CHARGING AHEAD

An Introduction to Electromagnetism

By Larry E. Schafer

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Contents

Acknowledgments

Larry E. Schafer, the author of *Charging Ahead: An Introduction to Electromagnetism*, teaches physical science and elementary science methods courses at Syracuse University, where he has also chaired teaching and leadership programs. His previous work for the National Science Teachers Association (NSTA) was the student-activity book *Taking Charge: An Introduction to Electricity* (1992, 2000). He has directed many funded projects designed to help teachers improve the science education in their schools, has worked with the New York State Education Department to create a statewide system of elementary science mentors, and has co-authored books for middle school science teachers and their students.

The book's reviewers were Chris Emery, a physics teacher at Amherst Regional High School, Amherst, Massachusetts; Dale Rosene, a science teacher at Marshall Middle School in Marshall, Michigan; Daryl Taylor, a physics teacher at Williamstown High School in Williamstown, New Jersey; and Ted Willard, senior program associate at the American Association for the Advancement of Science's Project 2061.

The activities in the book were field-tested by Mark M. Buesing and Suzanne Torrence, both physics teachers at Libertyville High School, Libertyville, Illinois, and Jay Zimmerman, a physics teacher at Brookfield Center High School, Brookfield, Wisconsin.

The book's figures were created by Kim Alberto, Linda Olliver, and Tracey Shipley, from originals by Larry Schafer.

The NSTA project editors for *Charging Ahead: An Introduction to Electromagnetism* were Judy Cusick and Anne Early. Linda Olliver designed the book and the cover. Catherine Lorrain-Hale coordinated production and printing of the book.

Overview

Charging Ahead: An Introduction to Electromagnetism is a set of hands-on activities designed to help teachers introduce middle-level and general high school students to electromagnetism, one of the most fascinating and life-changing phenomenon humankind has witnessed. In 1820, Hans Christian Oersted, a Danish physicist and schoolteacher, discovered that an electrical current produces magnetism. Little did he know that his discovery would have an impact on modern day lives in profound ways: that electrical motors would start cars, turn CDs and disk drives, run can openers, food processors, refrigerators, and clocks, operate pumps for maintaining life support, and run nearly all of the machines that produce and manufacture the many goods upon which we rely. Little did he know that this connection between electricity and magnetism would lead others (Michael Faraday and Joseph Henry) to discover ways of creating electricity from motion and magnetism and in so doing make it possible for human beings the world over to move about, heat and light their environments, and instantly and conveniently communicate.

Charging Ahead uses readily available materials to introduce students to electromagnetism, to the factors that determine the magnetic strength of electrical coils, to the application of electromagnetism in the construction of an electrical motor, and to the production of electricity through the construction of a generator. Throughout *Charging Ahead*, students are introduced to historical perspectives and to technological applications (circuit breakers, mag-lev trains, superconducting generators, etc.) of electromagnetism.

SCILINKS
THE WORLD'S A CLICK AWAY

Topic: electromagnetism
Go To: *www.scilinks.org*
Code: CH001

Topic: Hans Christian Oersted
Go To: *www.scilinks.org*
Code: CH002

Fitting *Charging Ahead* into Your Curriculum

Charging Ahead is a companion guide to NSTA's *Taking Charge: An Introduction to Electricity.* While students would benefit from experiencing the activities in *Taking Charge,* it is not necessary that students complete *Taking Charge* before attempting the activities in this book. Students will nevertheless need a basic understanding of electrical circuits to understand the ideas presented in *Charging Ahead.*

Key relationships are developed from what students experience in the activities. Abstract formulations and mathematical descriptions, although important, are minimized in *Charging Ahead*. The activities therefore serve as "end points" for middle school students and "starting points" for high school students who are on the path toward understanding abstract formulations of electromagnetism and electromagnetic induction.

Charging Ahead addresses the *National Science Education Standards* in a number of ways. Students learn about energy forms and energy transfer, engineering design and troubleshooting, and science-technology relationships. Students are challenged to solve problems and to think critically and creatively. See p. xii for a Guide to Relevant National Science Education Content Standards.

Organization

The activities in *Charging Ahead* use an inquiry approach to guide student understanding of the concept goals. Each student activity includes an introduction, a description of the materials needed, a statement of what students will learn, and procedures to follow. None of the activities require "high tech" equipment. Wires, flashlight batteries and bulbs, magnets, and magnetic compasses are the basic materials used in the activities.

The procedure section of each activity is designed so that students can perform the activity without the teacher's constant involvement and direction. The procedure section presents students with problems to solve, questions to answer, and tasks to accomplish. It should be clear that students will occasionally face difficulty as they work through the procedures. Underlying the design of these activities is the idea that students will more meaningfully understand the concepts and relationships if they are challenged to figure some things out for themselves.

