SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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SS&C Research and Development Center
Gerry Wheeler, *Principal Investigator*
Erma M. Anderson, *Project Director*
Nancy Erwin, *Project Editor*
Rick McGolerick, *Project Coordinator*
Arlington, Va., 703.312.9256

Evaluation Center
Frances Lawrenz, *Center Director*
Doug Huffman, *Associate Director*
Wayne Welch, *Consultant*
University of Minnesota, 612.625.2046

Houston SS&C Materials Development and Coordination Center
Linda W. Crow, *Center Director*
Godrej H. Sethna, *School Coordinator*
University of Houston-Downtown, 713.221.8583

Houston School Sites and Lead Teachers
Jefferson Davis H.S., Lois Range
Lee H.S., Thomas Ivy
Jack Yates H.S., Diane Schranck

California Coordination Center
Tom Hinojosa, *Center Coordinator*
Santa Clara, Calif., 408.244.3080

California School Sites and Lead Teachers
Sherman Indian H.S., Mary Yarger
Sacramento H.S., Brian Jacobs

Iowa Coordination Center
Robert Yager, *Center Director*
University of Iowa, 319.335.1189

Iowa School Sites and Lead Teachers
Pleasant Valley H.S., William Roberts
North Scott H.S., Mike Brown

North Carolina Coordination Center
Charles Coble, *Center Co-Director*
Jessie Jones, *School Coordinator*
East Carolina University, 919.328.6172

North Carolina School Sites and Lead Teachers
Tarboro H.S., Ernestine Smith
Northside H.S., Glenda Burrus

Puerto Rico Coordination Center*
Manuel Gomez, *Center Co-Director*
Acenet Bernacet, *Center Co-Director*
University of Puerto Rico, 809.765.5170

Puerto Rico School Site
UPR Lab H.S.

* * * * * * * * * * * *

Pilot Sites
Site Coordinator and Lead Teacher
Fox Lane H.S., New York, Arthur Eisenkraft
Georgetown Day School, Washington, D.C., William George
Flathead H.S., Montana, Gary Freebury
Clinton H.S., New York, John Laffan*

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Bill G. Aldridge
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Dorothy L. Gabel
Indiana University

Stephen G. Druger
Northwestern University

George Miller
University of California-Irvine

National Science Education Standard—Physical Science

Motions and Forces

Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces, and moving magnets produce electric forces. These effects help students to understand electric motors and generators.

Teacher Materials

Learning Sequence Item:

1035

Magnetic Induction

January 1997
Adapted by: Stephen Druger

Electromagnetism: Moving Charges and Magnetic Forces. Students should learn that a moving magnet produces electricity in a conductor when either the magnet or the conductor moves, but that this occurs only for certain orientations (*Physics, A Framework for High School Science Education, p. 26*).

Contents

This micro-unit was adapted by **Stephen Druger** (Northwestern University, Evanston, Ill.)

1035

Learning Sequence

Electromagnetism: Moving Charges and Magnetic Forces. Students should learn that a moving magnet produces electricity in a conductor when either the magnet or the conductor moves, but that this occurs only for certain orientations (*Physics, A Framework for High School Science Education, p. 26*).

Science as Inquiry	Science and Technology	Science in Personal and Social Perspectives	History and Nature of Science
A Discovery on Both Sides of the Atlantic **Activity 1** Getting an Angle on Electromagnetism **Activity 2** Turning On an Electromagnet **Activity 3** The Electric Generator **Activity 4** An Old-Fashioned Practical Application **Activity 5** Making Currents **Assessment 1** A Rotating Magnet **Assessment 2** Induced Currents and Voltages **Assessment 3** Magnetic Brakes **Assessment 4**	The Electric Generator **Activity 4** An Old-Fashioned Practical Application **Activity 5**		A Discovery on Both Sides of the Atlantic **Activity 1**

Suggested Sequence of Events

Event #1

Lab Activity

1. A Discovery on Both Sides of the Atlantic (60 minutes)

Event #2

Lab Activity

2. Getting an Angle on Electromagnetism (40 minutes)

Event #3

Lab Activity

3. Turning On an Electromagnet (40 minutes)

Event #4

Lab Activity

4. The Electric Generator (30 minutes)

Event #5

Lab Activity

5. An Old-Fashioned Practical Application (40 minutes)

Event #6

Readings from Science as Inquiry, Science and Technology, Science in Personal and Social Perspectives, and History and Nature of Science

Suggested readings:

Williams, L. Pearce, "Michael Faraday." *The Physics Teacher* 3(2): 64–70, 1965.
Andrews, C.L., "Joseph Henry." *The Physics Teacher* 3(1): 13–17, 1965.
Jewett, J.W., Jr. , "Electromagnetic Induction." Chapter 23 in *Physics Begins with an M . . .: Mysteries, Magic, and Myth.* Boston: Allyn and Bacon, A Division of Simon and Schuster, Inc.,1994.

Assessment items are at the back of this volume.

