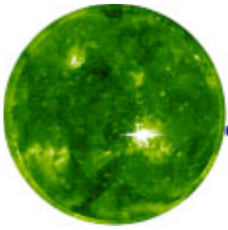


Mapping the Field of a Dipole Magnet

High School Grades

Lesson Summary
Students make a simple magnetometer and use it to map the field surrounding a bar magnet

Prior Knowledge & Skills
Understanding of:
- Force and motion

Ability to:
- Make and record observations and descriptions
- Manipulate common tools and follow assembly instructions

AAAS Science Benchmarks
The Nature of Science
The Scientific World View
Scientific Inquiry ★
The Physical Setting
The Universe ★
The Structure of Matter
Motion ★
Forces of Nature ★

NSES Science Standards
Science as Inquiry
Abilities to do Scientific Inquiry ★
Understandings of Scientific Inquiry
Physical Science★
Motions and Forces
Science and Technology
Understandings about Science and Technology
History and Nature of Science
Science as a Human Endeavor

NCTM Mathematics Standards
Data Analysis & Probability
Problem Solving
Reasoning and Proof

Teaching Time: Two to three 45-minute periods

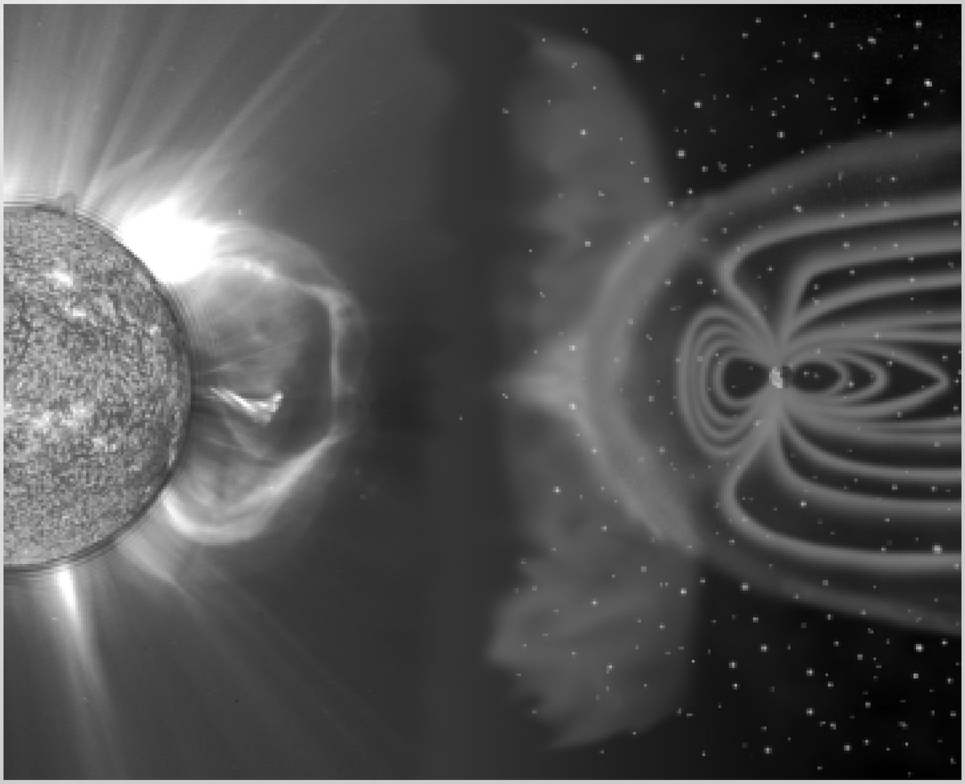
Materials per Team
- 2L clear plastic container (1)
- 2' sewing thread
- Bar magnet 100 mm x 7 mm (2)
- 3" x 5" index card (1)
- Mirrored sequin (1)
- Bright lamp or laser pointer (1)
- Scissors
- Meter stick
- Super Glue
- 1" of soda straw
- Large sheet of paper

Advanced Planning
Preparation Time: 30 minutes
1. Review lesson plans
2. Gather materials
3. Form student teams
4. Pre-cut soda bottle as necessary
5. Build and use a simple magnetometer