Each activity is accompanied by a teacher's guide to the activity. The guide is written so that the teacher acquires a brief overview of what will happen in the activity, directions for the construction of equipment and/or the selection of materials, time management recommendations, cautionary notes, ideas for extended activities, and answers to questions.

Assessment Methods

The teacher can use both formative and summative assessment with *Charging Ahead*. The answers that students give to the questions in each activity provide a formative record of their thinking and learning—showing students and the teacher what students understand, what is still fuzzy or missing, and whether students can now use what they know. The suggestions for further study at the end of each activity can be used to extend—and then test—students' learning. These extensions are authentic applications of the concepts students have just investigated. You may wish to build an assessment rubric for one or more of the extensions and use it as a summative assessment of your students' mastery of electromagnetism concepts.

Special Considerations

The first and second activities are fairly straightforward. They call on students to examine the relationship between electrical flow and magnetism and investigate how to increase the magnetic forces created by a current-carrying wire. The third and fourth activities challenge students to build an electric motor and an electric generator. Electrical motors and generators built from readily available materials are somewhat temperamental. While each design has been thoroughly tested (75 percent of sixth graders had an electrical motor going in 30 minutes), neither students nor teachers should expect success without some "troubleshooting." Success can be greatly improved by using the recommended materials and by carefully following the directions and suggestions. The need to "troubleshoot" to get things to work should be taken as an opportunity to help students value the creative and persistent work done by engineers who design and debug the devices that reliably work.

Initial construction of motor and generator parts will take some time. Students can help with the construction of those parts. Once the parts are constructed, they can be used repeatedly by different classes of students.

As a consequence of taking part in electricity activities, some students may become very interested in motors, generators, and other electrical devices. They may be inclined to examine these devices on their own in backyards and basements. The investigation of household electrical devices can lead to serious injury. Therefore, please warn students that they should not investigate electrical devices without the help and supervision of a knowledgeable adult.

The activities in *Charging Ahead* are safe since small currents and voltages are used. Short circuits are sometimes used in the activities and these circuits can produce hot wires. Student should be warned to keep short circuits on only for short periods of time (a few seconds). In such short periods of time, the wires wil not significantly heat up nor will batteries quickly wear out.

The four *Charging Ahead* activities build on each other, connecting science content as described in the *Atlas of Science Literacy* map on p. xi. You can compare the concept goals at the start of each activity with your own instructional goals to determine which activity to use.

A Learning Map on Electricity and Magnetism

What Is This Map?

The map on page xi is a way of considering and organizing science content standards. The map uses the learning goals (or parts of them) of the American Association for the Advancement of Science's *Science for All Americans* (1989) and *Benchmarks for Science Literacy* (1993). Content standards from the *National Science Education Standards* (*NSES*) (National Research Council 1996) overlap nearly completely with those goals. Arrows connecting the goals imply that understanding one goal contributes to the understanding of another. Goals that deal with the same idea are organized into vertical "strands," with more sophisticated goals above simpler ones. Descriptive labels for the strands appear at the bottom of the map.

The science content on the map lists the ideas relevant to students' understanding of electricity and magnetism that are both important and learnable. Your students may well learn more, but will learn better after the basic science literacy described on the map has been achieved. This map traces the ideal development of electricity and magnetism knowledge from kindergarten to twelfth grade. Horizontal lines represent the level of grade appropriateness.

Charging Ahead provides instructional methods that primarily achieve learning goals for the map strand labeled "electromagnetic interactions." The map suggests what ideas students must have before trying to examine the relationship between electricity and magnetism. Unit activities as presented may not be sufficient for students to become proficient with some of the basic or extended ideas in the map strand; checking the progress of your students along the way will help you see how to adapt instruction. Unit activities may also touch on concepts outside of what the various science standards consider essential for basic science literacy. Therefore, you may decide to focus activities to make sure your core learning goals are achieved.

How Can I Use the Map?

An *Atlas* map is designed to help clarify the context of the benchmark or standard: where it comes from, where it leads, and how it relates to other standards. With the map as a guide, you can make sure your students have experience with the prerequisite learning, and you can actively draw students' attention to related content—getting their framework for learning ready!

In addition to using the map to plan instruction, you may wish to annotate the map with common student misconceptions to address or common accurate conceptions that you can invoke to dispel these misconceptions. Motivating questions that have worked for you, and phenomena to illustrate points, may also find a place on your annotated map.

The map can help you connect your instruction to your state science standards. As of this writing, 49 of the 50 states in the United States have developed their own standards, most modeled directly on the *National Science Education Standards* or the *Benchmarks for Science Literacy*. The correlation between the *NSES* and *Benchmarks* in science content is nearly 100 percent. So there is a unity of purpose and direction, if not quite a common language. Fortunately, the National Science Foundation, the Council of Chief State School Officers, and other groups have funded and developed websites to guide educators in correlating these national standards with their state goals (e.g., the ExplorAsource website at *www.explorasource.com/educator*. The websites of many state departments of education also provide this correlation service for educators.

