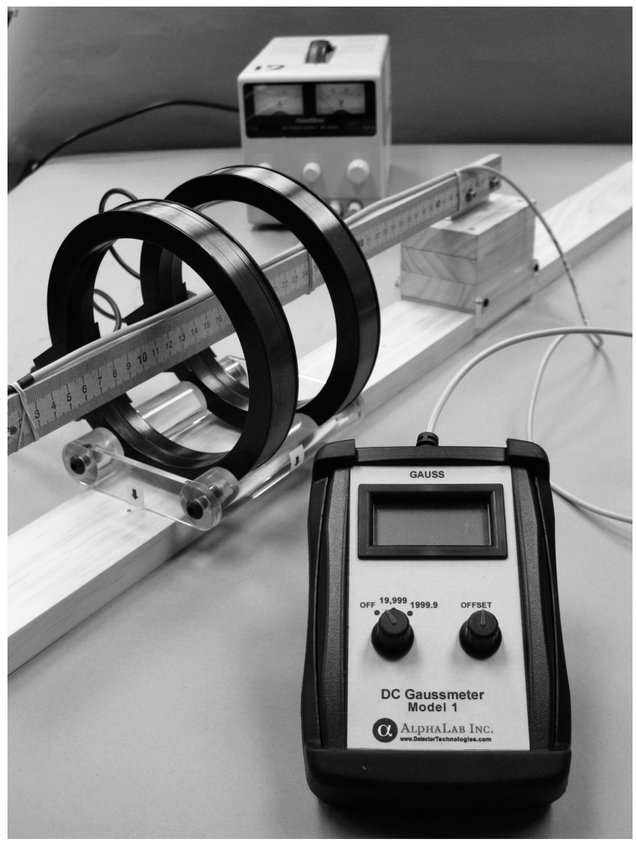
Chapter 5

Magnetic Fields and Forces



Helmholtz coils and a gaussmeter, two of the pieces of equipment that you will use in this experiment.

5.1 Introduction

Just as stationary electric charges produce electric fields, moving charges (currents) give rise to magnetic fields. In this lab you will investigate the magnetic field produced by different arrangements of currents, starting with the field of the Earth itself. You will then study the field of a straight wire, and use a sensitive force-measuring apparatus (for which our depertment recently received a national award!) to study the right-hand rule and the force on a current-carrying wire. Next, you'll study the field of a circular coil, and a special arrangement of two coils known as Helmholtz coils. Finally, you will also use a Slinky to understand the field of a solenoid. This laboratory normally takes two lab periods to complete.

Reading and Key Concepts

Before starting this lab, you should be familiar with the following physical concepts. If you need to review them, or if you haven't yet discussed them in your lecture course, consult the indicated section in Cutnell & Johnson, *Physics*.

- Magnetic fields, §21.1-3
- Force on a current due to a magnetic field, §21.5
- Solenoids, §21.7
- Ampère's Law, §21.8

Apparatus

- Power supply, digital current meter; moving coil current meters
- Digital multimeter (GoldStar DM332 or similar)
- Compasses; dip-angle compass
- DC Gaussmeter
- Oersted Table
- 6V Lantern Battery
- Pair of matched solenoid electromagnet coils (Helmholtz coil pair: TEL502 or equivalent)
- Stand for Helmholtz coil pair
- Slinky solenoid and mounting board with hooks
- Probe stands for solenoid and Helmholtz coils measurements
- Magnetic Force Balance Table
- Digital Pocket Scale (Jennings JS-50x or similar)
- Rotating magnet stand

Figure 5.1: Measuring the magnetic field using the gaussmeter.

5.2 Preliminaries

5.2.1 Units

The SI unit for magnetic field is the *Tesla* (T). The Tesla is named after the eccentric but brilliant scientist Nikola Tesla, who developed many of the magnetic devices used to generate and use AC (alternating current) electrical power on a large scale.

One Tesla is equivalent to 10,000 *gauss*, where the gauss is an earlier unit that is still in common usage. Since the Tesla is a very large unit, corresponding to an unusually strong field, it is more common to use units of *millitesla* (mT) or *gauss* (G),

$$1\text{G} = 10^{-4}\ \text{T} \tag{5.1}$$

For example, the Earth's field is about 0.5 G. The gaussmeter that you will use in this experiment also measures in *gauss*.

