Lab 6. Magnetic Fields

Goals

- To visualize the magnetic fields produced by several different configurations of simple bar magnets using iron filings.
- To use small magnetic compasses to trace out the magnetic field lines of a single bar magnet on a large sheet of paper.
- To calculate the magnetic flux passing through the bar magnet by determining the locations of the points where the magnetic fields of the Earth and the bar magnet sum to zero.

Introduction

A magnetic field exerts forces on a compass needle such that the needle tends to align itself with the direction of the field. If the magnetic field is strong enough and additional non-magnetic forces (gravity, etc.) are negligible, then the compass needle points for all practical purposes in the direction of the field. In this lab the magnetic fields surrounding bar magnets are mapped out using a compass and iron filings.

The end of your compass needle that points toward the magnetic pole of the Earth in the northern hemisphere (when it is far away from other magnets and magnetic materials) is by definition a N (north-seeking) pole. Therefore Earth's magnetic pole in northern Canada is actually an S pole, since the N pole of the compass points to it and unlike poles attract. The N pole of the compass needle points toward the S pole of your magnet. The magnetic poles of all magnets can thus be labeled by means of a compass and the definition of an N pole.

Keep cell phones, credit cards, mechanical watches, etc. away from the big magnet on the TA table. Keep compasses at least 20 cm away from big magnet. The big magnet is used to "remagnetize" the bar magnets used in this laboratory. This can become necessary if the bar magnets are dropped or get too close to other magnets. If the poles are reversed on your bar magnet, or it is unusually weak, ask your teaching assistant to remagnetize it.

Mapping magnetic fields with iron filings

In the presence of a magnetic field, iron filings act like many small compass needles. By spreading them out on the paper above the magnet a "picture" of the magnetic field is produced. At your lab station you have a piece of particle board with some grooves in it to hold the bar magnets.

Do not pick up iron filings with the magnet. The filings are difficult to remove from the magnet. Place the jar on a clean piece of paper and open the lid. Filings often will spill out from under the lid. Gently lift the paper with filings off of the magnet. Let the paper sag to make a funnel of sorts, and then pour the filings into the jar. Then replace the jar cover.

Sketch field lines for isolated bar magnet

Draw a full scale outline of the bar magnet on fresh piece of paper and label the N and S poles. Place the bar magnet in the middle groove of the particle board and cover it with a second piece of white paper. Sprinkle iron filings around on the surface of this second sheet of paper. Gently tapping the board will often make the pattern of field lines more clear. Now on the first sheet of paper, with the outline of the bar magnet already drawn, make a careful free hand sketch of the magnetic field lines shown by the iron filings. **On your sketch include the direction of the field lines by means of arrows. By convention the field lines outside the magnet itself go from the N pole to the S pole.** Each member of your lab group is expected to draw their own sketch.

Sketch field lines for more complex configurations

Now repeat this process for the following configurations of bar magnets. In each case sketch the magnetic field lines and indicate the direction of the field lines everywhere on your sketch.

1. Place two bar magnets end-to-end in the same groove along the middle of the particle board with their N poles several centimeters apart.
2. Place two bar magnets side by side in parallel grooves with either like poles near or unlike poles near each other.
3. Pick another configuration of your choice.

Analyze your drawings

1. Describe the general characteristics of the fields that you observe.
2. On your sketches label the regions where the magnetic field is especially strong and where it is especially weak for each configuration. Are there any points where the field is essentially zero? Identify these locations clearly as well. Include the reasoning you use to identify these regions of strong and weak fields.
3. Can you find any places where the magnetic field lines cross? If there were a point in space where two field lines crossed, what would the direction of the field be at that point? If magnetic fields from two difference sources are present at some point in space—for instance, the magnetic fields of Earth and the bar magnet—will some iron filings feel forces from one field and other filings feel forces from the other field, or will all filings feel forces from both fields simultaneously? Discuss/explain.

Mapping a magnetic field with a compass

Equipment set up

1. Tape a large sheet of paper to the hardboard sheet (area about 1 m^2) located at your lab station. Orient a bar magnet at the center of the sheet as directed by your TA.
2. Carefully outline the bar magnet and mark the orientation of its magnetic poles on the sheet of paper.

Map the field

1. You can start your map anywhere in principle, but let's start with a point about 10 cm from the center of the magnet. Place the compass on your paper. Use a non-magnetic pencil (Check this carefully!) to put dots on the paper at the tip and tail of the arrow of the compass.
2. Now move the compass (approximately one diameter) so that the tail of the arrow is at the point where the tip was previously. Put a dot at the location of the tip of the arrow. Repeat this procedure until you move off the edge of the paper or run into the magnet itself.
3. To complete the field line in the other direction go back to the initial position, but this time move the compass so that the tip of the arrow is where the tail was previously. This time put a dot at the location of the tail of the arrow and repeat.
4. Connect all the dots with a smooth curve. This now constitutes one magnetic field line. Before proceeding put arrows on the line to indicate which way the magnetic field is pointing.
5. Choose a new starting point and repeat the procedure until you have filled your paper with field lines. Check with your TA to make sure that you have sufficiently mapped the field.