Classroom Resources:
http://www.solarstorms.org/index.html

Live from the Aurora, pp. 41-50, NASA (2003)
http://sunearth.gsfc.nasa.gov/sunearthday/2003/educators_guide2003/pdf/lfa_educators_guide.pdf

LASP LABORATORY FOR ATMOSPHERIC AND SPACE PHYSICS

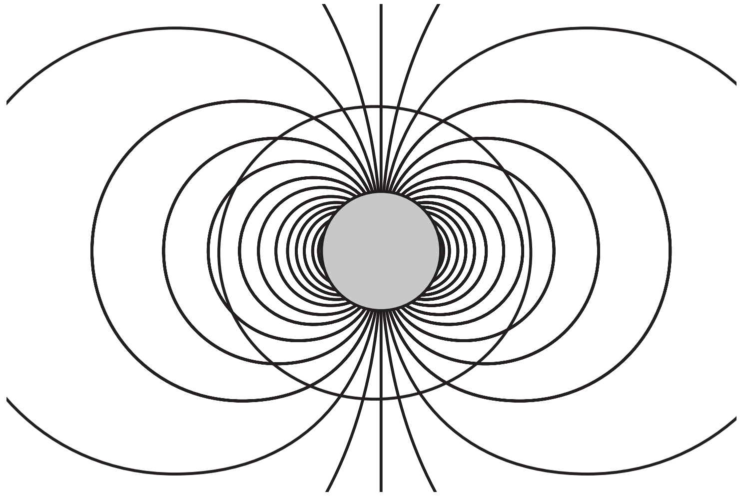


MAGNETISM

BACKGROUND:

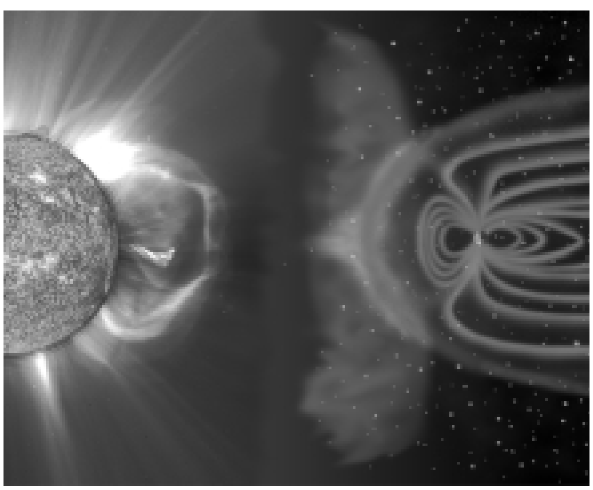
A spherical magnet in an otherwise empty region of space would have a magnetic field approximately modeled in the figure on the next page.

The Earth's magnetic field close to the Earth can be thought of approximately as a spherical magnet. Notice that at the poles the field is nearly vertical and at the equator it is nearly horizontal. More than 90% of the Earth's magnetic field measured is generated internal to the planet in the Earth's outer core. This portion of the geomagnetic field is often referred to as the Main Field. The Main Field creates a cavity in interplanetary space called the magnetosphere, where the Earth's magnetic field dominates in the magnetic field of the solar wind. The magnetosphere is shaped somewhat like a comet in response to the dynamic pressure of the solar wind. It is compressed on the side toward the Sun to about 10 Earth radii (R_E is 6400 km) and is extended tail-like on the side away from the Sun to more than 100 Earth radii.



The inner circle represents the outer core of the Earth. The outer circle represents the surface of the Earth

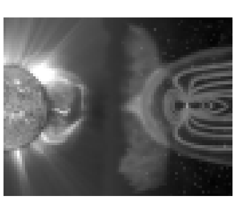
The shape of the Earth's magnetic field is formed by the interaction of several important features. One feature is, of course, the Earth's internal magnetism. Another feature is the interplanetary magnetic field. This magnetic field arises at the Sun and extends into interplanetary space. The interplanetary magnetic field



is formed by currents of plasma within the Sun and within the solar wind. This magnetic field pattern spirals outward from the Sun to fill space throughout the solar system. The third significant feature contributing to the shape and activity of the Earth's magnetic field is the solar wind, the plasma streaming constantly from the Sun in all directions.