Assessment Recommendations

This teacher materials packet contains a few items suggested for classroom assessment. Often, three types of items are included. Some have been tested and reviewed, but not all.

1. Multiple choice questions accompanied by short essays, called justification, that allow teachers to find out if students really understand their selections on the multiple choice.

2. Open-ended questions asking for essay responses.

3. Suggestions for performance tasks, usually including laboratory work, questions to be answered, data to be graphed and processed, and inferences to be made. Some tasks include proposals for student design of such tasks. These may sometimes closely resemble a good laboratory task, since the best types of laboratories are assessing student skills and performance at all times. Special assessment tasks will not be needed if measures such as questions, tabulations, graphs, calculations, etc., are incorporated into regular lab activities.

Teachers are encouraged to make changes in these items to suit their own classroom situations and to develop further items of their own, hopefully finding inspiration in the models we have provided. We hope you may consider adding your best items to our pool. We also will be very pleased to hear of proposed revisions to our items when you think they are needed.

Science as Inquiry/
History and Nature of Science

A Discovery on Both Sides of the Atlantic

Electric currents can produce magnetism, but can magnetism produce electric currents?

Overview:

Students observe that a magnet moved into a coil of wire produces an electric current. They observe that a current is induced when the magnet moves but not when it is merely nearby. They also observe that the direction of the current is reversed either when the north and south poles of the magnet are interchanged or when the direction of motion of the magnet is reversed.

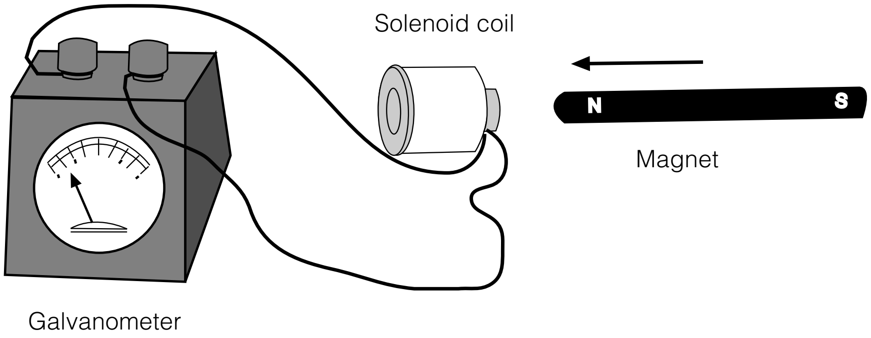
Materials:

Per lab group:

bar magnet
magnet solenoid coil (often available as surplus)
insulated wire
galvanometer

Procedure:

Have students connect the solenoid to the galvanometer and hold the bar magnet in front of the solenoid so that the axes of the solenoid and the magnet coincide (see figure). They should then watch for a significant deflection of the galvanometer, indicating a current, in four cases: (a) when the bar magnet is held stationary in front of the coil, (b) when the bar magnet is being moved into the coil, (c) when the bar magnet is at rest inside the coil, and (d) when the bar magnet is being moved away from the coil.



Students then reverse the direction of the magnet, interchanging north and south poles, and repeat their observations. They find moving the bar magnet and interchanging the poles reverses the direction of the current.

Next, students compare a rapid movement of the magnet into or out of the coil with a slow one, noting that the rapid motion produces a much stronger response.

Finally, have students orient the bar magnet so that its axis is perpendicular to the axis of the solenoid and move the bar magnet directly toward (or away from) the side of the solenoid. They observe that little if any current is produced this way. For best results, they should bring the magnet no closer than 5 cm or so to the side of the solenoid and repeat this same motion at the same speed and at the same distance to bring it directly toward the circular front of the solenoid.

Background:

A changing magnetic field, according to Faraday's law, produces an electric field. Bringing a bar magnet closer to a single loop of wire connected to a voltmeter at both ends changes the magnetic field within the loop, and the changing magnetic field should produce an induced voltage.

The precise relationship is that the induced electromotive force (emf), meaning essentially the induced voltage, is the time rate of change of the magnetic flux, where the magnetic flux is the area of the loop multiplied by the average component of the magnetic field **B** perpendicular to the area. (For a coil of N turns of wire with the same flux through each, the induced emf would be increased by a factor of N.) The "average" referred to is to be taken over the area at a given instant of time.[1] The direction of the induced electric field, according to Lenz's law, is always such that the current it would produce (and the resulting magnetic flux) would oppose the change in flux through the circuit.

With the magnet facing the side of the solenoid, the magnetic field has only a small component perpendicular to the cross-sectional area of any turn of wire. Moving the magnet directly toward the side of the magnetic solenoid coil would therefore involve little change in flux and produce little induced current. In practice a small current is still induced, since the required relative orientation to produce zero total induced emf is not achieved all along the coil, especially if the magnet is brought too close to the end of the solenoid. While students are likely be familiar with some conceptual aspects of a magnetic field, the precise mathematical definition of the magnetic field is intended for grade 11.