The map can also provide a way to think about the design of student assessment . The goal of your summative assessment is to determine whether students can apply their learning to new situations—to show you, and to show themselves, that they have a new tool for understanding.

Are There Other Maps?

These maps are being copublished by AAAS and NSTA in a new two-volume work, *Atlas of Science Literacy*. The complete *Atlas* will contain nearly 100 similar maps on the major elementary and secondary basic science topics: gravity, cell functions, laws of motion, chemical reactions, ratios and proportionality, and more.

The connected learning goals displayed in *Charging Ahead* are only part of a map that is—at the time of this printing—subject to revision. As additional maps are developed and tested, they will be linked to the *Charging Ahead* page on the NSTA website and added to successive editions of *Charging Ahead*.

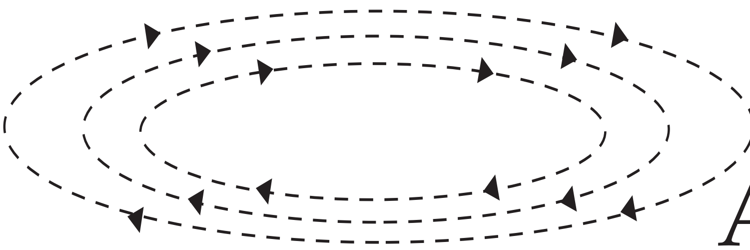
Map, Assessment, and the Constructivist Process

Use the map as an aid to your constructivist teaching methods, allowing students to recognize and integrate concepts—either those never learned or those incompletely remembered—into the big picture of why these concepts are useful to know.

Before you undertake any of the four activities in this book, it is important to know whether your students have mastered the principles in the map that lead to their current grade level. You may, for example, be surprised to learn that some of your high school juniors do not really understand that "magnets can be used to make some things move without being touched," a concept that, according to the strand map, should be mastered by grade three. Students may also have a mix of true and false understandings about electricity and magnetism as they begin the *Charging Ahead* activities. It may be wise to ascertain—perhaps by having each student do a "web" of everything he or she can think of about the term "magnetism" and reviewing those webs—to ensure that all students are starting with the basic information they need to build on in order to understand the concepts presented in these activities.

Activity 1

Student Worksheet



A Bonus from Electrical Flow—Magnetism

Background

When you create a closed circuit with a battery, electrons flow through the wires, the bulb lights up and gets hot, and the wires and battery warm up. Besides the chemical reactions going on inside the battery, is anything else happening? It is hard to tell unless you can use some detection device. In this investigation, you will use a compass to detect magnetism. You will use the compass to investigate the relationship between electrical flow and any magnetism that is produced from that flow.

Topic: electrical circuit
Go To: *www.scilinks.org*
Code: CH003

Topic: magnetic effect
Go To: *www.scilinks.org*
Code: CH004

Concept Goals

- A current-carrying wire produces a magnetic effect (deflects a compass needle) in the region around the wire. That magnetic effect is called *electromagnetism*.
- Electrons move along a wire from the negative end of the battery to the positive end of the battery.
- The direction of the electron flow in a wire determines the direction of the magnetic field around the wire.
- The strength of the magnetic influence (field) around a wire becomes less at greater distances from the wire.
- Magnetic fields (regions of magnetic influence) have direction and "strength."
- The direction of the magnetic field at a particular point in space is the direction a compass needle would point if the compass were located at that point.

Materials

For each group:

- *one ìDî battery (dry cell) and one battery holder*
- *one directional, magnetic compass with a needle that is free to move easily without sticking*
- *one 60-cm piece of #24 enamel-coated (insulated) wire (with sanded ends) or #22 plastic-coated wire (with stripped ends)*

■ A left hand is an effective model for showing the relationship between the direction of the magnetic field and the direction of electron flow.

Procedure

1 If you have not used a compass recently, you may want to refresh your memory. The colored or pointed end of the needle usually points approximately toward the Earth's geographic north. Hold the compass out in front of you, away from any metal objects, and note that the colored or pointed end of the needle always points in the same direction, even when you rotate the base or case of the compass.

