Magnetism

This lab is a series of small experiments investigating the properties of the magnetic field. First we will investigate the polarity of magnets and the shape of their field. Then we will explore the magnetic field strength using a computer-based magnetic field sensor. Last, we observe voltages produced by changing magnetic fields.

***WARNING: Keep magnets away from computers and any computer disks!***

I. Theory

A. Magnets.

Most magnetic fields that we observe look quite a bit like a dipole field, shown in figure 1. Note that field lines come out of the North Pole and go into the South Pole. In an ideal dipole, the lines start at north poles and end at south poles. However, single magnetic poles do not appear to exist in nature. In the bar magnet, the field lines continue through the magnet, forming closed loops.

The Earth has a magnetic field. This magnetic field is the result of the so-called "geodynamo" due to the interaction between the inner core and the outer core, which rotate at different rates. Recent simulations have been able to reproduce most of the more significant effects, including stability and periodic reversal on geological time scales. For our purposes, we can approximate it as a bar magnet, with a north and south magnetic pole.

People have used a compass to help them find their way around the Earth for a long time. The compass is a bar magnet, with a north and a south pole. Its north pole points towards the geographical North Pole, where Santa lives. Since like poles repel and unlike poles attract, this means that the Earth’s south magnetic pole is in the geographic north, and vice versa. The Earth’s south magnetic pole is somewhere in Newfoundland, Canada, about 16 degrees east of north as seen from San Francisco.

B. Induced EMF.

It is an experimental fact that changing magnetic fields induce voltages in electrical circuits. This is how motors and generators work. The induced current can only flow in one of two directions in a wire, and Lenz’s law predicts which way it goes:

Figure 1. Magnetic dipole field.
**Lenz’ Law:** The polarity of an induced emf is such that the induced current produces an induced magnetic field that opposes the change in flux causing the emf.

Figure 2 shows an example where an increasing magnetic field in the upward direction causes current to flow in a clockwise sense in the wire loop. This creates a downwards field which cancels out part of the change.

**C. Field strength versus distance**

The strength of a magnetic field varies with distance from the magnet. The strength of the magnetic field could vary inversely as the square of distance, like the strength of a gravitational field or an electrical field. Or, the strength of the magnetic field could vary in a different way relative to distance.

Unlike a gravitational field or an electric field, which are radial, the magnetic field consists of complete loops that surround and go through the magnet.

**II. Experimental Procedure**

Start by removing the tape labels for S and N on the magnets on your table. This is a good time to note that the polarity of permanent magnets can sometimes be reversed. You may find that this has happened to some of the compass needles!

**A. Determining the Polarity of an Unmarked Magnet.**

There are two simple ways to determine the polarity of a magnet, as follows. As a preliminary, determine which end of your compass needle is its north pole by seeing which way it aligns in the Earth’s magnetic field.

- (First method) Now choose a bar magnet and use the compass to determine which end is its north pole and which is its south pole. Label them, using masking tape.
• (Second method) Next, suspend the same bar magnet by a long string so that it hangs horizontally. From its behavior in the earth’s magnetic field, determine which end is N and which end is S.

Q1. Which of the two methods used to find the polarity of your magnet is better? Why?

Determine the polarity of each magnet at your lab table using whichever of the two methods above you think best. Label the ends of your magnets with masking tape and pencil.

B. Mapping magnetic field patterns.

Here is a method for visualizing the pattern of the magnetic field around a magnet. Remember that the magnetic field lines leave the north pole and enter the south pole, forming closed loops.

• Take a sheet of butcher paper and tape it down to your table. All permanent magnets should be moved far away, or they will distort the field pattern you are trying to measure.
• Using your compass, (and all other magnets far away) draw a line that represents the direction of the Earth’s field across the center of the paper.
• Place a bar magnet on this magnetic N-S line with its magnetic north pole pointing (geographic) north, and tape it down. Trace its outline on the paper and label the poles.

Now, place a small compass near the N pole of the magnet and draw an arrow on the paper at the position of the N pole of the compass needle and pointing in that direction. Move the compass so that the S pole of the needle is at the tip of the arrow you just made. Now make an arrow at the new position of the N pole of the compass needle. Continue this procedure until the path returns to the S pole of the bar magnet or until the path leaves the paper. Connect the dots to form a smooth curve. Repeat until you have drawn 3 or 4 complete field lines on each side of the magnet. Make a sketch in your book of the field lines you found. (You will not turn in the butcher paper!)