A problem of nomenclature deserves to be mentioned here. The vector quantity **B** describing the magnetic field in direct relation to magnetic forces and to Faraday's law probably deserves to be called the "magnetic field strength" or "magnetic field," but those terms, for historical reasons, are assigned

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[1] For a nonplanar circuit loop with a nonconstant magnetic field, the flux is correctly calculated by constructing any reasonable surface whose edges are the circuit, dividing up the bounded surface into numerous small surface elements, calculating the component of B perpendicular to each surface element multiplied by its small area, taking the flux to be the sum of these contributions, and in the end evaluating the limiting value of such a sum when the largest element has infinitesimal extent. The properties of the magnetic field assure that the result will be independent of how the bounded surface used in calculating the flux was chosen.

instead to the related magnetic field quantity **H** that enters directly in Ampère’s law. Outside any ferromagnetic material, the two fields **B** and **H** are proportional to each other. The same is true even in some “soft” ferromagnetic materials (such as magnetically “soft” iron), although not *inside* ferromagnets that might be permanently magnetized. Moreover, in the Student Materials magnetic fields are discussed only at a descriptive level rather than a quantitative level at this point. Therefore, little confusion seems likely to result from referring descriptively merely to the “magnetic field,” although it is generally **B** that is intended as the directly relevant physical quantity in connection with Faraday’s law and magnetic forces on moving charges.

The essential point of this activity is to demonstrate to students that the current is induced by moving the magnet, not by the mere presence of the magnet itself. Activity 3 demonstrates that this results from the change in the magnetic field within the coil.

The solenoid used in this activity can be a surplus magnet coil, or a spool of magnet wire available from retailers such as Radio Shack, or simply insulated wire or magnet wire wound around a cardboard mailing cylinder. Many galvanometers are sensitive enough to show a response even if the solenoid consists of only a few turns of wire. Some electronic multi-meters (e.g., the self-scaling multimeter sold by Radio Shack) are sensitive enough when used as a voltmeter to replace the galvanometer in this activity, but the time required for the meter to readjust to zero millivolts just after the magnet has moved can easily lead students to wrong conclusions in the present activity.

Adapted from: none

Teacher Sheet

Science as Inquiry

Getting an Angle on Electromagnetism

Is it because the magnet moved?

Overview:

Here students observe that moving a coil closer to or farther away from a nearby magnet has the same effect in producing an electric current as does moving the magnet while holding the coil fixed in position. They also observe that merely rotating the coil in front of the magnet, so that the two axes change from being aligned to being perpendicular, also produces a current in the coil.

Materials:

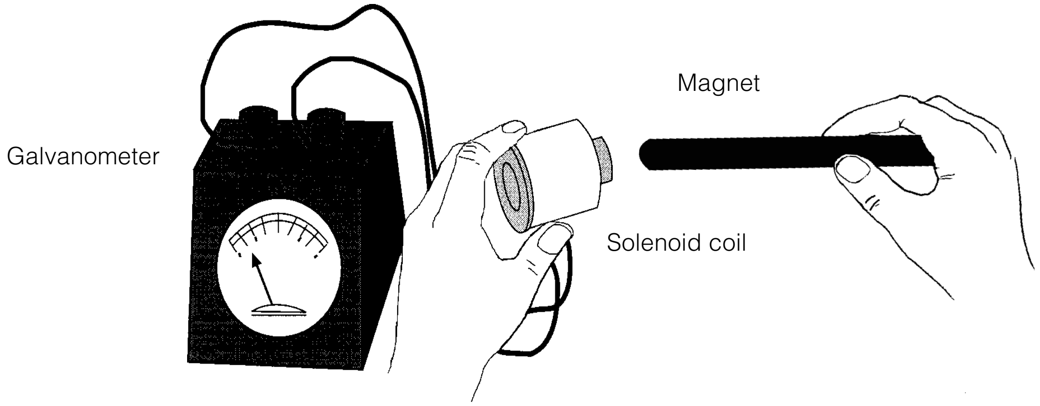
Per lab group:

bar magnet
magnet solenoid coil (often available as surplus)
insulated wire
galvanometer

Procedure:

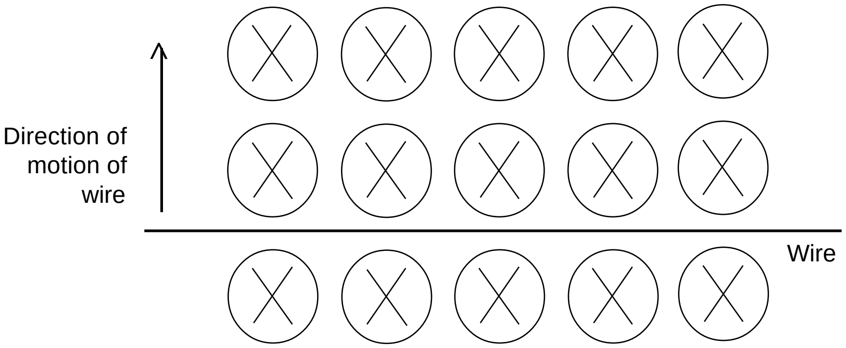
Students connect the galvanometer to the coil as in Activity 1 and try moving the coil toward and away from the magnet with the magnet held at rest. They observe that this, too, produces a current in the galvanometer, but only when the coil is moved, not when it is at rest near the magnet.