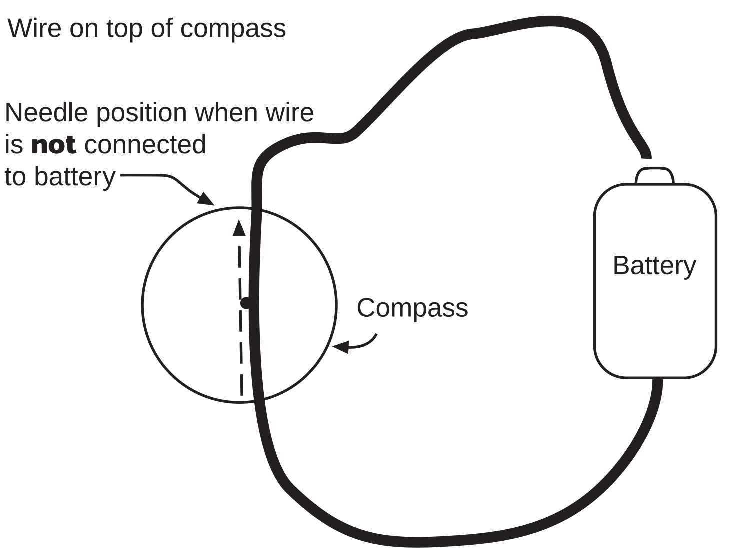
Move your compass close to an iron or steel object and notice that the compass needle is attracted to the object. It is important, therefore, to keep the compass away from iron or steel objects when you are using it to detect magnetism from other objects. Iron or steel under the desktops can influence the direction in which the compass needle points.

The compass needle is nothing more than a small, light magnet that easily spins about its center when it interacts with other magnets. The compass needle is attracted to iron and steel objects because the needle itself causes those objects to become temporarily magnetized.

2 In 1820, Hans Christian Oersted, a Danish physicist and schoolteacher, made the observation you are about to make. His discovery set the stage for the development of many modern conveniences, including electrical motors and the generation of electricity from motion.

Figure 1.1

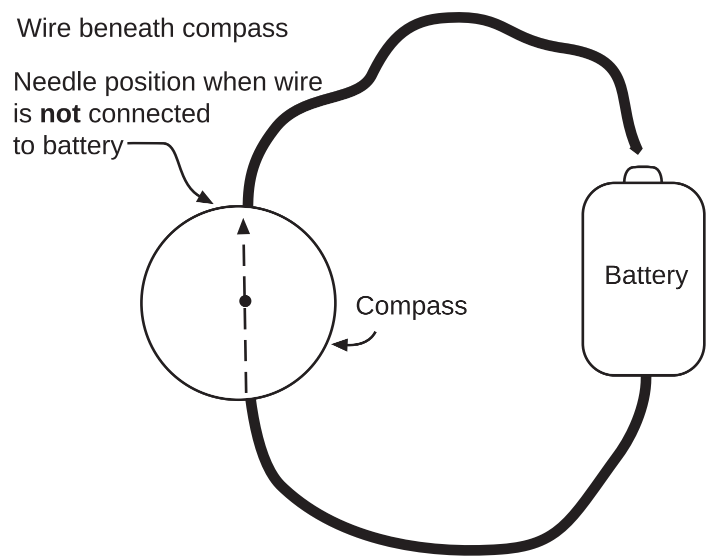
Wire on top of compass



a Place the compass on the table at least 15 cm away from the battery. Connect one end of the wire to the battery. Place the wire in a straight line directly over the compass and in line with the needle. Briefly touch (no more than two seconds) the other end of the wire to the battery and observe what happens to the compass needle.

Draw an arrow on the compass illustration in Figure 1.1 to show the direction of the needle when a current-carrying wire is *on top of* the compass. The pointed end of the arrow represents the "north-seeking" end of the needle. Also draw an arrow on the wire showing the direction in which the electrons are moving in the wire. Recall that electrons move along a wire from the negative end of the battery to the positive end of the battery.

Figure 1.2



b Repeat the above activity, but this time place the wire *under* the compass and align the wire with the compass needle. Draw an arrow on the compass drawing (Figure 1.2) to record the direction of the needle when a current-carrying wire is *under* the compass. Also, draw an arrow showing the direction of electron flow in the wire. Remember to keep the electricity flowing in the wire for only two seconds.

c Note the direction in which the needle moved ("deflected") in 2b above. With the wire under the compass and without changing the positions of the compass or the wire, what can you do to make the deflected needle point in the opposite direction? Describe your solution in the space below.

d It should be clear that a current-carrying wire is somehow creating a magnetic influence in the space around it. What can you do to find out how the "strength" of that influence changes with different distances from the wire? Describe your solution, your conclusion about distance and "strength," and how your observations support your conclusion.

e A magnetic field is a region of space in which there is a magnetic influence. There is a magnetic field in the space around a magnet. A compass can detect a magnetic field if the field is strong enough. Because the compass needle is deflected in the region around the current-carrying wire, you can conclude that there is____around a current-carrying wire.

f Magnetic fields have both "strength" and direction at each point in space. The direction is the direction that a compass will point if it is held at that point in space. The magnetic field both above and below a current-carrying wire is: (circle 1 or 2)

1 in line with the wire.

2 across the wire.

g To change the direction of the magnetic field above a wire, you would have to change the __________________ of the electron flow in the wire. Without moving the wire above the compass, you can do this by

____.

h The magnetic field around a current-carrying wire is "stronger": (circle 1 or 2)

1 closer to the wire.

2 farther away from the wire.