Humans have been aware of and made use of the magnetic field of the Earth for the past 2 millennia. Mariners, following the example of the Chinese, used the magnetic properties of magnetite and magnetized metals to find their way relative to the fixed orientation of the compass needle in the Earth's magnetic field. Today, we use magnets in a variety of ways, from floating fast spinning CDs in our computers, stereos and TVs, to magnetic resonance imaging, to sticking paper to our refrigerators. Magnetism is a noncontact force. The magnet can affect materials across an intervening space. That is, we do not have to be at the location of the source object to detect it. We say that a magnet creates a magnetic field or a region of influence in the space around the magnet.

In the following activities, students will investigate the shape of the magnetic field of a bar magnet and extend their understanding of magnetism to a more complex magnetic system—the Sun-Earth system. The bar magnet is the prime example of a dipole magnet. Data will be collected in Activity 1 by placing a student-made magnetometer at various locations relative to a bar magnet and recording the direction of alignment of the magnetometer. Students will learn about magnetic field direction by examining the data. During the Activity 2, students will be prompted to consider whether the magnetic field of the Earth is represented in their data, and be further prompted to remove the effect. Of course, the magnetic field of the Earth is always present, but it is overwhelmed by the dipole



field close to the source magnet. Due to the field strength of the bar magnet decreasing as the cube of the distance to the magnet, the influence of the Earth's field will easily be seen within 50 centimeters of the bar magnet. Activity 3 asks students to use the magnetometer to map the combined field of two aligned dipoles and two anti-aligned dipoles. This sets the stage nicely for an investigation into the interacting magnetic fields of the Sun and of the Earth in Activity 4.

NATIONAL SCIENCE STANDARDS:

National Science Standards (NSES)

Content Standards (Grades 9-12)

- Scientists conduct investigations for a wide variety of reasons. For example, they may wish to discover new aspects of the natural world, explain recently observed phenomena, or test the conclusions of prior investigations or the predictions of current theories.

  This is done if the student is considered to be a scientist discovering a new aspect of the world (magnetism) in order to understand aurora and other Sun-Earth interactions.

- Scientists rely on technology to enhance the gathering and manipulation of data. New techniques and tools provide new evidence to guide inquiry and new methods to gather data, thereby contributing to the advance of science. The accuracy and precision of the data, and therefore the quality of the exploration, depends on the technology used.

  Addressed through the building of the magnetometer and analysis of maps generated from magnetometer.

- Scientific explanations must adhere to criteria such as a proposed explanation must be logically consistent; it must abide by the rules of evidence; it must be open to questions and possible modification; and it must be based on historical and current scientific knowledge.

  The discussion questions are designed to create the above environment of explanation.

Benchmarks for Science Literacy

Project 2061 (Grades 9-12)

- Magnetic forces are very closely related to electric forces and can be thought of as different aspects of a single electromagnetic force. Moving electric charges produce magnetic forces and moving magnets produce electric forces. The interplay of electric and magnetic forces is the basis for electric motors, generators, and many other modern technologies, including the production of electromagnetic waves.

  As we relate the solar wind (stream of charged particles) to interaction with magnetosphere, we address this.

- Scientists assume that the universe is a vast single system in which the basic rules are the same everywhere. The rules may range from very simple to extremely complex, but scientists operate on the belief that the rules can be discovered by careful, systematic study.

- We are studying experiments in a lab to understand Sun-Earth interactions. What we do in the lab must explicitly replicate and inform about these interactions.

  Use tables, charts, and graphs in making arguments and claims in oral and written presentations.

  Explicitly built in to creation of maps and interpretation of maps.

Grade 8:

- Electric currents and magnets can exert a force on each other.

  Explicitly built into lessons.

- When similar investigations give different results, the scientific challenge is to judge whether the differences are trivial or significant, and it often takes further studies to decide. Even with similar results, scientists may wait until an investigation has been repeated many times before accepting the results as correct.