With the magnet held in front of the center of the horizontal solenoid, students should try to rotate the solenoid coil without changing the average distance to the magnet, so that the axes of the solenoid and the magnet are changed from being parallel to being perpendicular. They observe that this produces a current when the rotation occurs but not when the solenoid is merely held at rest. By rotating the solenoid back, they observe that the induced current is then in the opposite direction.



Background:

The effect of a magnetic field on a wire moving through it may be explained in a way that might appear at first glance to be unrelated to Faraday's law: An electric charge moving through a magnetic field experiences a velocity-dependent force perpendicular to both the field and the instantaneous velocity **v** of the charged particle. Thus, as illustrated below, when a metallic wire is moving through a magnetic **B** field perpendicular to the wire, the positive charges and the relatively free conduction electrons each experience forces in opposite directions along the wire, providing an "electromotive force" (or "induced voltage") that produces a current of conduction electrons[2].



Magnetic field (pointing down into the page)

If a circular loop were being moved through a spatially uniform magnetic field in this way, the forces on electrons at diametrically opposite locations on the loop would cancel in attempting to produce a clockwise current and an equal counterclockwise current—to produce a net current, the magnetic field cannot be both spatially uniform and constant in time. But moving the loop through a spatially nonuniform magnetic field would ordinarily produce a nonzero time rate of change of the magnetic flux, consistent with the conditions under which Faraday's law implies an induced electromotive force. It can indeed be shown from Maxwell's equations of electromagnetic theory that the induced electromotive force calculated from the Lorentz force on the charge carriers agrees with the electromotive force predicted by Faraday's law (perhaps not surprisingly, since Faraday's law is one the four Maxwell equations that apply simultaneously in describing the behavior of magnetic and electric fields).

The equivalence between moving the loop closer to the magnet and moving the magnet closer to the loop is indeed implied by the principle of relativity, which states that the laws of physics are the same in all inertial frames. Viewed from the magnet's frame of reference, the wire is moving when the magnet is

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[2] The Lorentz force is given in terms of the electric field **E** and magnetic field **B** at each point (in mks units) by $\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ for charge q. The cross product of two vectors, such as $\mathbf{v} \times \mathbf{B}$, is perpendicular to both **v** and **B**.

stationary, but viewed from a frame of reference fixed in the coil the magnet is moving. The two situations must be physically equivalent for relative motion at a constant velocity.

The main point of this activity is for students to observe that the relative motions of the magnet and the coil produce qualitatively the same effect whether it is the magnet or the coil that moves. Neither the principle of relativity as it would apply to electromagnetism nor the Lorentz force on a moving charge is likely to be available as an explanation for students at this point unless they already have carried out such activities as observing the deflection of a beam of electrons when a magnet is brought near a cathode ray tube (something you should not try on a color TV, by the way, because permanent damage to the picture tube can result).

Both explanations, in terms of the Lorentz force or in terms of Faraday's law, involve the direction of the applied magnetic field. In Faraday's law, the change in magnetic flux is the area of the current loop times the average **B** field component *perpendicular* to the area of the current loop, and the time rate of change of the magnetic flux gives the induced emf. Therefore, if either the coil or the magnet is rotated so that the field is no longer perpendicular to the cross section of the coil, this rotation changes the magnetic flux and thereby induces a current to flow through the galvanometer.

Adapted from: none

Teacher Sheet

Science as Inquiry

Turning On an Electromagnet

Can we induce a current without moving the coil on the magnet?

Overview:

In this activity students observe that a current can also be induced to flow by merely changing the magnetic field within the coil, without moving either the magnet or the coil. Instead, the magnetic field is turned on and off using a battery-driven coil around an iron bar as an electromagnet.

Materials:

Per lab group:

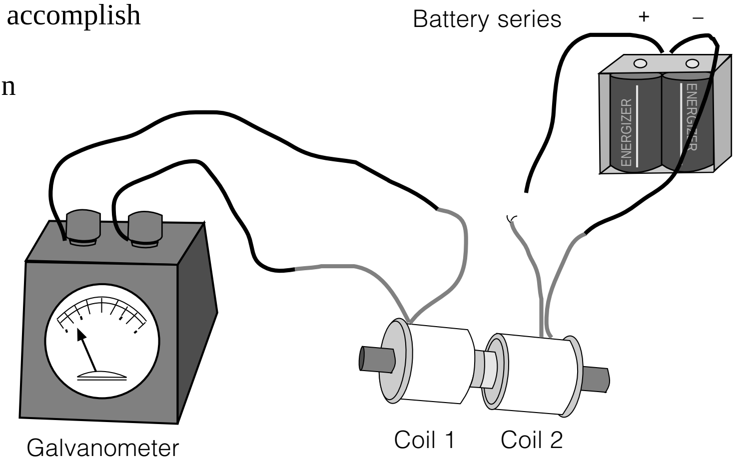
3–6 volt d.c. power source (e.g., AA, C, or D cells in series and matching battery holder)
iron rod (to fit inside solenoid)
aluminum rod (of similar size)
magnet solenoid coils (often available as surplus), 2
galvanometer
paper clips (iron)
insulated wire
insulating electrical tape