3 You can use your left hand as a model of the relationship between the direction of the electron flow and the direction of the magnetic field (the direction the compass would point) created by that flow.

A Left-hand Model

Pretend to grasp the wire with your left hand. Wrap your fingers around the imaginary wire in such a way that your left thumb points in the direction of electron flow (Figure 1.3). Your fingers will then wrap around the wire in the direction of the magnetic field. You can rotate your hand around the wire to see which way your fingers point at any position around the wire (Figure 1.4).

Practice using the left-hand model by answering the following questions associated with Figure 1.5. (circle the correct answer)

a The magnetic field directly *above* the wire at "a" would point:

1 to the left.

2 to the right.

3 straight up out of the page.

4 straight down into the page.

Figure 1.3

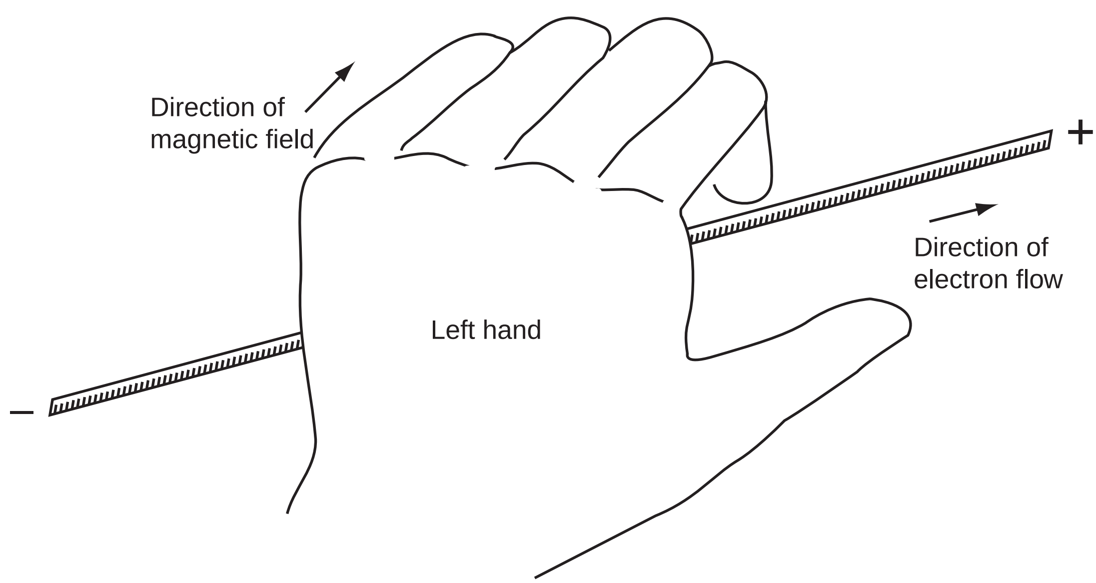


Figure 1.4

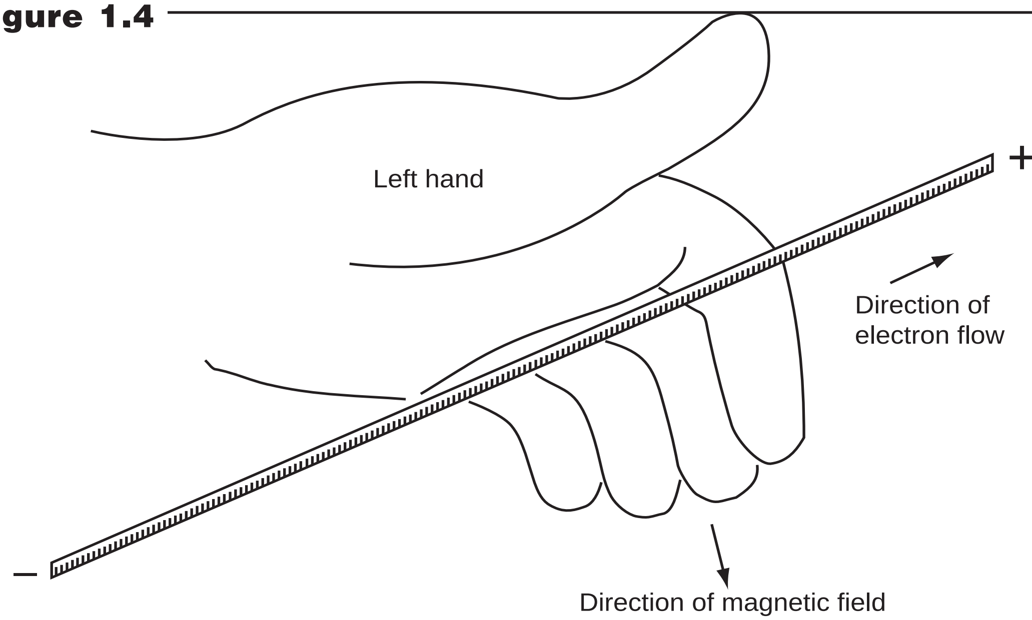
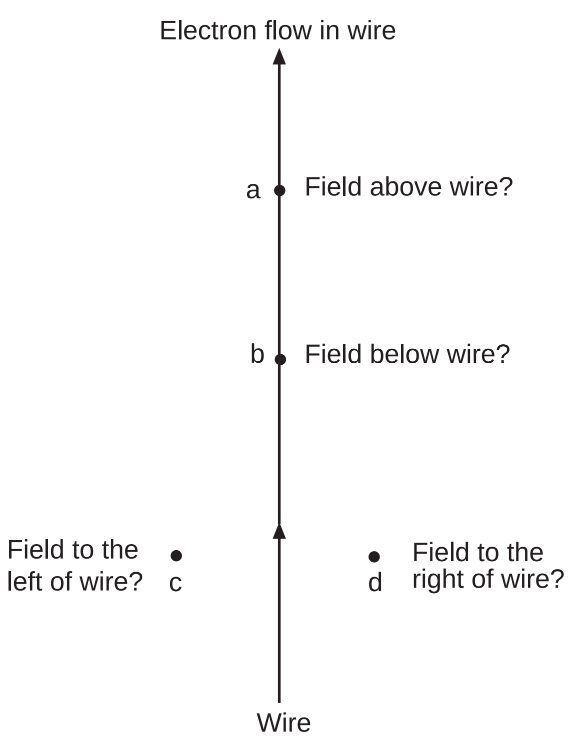