Use a meter stick to draw the perpendicular bisector of the magnet. Place the compass on the bisector and slowly slide it out along this line, carefully observing the behavior of the compass needle. There should be a point at which the compass needle acts strangely. [Note: you will not see this effect unless the north pole of the magnet is pointed north!] Place the compass on the bisector on either side of this point.

Q1. Explain what you observe. Why is it necessary to have the bar magnet in the orientation where its north pole points north to see this effect?

C. Wire coils and magnets:

Lenz’s law states that the effect of a changing magnetic field on a coil is to make a current flow that will create magnetic field which tends to cancel out the change in applied magnetic field. When you see a positive voltage at the meter, current is flowing in the “+” terminal and out the “-” terminal. In other words, the needle of the meter moves towards the terminal where the current enters. You should be able to predict the direction of the magnetic field in the center of the coil caused by this current.

Now, explore how changing magnetic fields cause voltages in coils.

• Connect the wire coil on your lab table to the galvanometer. (As usual, draw the circuit, before connecting it.)
• Move a bar magnet into the center of the coil, watching the galvanometer as you do so.
• Hold the magnet without moving in the center of the coil.
• Move the magnet in and out of the coil.

Describe what happened in each of the above steps in your lab book. Including diagrams might save you lots of words.

D. Just coils:
Create a magnetic field with one coil and detect it with the other.
• Put the two coils on top of each other so that the field created by current in one passes almost entirely through the other.
• Connect one wire to the red terminal of the fixed +5V source on the bottom right corner of the power supply, but don't connect the other wire yet. Your diagram in your lab book should be clear about the polarities.
• Using Lenz’s law, predict whether the meter (across coil 2) will read positive or negative when you connect the other wire of coil 1 to the black terminal of the fixed 5V source. Record your prediction (and how you made it) in your lab book.
• Try it!

Q2. Explain whether or not you prediction was correct.

E. Quantitative magnetic field measurements with the Science Workshop sensor
The purpose of this laboratory activity is to discover how the strength of the magnetic field of a permanent magnet changes with distance. See section I.C. for the theory.

In this activity, the Magnetic Field Sensor measures the magnetic field strength of a small but powerful neodymium magnet as the distance between the sensor and the magnet changes. You will measure the distances and enter them into the Science Workshop program using the keyboard.

The Science Workshop program records and displays the magnetic field strength and the distance. You will use the program’s built-in curve fitting function to determine the relationship between the strength of the magnetic field and the distance from the magnet.

1. Computer Setup
• Connect the Magnetic Field Sensor to Analog Channel A.
• Open Science Workshop from the desktop
• Click “File” then “Open”, to open the document (‘secn” is your section number) C:\labs\ph122\secn\magnets\P51_PERM.SWS
  o The document opens with a Digits display of magnetic field strength and a Graph display of magnetic field strength vs. distance.
  o Note: For quick reference, see the Experiment Notes window. To bring a display to the top, click on its window or select the name of the display from the list at the end of the Display menu. Change the Experiment Setup window by clicking on the Zoom box or the Restore button in the upper right hand corner of that window.
• Under Sampling Options… make sure that Periodic Samples = Fast at 10 Hz, and Keyboard with Parameter = Distance and Units = m.
Now click on MON, move the window out of the way, and watch how the magnetic field readout changes when you move a magnet near the probe. Then move the magnet away and zero the probe by pressing the “tare” button on the side of the sensor. We sometimes find that the probe only works well for negative fields. See if this is the case with your probe.

2. Sensor Calibration & Equipment Setup

You do not need to calibrate the Magnetic Field Sensor. The Magnetic Field Sensor produces a voltage that is directly proportional to the magnetic field strength as follows: 10 millivolts = 10 gauss (where 1000 gauss = 0.1 tesla). The sensor’s range is ±2000 gauss.

- Place the meter stick on a flat surface away from the computer.
- Place the Magnetic Field Sensor so the end of the rod is even with the zero end of the meter stick.
- Select AXIAL by pressing the FIELD SELECTOR SWITCH on the top of the sensor box.
- Put the sensor on the 1x scale. Zero the sensor by pressing the ZERO button on the top of the sensor box. (The interface will not have started sampling yet.)
- Place the magnet next to the 0.5 cm mark on the meter stick with the north pole of the magnet facing the sensor.