Procedure:

Have students connect one solenoid coil (coil 1) to the galvanometer and the second coil (coil 2) to the battery, leaving one contact to the battery unconnected so they can turn the current on and off by touching the wire to the contact. (Alternatively, an on/off switch may be included in the circuit to accomplish this.)

With the battery-connected coil placed on the iron rod, students test the ability of the rod to act as a magnet by attracting small iron objects, such as paper clips, with and without the current flowing. They compare this with the effectiveness of an aluminum rod used in same way.

Next, the first coil (coil 1) is also placed on the iron rod (see figure), and the current to the second coil is turned



on, left on for a second or two, and then turned off. Students should observe that there is a brief (i.e., “transient”) current in the first coil immediately after the battery current in the second coil is turned on or off, but that the galvanometer settles down to a reading of zero current in the first coil when there is either a steady current or no current produced by the battery in the second coil. Students then reverse the flow of the battery current by interchanging which wire connects with which battery terminal, observing that this reverses the direction of the induced transient current.

Finally, students try the same procedure again, but this time they should place the coils next to each other without the iron rod (perhaps with a pencil or other nonmagnetic object through their centers to hold the coils in position). A far smaller but definitely observable response is seen in the galvanometer circuit when the battery-driven circuit is connected or disconnected.

Background:

Care should be taken that students do not inadvertently connect the battery wires to the galvanometer at any time because of the damage likely to result. It is also advisable to test the response of the equipment to be used beforehand, since the galvanometer response with the iron rod inserted can easily be much stronger than desired. Use lower battery voltage, or place a flashlight bulb in series in the battery-powered circuit, to reduce the battery-driven current in that part of the activity if necessary.

Simply turning an electromagnet on or off is one more way to change the magnetic flux through the solenoid connected to the galvanometer and to thereby produce a current. This is accomplished in the present activity by using the coil connected to the battery as the source of the magnetic field. Since the magnetic flux increases in the coil connected to the galvanometer when the current is turned on and decreases when the current is turned off, the induced current in the two cases is in opposite directions.

Changing the direction of the current by interchanging battery contacts reverses the direction of the magnetic field. This reverses the sense of the change in flux (going from positive to zero when the current is turned off in one case and negative to zero when the current is turned off in the other). The result again is to reverse the direction of the induced current flow. In each case, in the period while the battery is left connected to the first coil, the galvanometer reading for the second coil will be seen to die down to zero with no induced current flowing, since there is no changing magnetic field and hence no time rate of change of magnetic flux.

The presence of the iron rod increases the magnetic field (meaning increasing **B**) for a given current flowing through the coil connected to the battery. This implies a much greater change in **B** field in the coil when the current is turned off (or turned on), producing a greater induced emf and greater current. However, even if the iron rod is absent, so that there is nothing present to be magnetized, the change in current flow through the first coil still produces a changing magnetic field that induces a detectable, though much smaller, current to flow in the second coil.

A transformer is an example of a useful practical application of the principles explored in this activity. The a.c. input current is continuously changing in the primary winding of magnet wire around an iron core. This produces a changing magnetic flux within a second coil (the secondary winding) around the same core, resulting in an induced emf. If the number of turns of primary winding were the same as the number of turns in the secondary, and if ideally the flux were the same through the two coils, then the induced voltage would be the same as the driving voltage. If however there were N times as many turns in the secondary winding, this would be the same as having N such secondary windings identical to the primary winding in series, each with an induced voltage the same as in the primary coil, thus giving N times as great a voltage in the secondary winding of the transformer. It follows that ideally the ratio of the induced voltage to the driving voltage is the ratio of the number of turns of wire in the primary and secondary coil, so that the relative number of turns in the primary and secondary coils of a transformer determines whether the transformer increases or decreases the voltage and by what ratio it does this.

Adapted from: none

Science as Inquiry/
Science and Technology

The Electric Generator

Rotating a coil of wire between magnetic poles

Overview:

In this activity students examine the construction and means of functioning of a simple hand-cranked generator used to light an incandescent bulb, acquiring some feeling for how much power it takes to light a bulb and how the operation of the generator can be explained in terms of other activities in this unit.