Figure 1.5



b The magnetic field directly *below* the wire at "b" would point:

1 to the left.

2 to the right.

3 straight up out of the page.

4 straight down into the page.

c The magnetic field directly *to the left* of the wire (neither above nor below the wire) at "c" would point:

1 to the left.

2 to the right.

3 straight up out of the page.

4 straight down into the page.

d The magnetic field directly *to the right* of the wire (neither above nor below the wire) at "d" would point:

1 to the left.

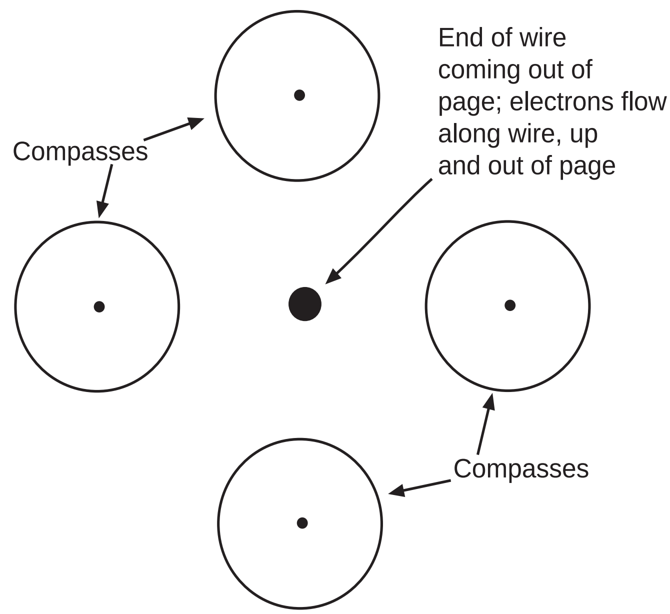
2 to the right.

3 straight up out of the page.

4 straight down into the page.

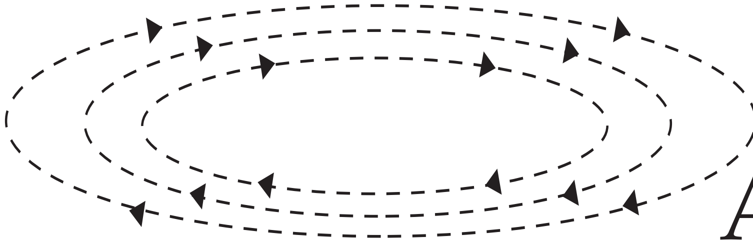
e Observe Figure 1.6 and assume that the dot in the center is the end of a wire that is coming out of the page. Further assume that electrons are flowing along that wire out of the page directly upward from the page. Use your left-hand model to determine the direction of the compass needle (direction of the magnetic field) at each of the compass points around the wire. Draw the compass needles in the four compasses and use the pointed head of the arrow as the "north-seeking" end of the compass needle.

Figure 1.6



Teacher's Guide To

Activity 1



A Bonus from Electrical Flow—Magnetism

What is happening?

In this activity, students discover that a current-carrying wire produces a magnetic field around it. They use a compass to detect this magnetic field, and they observe that the direction of the field is across the direction of the electron flow. Furthermore, the students learn that the field is "stronger" closer to the wire. In addition, the students learn that the direction of the magnetic field at a point in space is described as the direction the north-seeking end of a compass would point. Students can use their left hands to model the relationship between the direction of the electron flow and the direction of the magnetic field it produces. Students practice applying the model to different examples.