  As students predict multidipole fields, differences in maps will need to be accounted for.

National Educational Technology Standards (NETS)

Grades 9-12

- Technology research tools.
- Students use technology to locate, evaluate, and collect information from a variety of sources.

  Use of Internet as information collection tool explicitly built in.
- Technology problem-solving and decision-making tools.
- Students use technology resources for solving problems and making informed decisions.

  Explicitly addressed in activity about solar wind and magnetosphere interaction.

Mathematics Standards (NCTM)

Grades 6-8

- Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them.
- Formulate questions, design studies, and collect data about a characteristic shared by two populations or different characteristics within one population.
- Select, create, and use appropriate graphical representations of data, including histograms, box plots, and scatterplots.
- Develop and evaluate inferences and predictions that are based on data.
- Use observations about differences between two or more samples to make conjectures about the populations from which the samples were taken.
- Use conjectures to formulate new questions and plan new studies to answer them.

  Mapping of multiple dipole fields addresses these standards.

Measurement Standard for Grades 9-12

Understand measurable attributes of objects and the units, systems, and processes of measurement.

Apply appropriate techniques, tools, and formulas to determine measurements.

- Analyze precision, accuracy, and approximate error in measurement situations.

Discussion leads students through understanding what magnetometer measures. Measuring ambient field and finding local variations due to other sources and applying this knowledge to reinterpretation of dipole maps address this standard.

Communication Standard for Grades 9-12

- Organize and consolidate their mathematical thinking through communication.
- Communicate their mathematical thinking coherently and clearly to peers, teachers, and others.
- Analyze and evaluate the mathematical thinking and strategies of others.

Connections Standard for Grades 9-12

- Recognize and apply mathematics in contexts outside of mathematics.

Representation Standard for Grades 9-12

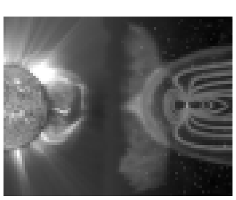
- Use representations to model and interpret physical, social, and mathematical phenomena.

INSTRUCTIONAL OBJECTIVES FOR ACTIVITIES 1 AND 2

Students will use the magnetometer to map the field of a bar magnet. The map will indicate direction of field only, and will resemble a dipole field. Students will use the magnetometer to map the ambient field due to the Earth. Students will analyze the maps produced for patterns and trends. Students will identify and examine methods for removal of the Earth's magnetic influence on the measurements used to make the map.

VOCABULARY:

- **Magnetic force:** The fundamental force exerted by a source magnet which will cause the motion of



a test magnet to change or to cause its orientation relative to a fixed direction to change.

- **Orientation:** The direction that defines the position of one object in relation to another. Within this activity, we take the definition of direction as the line joining the poles of a magnet relative to a fixed line (often determined by another set of magnetic poles.)
- **Magnetic Field:** An abstract representation of the effect of a magnet on the space in which it is found. The field is often represented by lines that show how a test magnet would align itself within a source field. This is different from the electrostatic field that represents the direction along which a positive particle would feel a force. For magnetism, the field line represents the direction along which a magnet feels a torque of Zero Nm.
- **Dipole:** A situation where two conjugate sources of field are in proximity and together influence the space around them. Magnetism is found in dipole constructions at its simplest occurrence. That is, one cannot separate the conjugate poles, often termed the North and South poles, of a magnet. In electrostatics, a positive charge is one monopole, a negative charge is the conjugate monopole, and each can be found independently of the other. In gravitation, a mass is a self-conjugate pole.
- **Super-position Principle:** The principle tells us that when two similar phenomena occur at the same time and place, we will see the sum of the two phenomena, rather than the original 2 separately. Vector addition is exploited to represent this principle.

ACTIVITIES:

Preparing for the Activity

Student Materials:

Materials for one magnetometer—4 students per group

- 2-liter soda bottle or tennis ball canister
- 2 ft. of sewing thread
- 1 small bar magnet
- 1—3 x 5 index card
- 1 mirrored dress sequin
- 1 adjustable high-intensity lamp
- scissors
- 1 meter stick
- super glue
- 1—1 inch piece of soda straw

Mirror sequins may be obtained from any craft store.