Materials:

Per lab group:

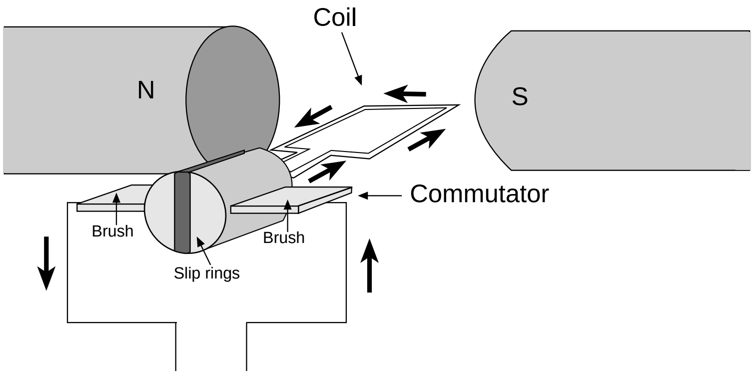
hand-cranked electric generator hooked up to light bulb

Procedure:

Students examine the hand-cranked generator to see how it is constructed, noting especially that there is a coil of wire that rotates in the space between the poles of a magnet. In some available generators, it is possible to see how the commutator is constructed to interchange which external wire is connected with each end of the coil when the coil is rotated through 180°. With the generator connected to the bulb, students try turning the handle, noting that it takes a surprising amount of work to light the bulb significantly and that the brightness of the bulb increases with increasing rate of rotation.

Background:

The hand-cranked generator typically used for classroom demonstration purposes consists of a coil that rotates through the field of a magnet, so that its flux is constantly changing by reason of the continuously changing angle between the magnetic field and a line perpendicular to the area of the loop. From the perspective of the rotating coil of wire, the magnetic field that was increasing up out of the coil is increasing in the opposite direction (relative to the coil) half of a complete rotation later. This means that the induced current flowing through the coil will be reversed. Arranging the contacts as shown in the following figure, in the form of a commutator that reverses which external wire is connected to which



Hand-cranked generator

lead of the rotating coil when the current will reverse itself, produces an output of consistently nonnegative voltage on one wire and nonpositive voltage on the other, even if the voltage is not truly constant except on average.

Students are likely to be surprised by the amount of effort it takes to light the bulb. It is therefore desirable to know beforehand the power rating of the bulb in watts to give students an idea of how this relates to the power consumption of typical electrical light bulbs in their homes.

Limitations on equipment availability might require having the entire class take turns lighting the bulb on one or two setups. If possible, students should observe how the commutator is constructed, but many hand-cranked generators available for classroom use do not have the commutator easily visible.

Variations:

Measure the power produced to light the bulb by having an ammeter in series with the bulb and a voltmeter to measure the potential difference across the bulb contacts. The power is then the voltage multiplied by the current. (Caution: somewhat incorrect results could be obtained by merely using a multimeter to measure the voltage output, and then measuring the resistance of the bulb, because the tungsten bulb filament has much lower electrical resistance when unheated.)

Adapted from: none

Science as Inquiry/
Science and Technology

An Old-Fashioned Practical Application

Faraday's law in the movies

Overview:

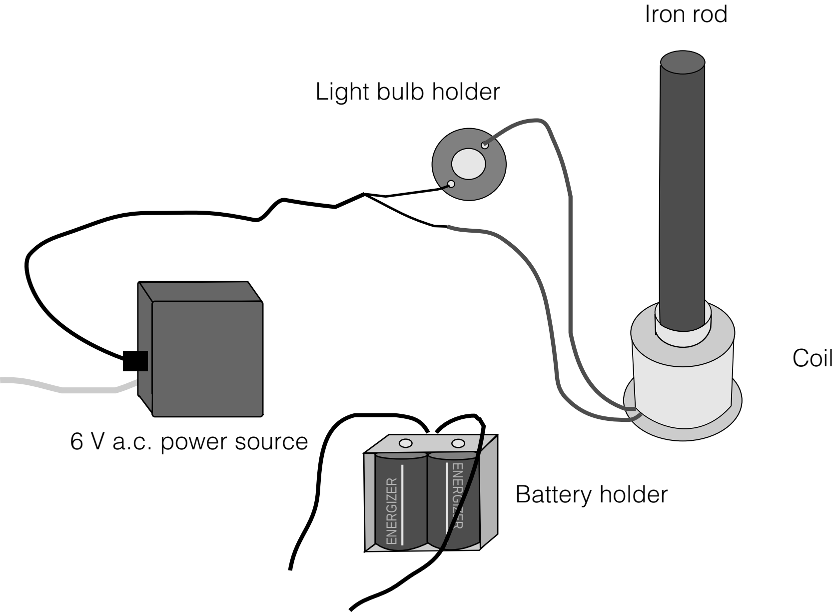
In this activity, students observe how inserting and removing an iron rod into and from a solenoid connected to a light bulb controls the brightness of the bulb when the circuit is driven by an a.c. power source, but not when driven by batteries. They thereby are led to analyze how the changing magnetic field in the a.c. case induces an electromotive force in the coil itself that impedes the alternating current. This is a method once commonly used for dimming theater lights.