**NOTE:** Keep the magnet away from the sensor when you zero the sensor.

3. Data Recording

- Click STOP to stop monitoring, then click the REC button to begin collecting data. The Keyboard Sampling window will open. Move the window so you can also see the Digits display of magnetic field strength.
  - Your parameter and units (Distance and meters) are displayed at the top of the Data list in the Keyboard Sampling window. The default value for Entry #1 is 0.0000
- Type in **0.005** as the location of the magnet for Entry #1. Click Enter to record your typed in value.
  - Your typed in value will appear in the Data list, and the window will prompt you to type in Entry #2.
- Move the magnet 0.5 cm further away to 1.0 cm from the end of the sensor. Type in **0.010** as Entry #2. Click Enter to record your typed in value.
  - Your typed in value for Entry #2 will appear in the Data list. The new default value for Entry #3 will reflect the pattern of the first two entries.
• Move the magnet another 0.5 cm away from the end of the sensor to 1.5 cm. Since the default value for Entry #3 is 0.015, click Enter to record it as the third value.
• Repeat the process of moving the magnet by 0.5 cm increments, and recording the values until the magnetic field strength reaches about 10 gauss, or doesn’t change as the distance increases.
• Click the Stop Sampling button in the Keyboard Sampling window to stop collecting data. The Keyboard Sampling window will disappear. Run #1 will appear in the Data List in the Experiment Setup window.
• Now save your experimental file, in case something hangs up later.

4. Analyzing the Data
Here the objective is to determine how the magnetic field of a dipole magnet decreases with distance from the magnet. You recall that the electric field of a point charge is given by \( E = \frac{kq}{r^2} \). This is a power law in \( r \), with exponent equal to \(-2\). Here you will analyze the strength of the magnetic field as a function of \( r \). Should the exponent be the same as for a point electric charge? We will see if your data is good enough to make a definite statement about this.

• Click the Graph display to make it active. Click the Statistics button to open the Statistics area on the right side of the Graph. Click the Autoscale button to rescale the Graph to fit the data.
• You are about to compare your data to a function of the form: \( B = a_1 + a_2 (x + a_3)^{a4} \)
• Your task is to see if the power \( a_4 \) is actually \(-2\) (like it is for electricity and gravity) or if it is a different number (like \(-3\) or \(-2.6\)).
• In the Statistics area, click the Statistics Menu button. Select Curve Fit, Power Fit from the Statistics Menu.
  o You may receive a message stating that there is no valid solution. If so, click on the \( a_4 \) parameter in the Statistics area. Type in \(-2\) and press <enter> or <return> on the keyboard to “lock in” your change. This corresponds to assuming a \( 1/r^2 \) type of field behavior. Write down the value of \( \chi^2 \) (the chi-squared). This is a measure of how well the curve fits the data; the smaller it is, the better the fit.
  o Now try different values of the \( a_4 \) parameter, and see what value (to one decimal place) gives the lowest chi-squared. Record values of \( a_4 \) and chi-squared in a table. When you find the value which gives the lowest chi-squared, you have carried out a least-squares fit to determine the coefficient of the power law that the magnetic field follows.
  o If you have trouble getting a good fit, you may want to try the following: Use the cursor to click-and-draw a rectangle around the section of data that appears to be most smooth. Then just fit that part of the data.

Q3. Does the magnetic field strength increase or decrease as the distance from the magnet increases?

Q4. Is the relationship between magnetic field strength and distance linear?

Q5. Which is a better fit: \( 1/r^2 \) or \( 1/r^3 \)? How do you know?

Q6. Based on the results of the curve fit in the statistics area, what do you conclude is the relationship between the magnetic field strength and the distance from the magnet?
Q7. The mathematical form used by Science Workshop to fit your data is $B = a_1 + a_2 (x + a_3)^{a_4}$. What is the physical interpretation of the fitting coefficient $a_1$?

Q8. Is the value of the fitting coefficient $a_3$ reasonable? Give its physical interpretation.

IV. EQUIPMENT
   - Horseshoe magnet
   - Two bar magnets
   - Roll of butcher paper
   - Compass
   - String
   - Two wire coils
   - Iron rod and Al rod and galvanometer
   - 5-V power supply
   - Science Workshop interface and computer system
   - Magnetic field sensor
   - Meter stick
   - Stand and hanger for hanging bar magnet