Bar magnets may be obtained from this Web site:
http://forcefieldmagnets.com/catalog/

Students could bring in 2-liter soda bottles.

A desk lamp could be substituted for the high-intensity lamp.

Additional materials for Activities 1-4

- Cow magnet (source: *www.mastermagnetics.com*, part # DMCP5). A strong bar magnet may be substituted.
- 3-4 sheets of poster paper, at least 2 ft on edge, per group.
- Tape
- Wall space for hanging and displaying student generated maps.

Time

5-6 class periods (45-50 minutes)

4 homework periods

Advance Preparation

- Students will need large, flat, clean and dry areas to work on. The floor is acceptable if sufficient table surface is not available.

- Scout the room for extraneous sources of magnetic fields. Computers, electrical lines, any operating electrical equipment, refrigerators, and of course magnets, are all items that will lead to systemic errors. While some can be minimized or removed, some cannot. Anticipate this when guiding the discussion following data collection.
- Practice before class using a magnetometer and making a dipole map for the recorded observations. Even a few minutes will give you significant insight for assisting students.

Activity 1
Mapping the Field of a Dipole Magnet

Teacher Instructions

1. Assignment for the evening before Activity 1

Please discover when magnetism was first noticed and exploited by human kind. What was done with the discovery? How was it explained? Was it put to general use or was it seen as a curiosity?

Suggested Web sites:

- Dr. David Stern (NASA) has an online book on magnetism at *http://www-spof.gsfc.nasa.gov/Education/Imagnet.html*
- From the official Web server of the State of Hawaii Schools *http://gamma.mhpcc.edu/schools/hoala/magnets/history.htm*
- A Timeline of Magnetism (and Optics) Phenomena *http://history.hyperjeff.net/electromagnetism.html*
- From the University of Washington, a Web site built by a graduate student *http://www.ocean.washington.edu/people/grads/mpruis/magnetics/*

2. Setting the Stage—opening discussion. Ask the question, "Where does a magnetic force begin and end in space around a magnet? What evidence reveals that a magnetic force is present." Try to elicit these responses from students' previous experience with magnets.
   - Magnets affect other magnets and metals.
   - Magnetic influence or strength is not related to size of magnet.
   - Magnetic influences extend through space, but get weaker with distance.
   - Magnets have well differentiated ends or poles. There are two poles.
   - Like poles repel; unlike poles attract.

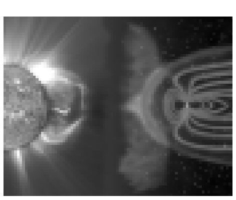
3. Handout materials and instructions for construction of magnetometer—see page 47.

When students have completed the magnetometer, hand out materials and instructions for remainder of activity. Give students 20-30 minutes to complete a map. Circulate, answering questions. Questions can be asked motivating students to think critically about the data and the data collection procedure. Some suggestions follow.

- Where on the line segment is the measured magnetic field direction best represented?
- Is the measured magnetic field parallel to the entire drawn directed line segment or just some part of the drawn arrow?
- What technique did you use to insure you made your arrow directly below the pivot or center point of the sensor magnet?
- Can you state the resolution (the smallest difference in position that also shows a difference in magnetic field direction) of your procedure?

One of the potentially challenging tasks is to draw a set of smooth curves on the maps representing the overall pattern revealed. Certain measurements may not fit the general curve. These individual measurements may have to be ignored, but a solid reason for doing so is required. It is pedagogically useful to prompt students to repeat measurements or to ask several other groups to make some measurements at the same location (but obscure the original troubling one to avoid bias!). This again gets back to the scientific method and it also raises the qualities of collegiality and cooperative effort, both celebrated qualities of work in groups and science labs.

The smooth curves should be approximately tangent to the arrow drawn at a location. This can be hard, and will be affected by such things as "lack of artistic talent," learning disabilities affecting hand-eye coordination and spatial awareness/representation. The goal is NOT a map that emulates the textbook



drawings of magnetic fields. The process is to have students collect data, identify patterns in the data, and to represent the patterns. The smooth curves are the representation of the pattern.