Materials:

Per lab group:

flashlight bulb and socket unit
magnetic solenoid coil
iron rod (to fit into center of solenoid)
6 volt a.c. power supply (e.g., surplus a.c. transformer unit)
3–6 volt d.c. power source (e.g., AA, C, or D cells in
  series and matching battery holder)
insulated wire
wire cutters

Procedure:



Have students connect the solenoid to the light bulb and the a.c. power supply with the iron rod inserted into the center of the solenoid (see figure). They observe how the light brightens when the rod is removed and dims when it is inserted again. By holding a small iron paper clip so its end is almost touching the end of the rod inserted in the solenoid, they can feel the vibrations induced by the changing magnetization of the rod. They should repeat this experiment using a d.c. power source (preferably batteries), observing that removing the iron rod from the solenoid now has no effect on the intensity of the light bulb and that paper clips are simply consistently attracted, without showing the characteristic 120-Hz vibration.

Background:

Driving the solenoid with a.c. current causes the north and south poles of the magnetic field to interchange once every 1/120 second, undergoing a complete cycle of changing the direction of the field and changing it back at the rate of 60 times per second.

Placing the iron rod inside the solenoid increases the magnetic field **B**, and therefore the magnetic flux, produced by a given current. For an oscillating (a.c.) current flowing through the solenoid wire, this increases the value of the maximum **B** field when it points to the right and its maximum when pointing to the left a half of a cycle later, so that the time rate of change of the magnetic field, and the time rate of change of the magnetic flux, are increased.

The changing magnetic flux in any coil of wire wound around the iron bar provides an electromotive force in the coil. This applies also to the same solenoid that is producing the magnetic field. According to Lenz's law, the resulting emf is one that would tend to oppose the change in magnetic flux.

On average over a cycle, this impedes the flow of current. Because changes in flux are enhanced by inserting the iron rod, its effect in reducing the current flowing through the bulb is enhanced. The result is that the bulb does not light as brightly with the bar in the solenoid. This phenomenon could more adequately be described in terms of the impedance of the circuit, but here we are interested in its direct relation to Faraday's law.

The 60-Hz alternation in the direction of the magnetic field compels the field to pass through a value of zero 120 times per second. The resulting rapid on/off character of the field is easily felt as a vibration induced in a paper clip held in front of and nearly touching the iron rod. It might be good to remind students of the humming sound sometimes produced by this same mechanism in electrical devices driven by a.c. household electrical power.

The steady d.c. current from a battery power source produces a constant magnetization of the rod with, therefore, no induced emf. The light bulb intensity in this case no longer depends on the position of the rod, and the iron rod magnetized by the constant current in the solenoid simply consistently attracts the paper clip held close to it, without producing any vibration.

Adapted from:
Epstein, L.C., *Thinking Physics Is Gedanken Physics*. San Francisco: Insight Press, 1979.
Jewett, J.W., Jr., *Physics Begins with an M . . . Mysteries, Magic, and Myth*. Boston: Allyn and Bacon, 1994.

Science as Inquiry

Making Currents

Item:

A bar magnet with its north pole pointed toward the cross-sectional area of a coil of wire is moved smoothly back and forth toward the coil at a rate of one complete cycle of motion per second. Each end of the coil is connected to a galvanometer. Which of the following is true?

A. The galvanometer will register a current in one direction only, but only when the magnet is moving.
B. The current will be in the same direction only but is produced each time the magnet stops moving in order to reverse its direction of motion.
C. The current flows in opposite directions when the coil moves toward rather than away from the coil.
D. The current flows in opposite directions but is produced only when the magnet stops to reverse its direction of motion.

Explain your reasoning.

Answer:

C. Students are expected to explain that the magnetic field in the coil increases when the magnet is moving closer and decreases when it is moving away. It is the change in magnetic field rather than merely having the magnetic field present that induces a current in the coil, doing so in opposite directions if the field is increasing rather than decreasing.

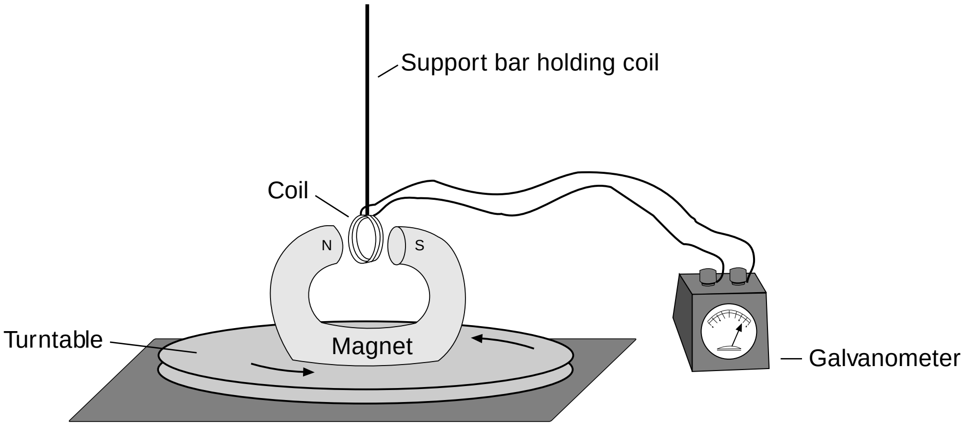
Alternatively, students also may note that in the activities they observed a current to be produced in one direction when they brought the magnet toward the coil and in the opposite direction when they pulled the magnet away, but that no current was produced when the magnet was merely held in position.