Time management

One class period (40–60 minutes) should be enough time to complete the activity and discuss the results.

Preparation

Collect the materials listed on page 2. Make sure that the batteries are not dead, that the compasses work, and that the ends of the wires are stripped (plastic-coated wire) or sanded (enamel-coated wire). If the students have not worked with enamel-coated wire, show them how to use sand paper to sand off the enamel from the ends of the wires.

Students may find that their compasses point in different directions without any current-carrying wires or magnetic materials nearby. Why don't all the compasses point north? Why do the compasses point in different

Caution

Short circuits are created when the wire is connected to the ends of the battery. The short circuit will heat up the wire and quickly wear down the battery. Caution the students to maintain a short circuit for only a couple of seconds at a time. They can do this by connecting one end of the wire to the battery and briefly touching the other end of the wire to the battery.

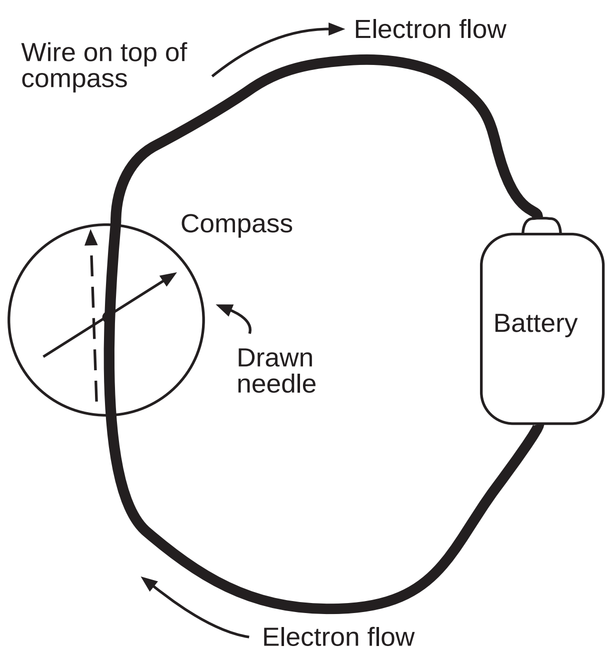
directions when they are moved around on the desks or in the room? Often the iron or steel in desks, filing cabinets, walls, etc. influences the direction of the compasses. For an accurate "north reading," a compass must be away from all iron and steel objects.

Suggestions for further study

Challenge groups to get together to see what happens when two current-carrying wires are held in line with a compass needle. Students should discover that when both wires carry electrons in the same direction over and in line with a compass needle, the needle deflection is greater than when just one wire is used. Students also should discover that when the wires carry electrons in opposite directions over and in line with the compass needle, the needle deflection is less because the magnetic fields exert forces on the needle in opposite directions.

Students have studied direct current electricity where the electrons move in one direction in the conductor. Alternating current electricity is used in our homes. The electrons in the alternating currents switch directions 60 times each second. If this electron jiggling is going on in the wires in our homes, what is happening to the magnetic field surrounding those wires? Have students consider this question and guide them to understand that the magnetic field around the wires in our homes must be jiggling or changing directions 60 times each second. When held near a current-carrying house wire, a typical compass needle does not show deflection. The inertia of the needle prevents the needle from changing directions 60 times each second. Just as the needle begins to move in one direction, it is forced in the opposite direction.

Figure 1.7



Answers to questions found within Procedure on pages 2ñ7.

2a. *Draw an arrow on the compass in Figure 1.1 to show the direction of the needle when a current-carrying wire is* ***on top of the compass.*** *Also draw an arrow showing the direction of electron flow in the wire.*

One answer is shown in Figure 1.7. If the terminals of the battery were reversed, the drawn arrow would be deflected to the other side of the wire.

2b. *Draw an arrow on the compass in Figure 1.2 to record the direction of the needle when a current-carrying wire* ***is under the compass.*** *Also, draw an arrow showing the direction of electron flow in the wire.*

One answer is shown in Figure 1.8. If the terminals of the battery were reversed, the drawn arrow would be deflected to the other side of the wire.