4. Assign the following questions for homework.

What is a dipole? It is the simplest representation of a magnetic field. Look at this site for some drawings of magnetic fields (ignore the formulas if you like) as produced by various sources. Do you recognize any? What is the difference between the field map for a single electric charge and for a bar magnet? A single electric charge is a source of electrostatic field, and is considered a monopole when it is not paired with an opposite charge.

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemag.html#c1

In class, you made a map of the magnetic field of a bar magnet. What is a field, as used in a physics statement like the previous statement? What, exactly, does the magnetic field map show someone looking at it?

What happens when two or more sources of magnetic field are interacting? How do they mutually influence space? Will an observer see each separate influence? Will an observer see some combination of the influence of the sources? How might someone with knowledge of the sources go about predicting what an observer with a magnetometer would record as the field of the combination? How would you represent the overlapping influences? If two magnetic field lines intersect, how would a magnetometer react (what direction would it choose to point) if placed at that location?

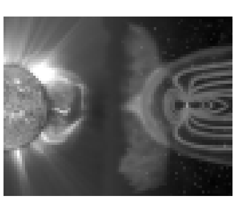
5. Conduct a discussion after students have completed all work and have answered the questions in the student activity.

Two approaches are possible to analyzing the data collected. One is to have student groups work with just the group map and compare answers across groups later, drawing out how data in isolation can lead to varying conclusions. An important part of science is cross-fertilization of thinking among separate groups. A second method is to place all maps on public display (perhaps with names obscured) and have the students examine all the results as they answer the questions. This will require that students add some set of information to the map, including orientation and symbol keys, a critical element of communication of scientific information.

Ask students to interpret, in writing and/or verbally, some or all of these questions.

- **What is a map representing? Is this data?** {Suggested response: The source magnet has created a preferred direction in the space represented by the map. The arrows show the direction a magnetic pole will point at that location.}
- **What is happening at locations between map arrows?** {Suggested response: Similar patterns of change of direction would be seen. These patterns would line up with those documented by direct observation.}
- **Is the change of directionality continuous or are there places where sudden changes or breaks occur?** {Suggested response: While the change of directionality ought to be continuous, concentrations of metal, other magnets disturbing the local field during the observations, current sources being accessed or stopped could all produce an odd or discontinuous change in field direction. Repeating the observation for the point and surrounding points may lead to an adjustment. Repeating the observation after moving the mapping station to a different location may lead to an adjustment but would also require redoing the entire map.}
- **By connecting adjacent observations in a smooth curve, sketch out the complete map appearance.** {Suggested response: This ought to result in the commonly seen dipole field graphic. In any event, the critical discussion questions should be, "How is this consistent? How do you explain the regularity (or irregularity) represented? Is this the most elegant (or simple) explanation or extrapolation consistent with the data that can be made? Is this the only possible appearance of the extrapolation of the data? How do you choose between different representations?"}