Science as Inquiry

A Rotating Magnet

Item:

A large horseshoe-shaped magnet is mounted on a turntable and is kept rotating. Explain what response you would expect to see, and why, if a device capable of detecting current flow is connected to the coil



Answer:

A current would be flowing because of the constantly changing relative directions of the coil and the magnet (or, more specifically, the change in the component of magnetic field perpendicular to the face of the coil). The current would change directions and reverse again during each rotation.

Such a change was seen in the activities to produce an induced current if the coil was moving. As the coil became closer to being perpendicular to the direction of the magnetic field the induced current was in one direction. As the coil moved further from being perpendicular, as it was later during rotation, the induced current was in the opposite direction.

Science as Inquiry

Induced Currents and Voltages

Item:

Two coils, each consisting of many turns of insulated wire, are wound around the same large iron ring. Switching on current from a battery in the first coil and then switching it off:

A. Will induce a voltage in the second coil when the current is turned on in the first, but not when it is turned off.
B. In both cases will induce voltages of the opposite signs in the second coil.
C. In both cases will induce voltages of the same sign in the second coil.
D. Induce currents to flow in the second coil without inducing a voltage difference.

Explain your reasoning.

Answer:

B. Changing the current in the first coil changes the magnetic field (and magnetization) of the iron ring, and changing the magnetic field through the second coil causes a current to flow through the coil. Currents flow in opposite directions when the magnetic field increases or decreases, as was seen in the activities carried out. That electromagnetic forces act to make the current flow means that there is an induced voltage difference, making (d) incorrect.

Science as Inquiry

Magnetic Brakes

Item:

If a magnet that is very strongly magnetized for its weight is allowed to fall freely through a plastic tube, it will accelerate at 9.8 m/s^2. When dropped through a copper tube of exactly the same diameter, however, it will fall noticeably more slowly.

What could explain this strange effect? And how could you use the *principle* involved (not necessarily using the same kind of magnet) to design a device for slowing down a rotating wheel at will without using the kind of automobile brake pads that wear out and must be replaced regularly?

Answer:

(Note: Magnets of this strength are commonly sold as “rare earth magnets” or “neodymium magnets” by scientific supply sources.)

The magnet falling past the conducting copper walls of the tube induces currents to flow as it falls. The currents in turn produce their own magnetic field, which is in a direction opposite to the change in field that produced them. The resulting forces slow the falling magnet. The effect cannot occur in the plastic tube since it is not a good electrical conductor.

Students might respond to the second part by proposing that the rotating wheel could have a second electrically conducting wheel mechanically connected to it, and that a lever or motor might be used to bring a strong magnet close to the conducting wheel whenever its speed needs to be decreased. Equivalently, an electromagnet in fixed position close to the conducting wheel could be switched on. In both cases the magnet near the moving conductor would cause currents to flow, inducing magnetic fields that oppose the motion of the wheel (meanwhile converting the mechanical energy to heat as the induced currents flow in the conducting wheel).

Another possibility is that an electric generator be coupled to the wheel. The generator contains a coil that rotates through a magnet and offers increased resistance to rotation when the current that tends to be produced by the generator is actually allowed to flow by turning on a switch. (This last answer offers the practical advantage that the current could be used to recharge a battery, thereby storing some of the kinetic energy in a recoverable form.)

Consumables

Item	Quantity per lab group	Activity
insulated electrical tape	—	3
insulated wire	—	1, 2, 3, 5

Nonconsumables

Item	Quantity per lab group	Activity
a.c. power supply, 6 volt (e.g., surplus a.c. transformer unit)	1	5
aluminum rod (same size as iron rod below)	1	3
bar magnet	1	1, 2
d.c. power supply, 3–6 volt (e.g, AA, C, or D cells in series and matching battery holder)	1	5
flashlight bulb and socket unit	1	5
galvanometer	1	1, 2, 3
generator (hand-cranked) hooked up to light bulb	1	4
iron rod	1	3, 5
magnet solenoid coil (often available as surplus)	1	1, 2, 5
magnet solenoid coils (often available as surplus)	2	3
paper clips (iron)	—	3
wire cutters	1	5

Key to activities:

1 A Discovery on Both Sides of the Atlantic
2. Getting an Angle on Electromagnetism
3. Turning On an Electromagnet
4. The Electric Generator
5. An Old-Fashioned Practical Application

Activity Sources

Epstein, L.C., *Thinking Physics Is Gedanken Physics.* San Francisco: Insight Press, 1979.
Jewett, J.W., Jr., *Physics Begins with an M . . . Mysteries, Magic, and Myth*. Boston: Allyn and Bacon, 1994.