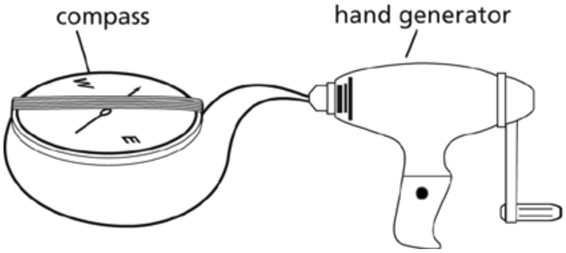
5. A compass is connected to a hand generator as shown in the diagram. To increase the deflection of the compass,

   a) rotate the generator faster.

   b) use fewer coils around the compass.

   c) reverse the rotation of the generator.

   d) rotate the compass 90˚.



SECTION 4 QUIZ ANSWERS

1 b) There is a positive linear relationship between the induced current and the deflection of the needle. As the current increases, the deflection of the galvanometer's needle increases.

2 c) 3. This is because in Direction 3, the wire is moving parallel to the field lines and does not cut across the field lines, which does not produce a force on the charges in the wire. For a current to be induced, the wire must cut through the magnetic field lines.

3 d) All of the above. If moving the north pole into the coil moves the needle to the right, then pulling the north pole out will move the needle in the opposite direction, or to the left. Similarly, moving the south pole into the coil will move the needle opposite to putting the north pole in the coil, or to the left. Moving the coil toward the south pole would produce the same results as moving the south pole toward the coil. Hence, all of the choices would move the needle of the galvanometer to the left.

4 b) Increasing the number of turns in the coil. Increasing the size of the galvanometer will not change how much the galvanometer is deflected, although it may make it easier to read the amount of deflection if the needle is longer. Increasing the radius of the coil does not increase the strength of the interaction between the magnetic field and the coil but may reduce it because the strength of the field is weaker the further from the magnet. Moving the magnet more slowly would decrease the strength of the interaction.

5 a) rotate the generator faster. Increasing the rate at which you turn the hand generator increases the speed at which the coil cuts through the magnetic field in the generator and thus, increases the current induced. This increased induced current would produce a larger induced magnetic field, which would deflect the compass needle more. Decreasing the number of coils around the compass would decrease the interaction between the induced current and the magnetic needle of the compass, so it would not deflect as much. Reversing the rotation of the generator would only reverse the direction of the current and the angle of the compass. Turning the compass 90˚ would not change anything but the listing of where the labels in the compass N, S, E, and W were located.