- **Place your map on the wall next to those made by others. Identify similarities and differences. Decide if the trends seen across all the maps reveal a generally applicable phenomenon or not. Give significant reasons for your decision.** {Suggested response: Barring excessive error or egregiously sloppy data collection, the maps should be very similar in appearance. The conclusion ought to be that as different observers using different magnets and magnetometers got very similar maps, the standard of repeatability has been met for this observational technique. That suggests that we are seeing a real phenomenon and not some sort of random effect.}
- **If you rotated your source magnet 90 degrees, what sort of changes would you expect in the map if you did new observations?** {Suggested response: The map would be rotated 90 degrees in the same direction. But, the observation lines would not be rotated exactly 90 degrees as the field of a magnet is not circular but rather lobe shaped.}
- **You were not able to do this, but what would you expect to see if you made observations at points inside the source magnet?** {Suggested response: A continuation of the field connecting the poles.}
- **Suppose you were able to map the field in a plane 30 cm above the plane of the source. What sort of a map would you predict seeing? Can you use the map you have made to demonstrate your prediction is reasonable?** {Suggested response: Similar map. You can simply rotate the plane of the map already made to make a reasonable prediction for what the map would look like for different planes in space. This assumes, naturally, that the magnet is a symmetrical shape.}
- **How much has the magnetic field of the Earth altered the map of the field produced by the source?** {Suggested response: The effect will depend on the orientation of the source relative to geomagnetic north. At the outer edges of the map, a trend may be seen which is slightly different from the trend seen near the source. It is possible that students will not see this if they were not particularly precise in recording observations.}
- **How might we identify and remove the effect of the Earth's magnetic field on the map you produced?** The goal of this question is to develop an experimental design and technique for handling combined data sets. This is a lead-in for strategies to combine field maps. {Suggested response: If we make a map of the field of a source magnet, then remove the source from the room and map the Earth's magnetic field at the same location as the original map, we will have an indication of the directional influence of the Earth's field on the map of the source magnet. N.B.: Without knowing the strengths of the magnetic fields mapped, we cannot directly add or subtract these measurements}.



Student Activity
Constructing the Magnetometer

1. Obtain a dry label-free 2-liter soda bottle. Slice the bottle 1/3 the way from the top.
2. Cut the index card so that it fits inside the bottle without touching the sides to create a sensor card.
3. Glue magnet at the center of the top edge of the card. Cut a 1-inch piece of a soda straw and glue to top of the magnet. (See Figure 1.)

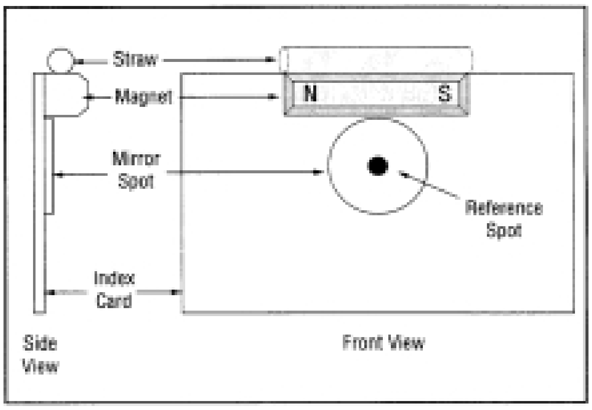


Figure 1. Sensor card set-up, IMAGE poetry

4. Glue the mirror sequin to the front of the magnet. Mark a spot in the middle of the sequin with a permanent marker. This is called the reference spot that will be seen as a dark spot on the wall.
5. Pull the thread through the soda straw and tie it into a small triangle with 2-inch sides.
6. Tie a 6-inch piece of thread to top of the triangle in #5 and thread it through the hole in the cap. Secure the string on the outside of the bottle with tape.
7. Put the bottle top and bottom together so that the "Sensor Card" is free to swing (not touching the bottle) with the mirror spot above the seam.
8. Tape the bottle together and glue the thread through the cap. (Figure 2)