Analyze your map

1. Are there any regions on the map that the field lines seem to avoid? What is the magnetic field at these points? Explain your reasoning. How many such points are there on your map?
2. Look at the magnetic field maps drawn by the other lab groups in your lab section. Each map has been made with the bar magnet in a different orientation. Sketch simple halfpage diagrams of these other map configurations to include with your lab notes. Do these other maps have any features in common with your map? How do they differ from your map? Explain.

Calculating the magnetic flux of the magnet

When a magnet is immersed in the Earth's magnetic field, the resulting field is the vector sum of the magnet's field and Earth's field. In regions where the magnet's field is larger than Earth's field, a compass aligns itself more with the magnet's field. In regions where Earth's field dominates, a compass aligns more with Earth's field.

You should be able to see this effect on your magnetic field map. As you move away from the bar magnet and its field gets weaker, Earth's field, which is essentially constant everywhere on your map, begins to dominate. Use your knowledge of the magnetic field due to a bar magnet alone to predict the direction of the field due to only the bar magnet at the "special" point(s) that field lines have avoided. Note the direction of Earth's magnetic field at this same "special" point. This result suggests that the sum of the fields from the bar magnet and the Earth cancel at this point, summing to zero net field. Look at the other map configurations to determine whether this seems to be a general result.

Magnetic field lines exit the N pole of the magnet, circle around, enter the S pole of the magnet, and return through the magnet to the N pole. Since magnetic charges have never been observed, we can safely assume that every field line observed outside the magnet passes through the magnet itself. A useful measure of the strength of a magnet is the magnitude of the magnetic flux, Φ_{BAR}, passing through the magnet. This flux equals the product of the average magnetic field inside the magnet and its cross sectional area.

The pattern of magnetic field lines *outside* a magnet looks much like the pattern of electric fields lines from an electric dipole. That is, the vector sum of a radially outward field from a N pole and a radially inward field into a S pole will circle around from the N pole to the S pole outside the magnet, as observed. The critical difference between magnetic and electric dipoles is that the magnetic field lines complete the circuit through the magnet, running from the S pole to the N pole. In addition, the N and S poles are not right at the ends of the physical magnet. A sketch of the relation between a "fat" physical magnet and the ideal, thin magnet used to model it is shown in Figure 6.1.[1] Although the magnetic field is only approximated by the dipole field, the approximation is quite good at positions far from the magnet.

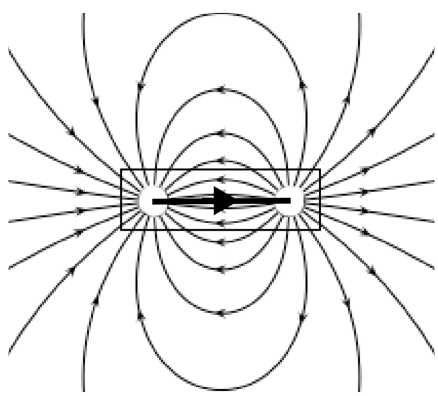

Figure 6.1. Sketch of the magnetic field due to an ideal, infinitely thin permanent magnet. The thick dark line represents the ideal magnet, while the dotted line outlines the corresponding physical magnet.

We will use this approximation to determine the magnetic flux of the bar magnet. That is, we will treat the magnetic field *outside* the magnet, $\mathbf{B_{BAR}}$, as the sum of a vector directed away from the N pole, $\mathbf{B_N}$, and another vector directed into the S pole, $\mathbf{B_S}$.

[1]The image of the field lines, without the magnets, was supplied by the Wikimedia Commons.

$$\mathbf{B_{BAR}} = \mathbf{B_N} + \mathbf{B_S} \quad , \tag{6.1}$$

where $\mathbf{B_N}$ and $\mathbf{B_S}$ vary with distance like electric fields (Coulomb's law). In the case of magnets, however, the source of these fields are the magnetic fluxes leaving the N pole and entering the S pole. At distances far from the poles, the equation for the magnetic field due to one pole can be obtained from Coulomb's law by replacing q/ε_0 with Φ_{BAR}. (The total electric flux from a positive point charge is q/ε_0 by Gauss's Law.)

$$\begin{aligned}
\mathbf{B_N} &= \frac{\Phi_{BAR}}{4\pi\, r_N^2} \qquad \{\text{Pointing radially away from the north pole}\}, \text{ and} \\
\mathbf{B_S} &= \frac{\Phi_{BAR}}{4\pi\, r_S^2} \qquad \{\text{Pointing radially away from the south pole}\}.
\end{aligned} \tag{6.2}$$

Figure 6.2 shows a typical null point and the vectors $\mathbf{B_N}$ and $\mathbf{B_S}$ showing the contribution of the magnet's N and S poles to the magnetic field at the null point. In the equations and the diagram, r_N is the distance from the N pole of the magnet to the null point and r_S is the distance from the S pole of the magnet to the null point. Since the magnetic field is a vector quantity we must be careful to add the fields associated with the N and S poles as vectors.