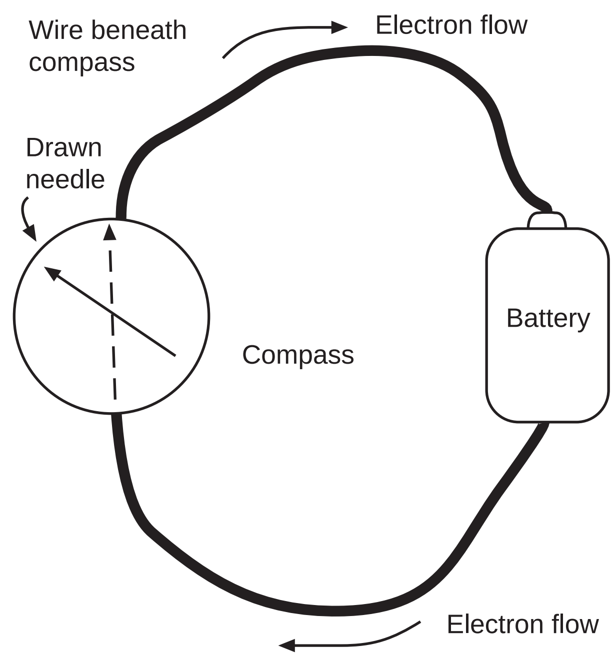
2c. *Note the direction in which the needle moved ("deflected") in 2b above. With the wire under the compass and without changing the positions of the compass or the wire, what can you do to make the deflected needle point in the opposite direction?*

The solution is to keep the wires and compass the same, but switch wires on the terminals of the battery. This sends the electrons in the opposite direction through the wire.

2d. *What can you do to find out how the "strength" of the magnetic influence around the current-carrying wire changes at different distances from the wire? Describe your solution, your conclusion about distance and "strength," and how your observations support your conclusion.*

Change the distance between the current-carrying wire and compass. Note that there is greater deflection in the compass when the wire and compass are closer. Assuming that more deflection means a "stronger" interaction, the conclusion is that the magnetic influence is "stronger" closer to the wire.

Figure 1.8



2e. *When a compass needle is deflected in the region around a current-carrying wire, you can conclude that there is* ***a magnetic field*** *around the wire.*

2f. *The magnetic field both above and below a current-carrying wire is: (1) in line with the wire or (2) across the wire?*

(2) across the wire.

2g. *To change the direction of the magnetic field above a wire, you would have to change the* ***direction*** *of the electron flow in the wire. Without moving the wire above the compass, you can do this by* ***switching the ends of the wire on the terminals of the battery.***

2h. *The magnetic field around a current-carrying wire is "stronger": (1) closer to the wire or (2) farther away from the wire.*

(1) closer to the wire.

3a. *The magnetic field directly above the wire at "a" would point: (1) to the left, (2) to the right, (3) straight up out of the page, or (4) straight down into the page.*

(1) to the left.

3b. *The magnetic field directly below the wire at "b" would point: (1) to the left, (2) to the right, (3) straight up out of the page, or (4) straight down into the page.*

(2) to the right.

3c. *The magnetic field directly to the left of the wire (neither above nor below the wire) at "c" would point: (1) to the left, (2) to the right, (3) straight up out of the page, or (4) straight down into the page.*

(4) straight down into the page.

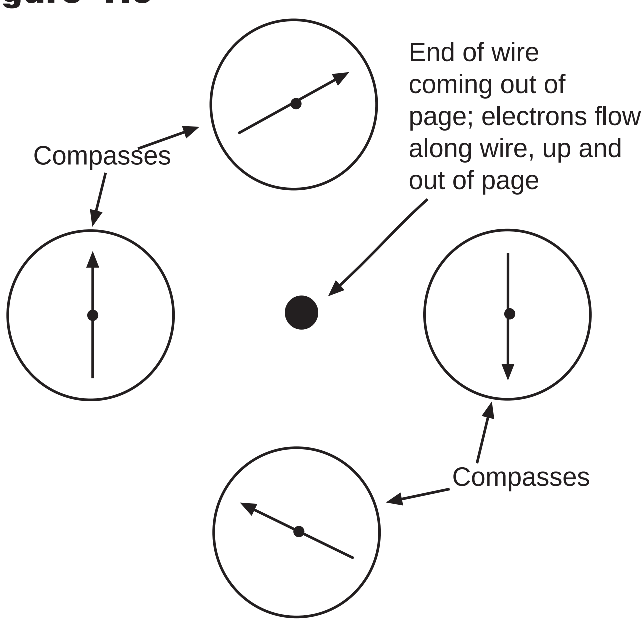
3d. *The magnetic field directly to the right of the wire (neither above nor below the wire) at "d" would point: (1) to the left, (2) to the right, (3) straight up out of the page, or (4) straight down into the page.*

(3) straight up out of the page.

3e. *Observe Figure 1.6 and assume that the dot in the center is the end of a wire that is coming out of the page and that electrons are flowing along that wire directly upward from the page. Use the left-hand model to determine the direction of the compass needle at each of the compass points around the wire. Draw the compass needles in the compasses; use the pointed head of the arrow as the "north-seeking" end of the compass needle.*

The compass directions are shown in Figure 1.9.

Figure 1.9



Note: *The left-hand model is the same as the right-hand rule found in physics textbooks. Here, the direction of electron flow is used. The right-hand rule uses current direction (positive charge flow).*