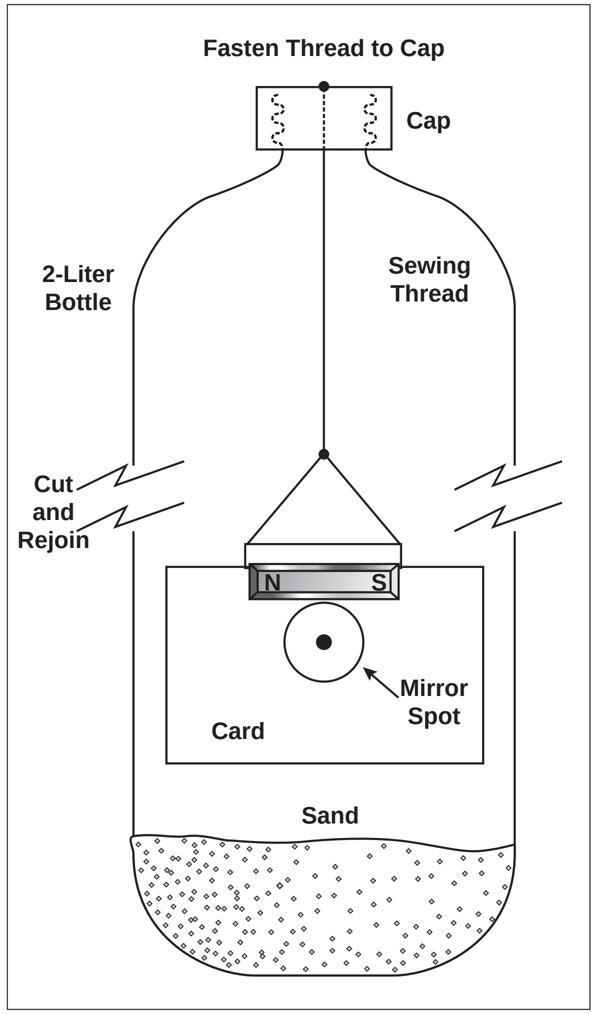


Figure 2. Constructed soda bottle magnetometer, IMAGE poetry

Student Activity 1
Mapping the Field of a Dipole Magnet

Goal: Obtain a good quality representation of the total magnetic field around a bar or dipole magnet.

In today's activity, you will work with a partner using a magnetometer to collect data on how a source magnet affects a test magnet in its vicinity. The test magnet will be the magnet in your magnetometer. The source magnet will be a magnet provided by your teacher. The data you will collect is the direction along which the test magnet lines up at different locations in the vicinity of the source magnet.

What you are mapping is the magnetic field in the vicinity of the source magnet.

Materials:

1. Magnetometer
2. Bar magnet
3. Large sheet of paper
4. Meter stick
5. Pencil

Data Collection Procedure:

- Along all edges of the paper, mark points separated by 10 cm and use them to draw a grid on the paper.
- Place the paper on a lab desk. Use tape to mark the position of the 4 corners so that you could place another paper in exactly the same position. Also use the tape to help keep the map in place.
- Place a source magnet horizontally in center of paper. Tape it to paper.
- Outline the position of the source magnet on the paper. The particular orientation you choose is not under experimental control. That is, place the magnet at any angle you desire relative to the grid you drew. The orientation of the source relative to the paper and the room should be noted.
- Decide which ends of the test magnet in the magnetometer are the front and back.
- Use the magnetometer to determine the direction of the magnetic field at each grid point.
- Record the direction of alignment by drawing a short directed line segment that accurately shows the direction the magnetometer magnet is pointing at that location. The line segment should be centered on the point directly below the center of the magnetometer and should be about an inch long.
- Repeat at each grid intersection.
- Put a legend on the completed map that includes information about the orientation of the map relative to some fixed reference point in the room (a wall clock or a door for instance).
- Put a title on the map as follows: Bar Magnet Map, date, and your group identification

Data analysis questions to be completed by you and your partner. Write out your answers in your notebook..

1. Are all the arrows on your map pointing in the same direction? Why or why not?
2. How did you define the direction of an arrow? What observation was translated into the arrow direction?
3. Explain why you think your data are correct or incorrect. Are there any individual measurements that don't seem to fit the general pattern? Explain how they don't fit the pattern and what the causes might be.
4. If you put one magnet near the magnetometer, the direction the magnetometer points is changed. If you put two magnets near the magnetometer but at different locations, will you measure the combination of the effect of the two magnets or just the effect of one of them? Which one? Write a convincing argument!
5. While gathering data, did you record the effect of just the source magnet or the source magnet and other things contributing interfering sources of magnetic influence? Name the things that might have affected your measurements and state how they changed the direction the magnetometer indicated. Look closely at the lab table, top and bottom, for possible sources of these effects. Consider what you know about magnets from previous experiences for hints about what could be an interfering source of magnetic influence.
6. Can you subtract or otherwise remove the unwanted effects to get the effect of just the bar magnet? Design a procedure to do this. Identify assumptions you are making about magnetism in the design of the procedure. Identify the limitations of your procedure.
7. The magnetometer measures direction. Based on the map, what might you conclude about the strength of the magnet at different distances from a particular pole?