On the magnetic field map you made with a compass, choose one of the special "null" points where the magnetic fields of Earth and the bar magnet cancel one another. Earth's magnetic field actually points downward at an angle of about 70° relative to the surface of Earth at the latitude of Pullman, but the magnetic field map you have drawn lies only in a horizontal plane. Further, our compasses are constrained to rotate only about a vertical axis, so they respond only to the horizontal (parallel to Earth's surface) component of Earth's magnetic field. In other words the magnetic field of the bar magnet cancels only the horizontal component of Earth's field at a null point. That is,

$$\mathbf{B_N} + \mathbf{B_S} + \mathbf{B_{Earth}} = \mathbf{0} \qquad \{\text{horizontal component only}\} \tag{6.3}$$

at a null point. The magnitude of the horizontal component of Earth's field is 1.9×10^{-5} T here at Pullman. Show the direction of Earth's field on your map at your null point. Now you know the horizontal component of $\mathbf{B_{Earth}}$ (both direction and magnitude) at the null point. Define a coordinate system with its origin at the null point and with the positive x-axis in the direction of Earth's magnetic field at the null point, as shown in Figure 6.2. Draw this coordinate system directly on your field map. This choice of coordinate system simplifies the equations so that we only need to look at the x-components of $\mathbf{B_N}$ and $\mathbf{B_S}$. Then you can draw radial lines from the N and S poles of the bar magnet to the null point. The lengths of these lines give you r_N and r_S. After measuring the angles θ_N and θ_S (shown in Figure 6.2), you can calculate the x-components of the magnetic fields associated with $\mathbf{B_N}$ and $\mathbf{B_S}$ in terms of Φ_{BAR}. Since Φ_{BAR} is the only remaining unknown, you can complete the solution.

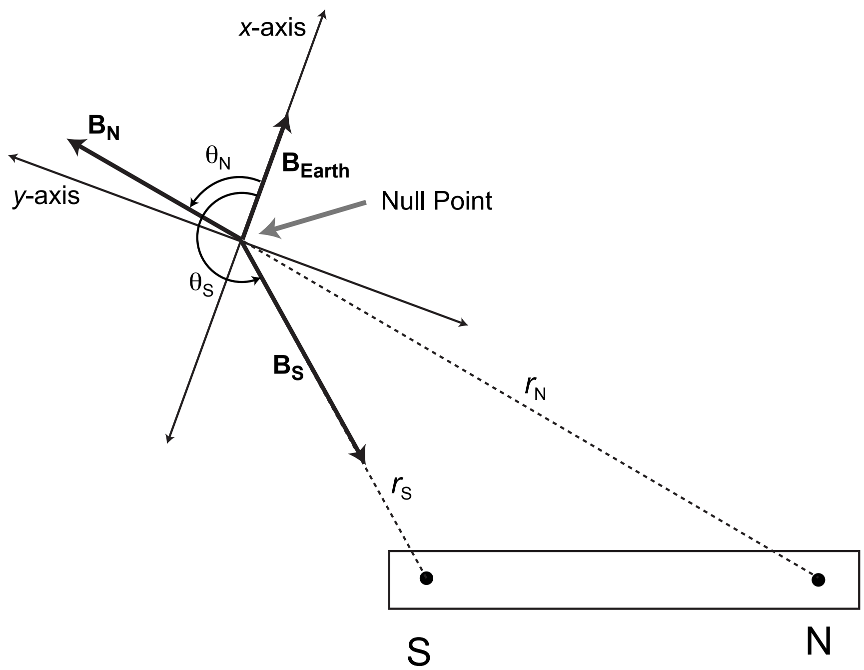

Figure 6.2. Diagram of a coordinate system with its origin at a null point and with its $+x$-axis pointing in the direction of the Earth's magnetic field vector, $\mathbf{B_{Earth}}$. Also shown are $\mathbf{B_N}$ and $\mathbf{B_S}$, vectors that mathematically represent the contribution of the N and S poles of the magnet to the magnetic field at the null point. The distances from null point to the N and S poles of the magnet are labeled r_N and r_S, respectively.

Before you leave the lab please:

- Return the bar magnet(s) to the TA Table.
- Put your rulers, compasses, and iron filings in the basket at your workstation.
- Straighten up your lab station.
- Report any problems or suggest improvements to your TA.