5.2.2 Equipment

Magnetic Field Sensor (Gaussmeter)

The device used to measure magnetic fields is traditionally called a "gaussmeter" (for reasons explained in Section 5.2.1). The magnetic field is a vector quantity, and while the compass is only sensitive to its direction, the gaussmeter is sensitive to both its magnitude and direction. The sensitive area of the probe is a small spot located a few mm from the end of the probe tip, marked with a white dot. The probe measures the *component* of the magnetic field that is perpendicular to the probe face. This is illustrated in Figure 5.1.

In this experiment, you will use the 1999.9 G setting on the gaussmeter.

5.3 The Experiments

5.3.1 The Earth's Field

Procedure

The Earth's magnetic field is both familiar and a potential source of systematic error in many of our experiments, so it is important to know both its magnitude and its direction. In order to measure the magnitude of the Earth's field, we must first align the gaussmeter with the field. On the table in the middle of the room, there is a piece of tape indicating the direction of the field *in the plane of the table*. Use one of your compasses to confirm that it is correctly oriented. Note that this does not tell us anything about the *vertical* component of

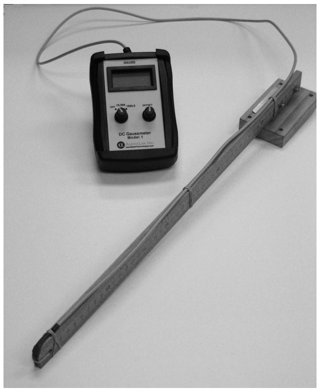


Figure 5.2: Gaussmeter.

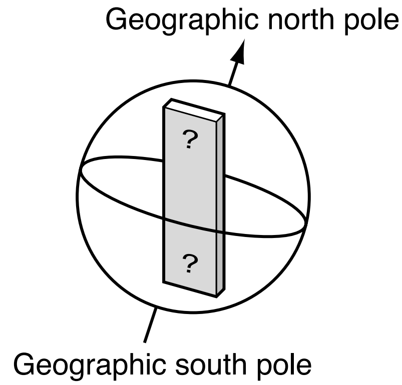


Figure 5.3: The earth is a magnetic dipole.

the Earth's field. Now, line up the dip compass with the piece of tape – when the needle stops moving, it should be pointing in the direction of the Earth's field. Line up your gaussmeter and take a measurement. We will call this measurement B_+. Then, point your meter in the exact *opposite* direction and take another measurement. This measurement is B_-. To find a value for earth's field, take $B_E = \frac{1}{2}(B_+ - B_-)$. (Note that this is not an average, since the average would involve taking the sum. Why do we take the *difference* of the two measured values here?)

Analysis

Record your data on your worksheet. Include a sketch indicating the direction of the field relative to the floor or vertical.

You should observe that the magnitude of the earth's field at Ann Arbor is about 0.5 gauss, and it points nearly *vertically* (and a little northward) into the earth. The angle which the earth's field makes with the vertical is called the "dip angle." The dip angle will depend on the position on the earth's surface (i.e., the *latitude*) relative to the earth's north-south axis. At the latitude of Ann Arbor (43°; i.e., about half way between the equator (0°) and the north pole (90°)), the dip angle will be about 20° with respect to the vertical.

Your compass lines up with magnetic fields because it is a magnetic dipole – the north pole points in the direction of the magnetic field. You know that the *magnetic* north pole of the compass usually points (roughly) toward the *geographic* north pole of the Earth. You can think of the Earth's magnetic field as being generated by a bar magnet, as illustrated in figure 5.3. How is this bar magnet oriented? That is, what kind of *magnetic* pole is found near the north *geographic* pole?

5.3.2 Magnetic Field Near a Current-Carrying Wire

Procedure

Connect the 6V lantern battery to the oersted apparatus shown in Figure 5.4. Arrange four small compasses at equidistant points around the wire on the stand. Press the red button on top of the apparatus to complete the circuit and note the change in the compass needles. **WARNING: Do not leave the switch closed for more than a few seconds. This**

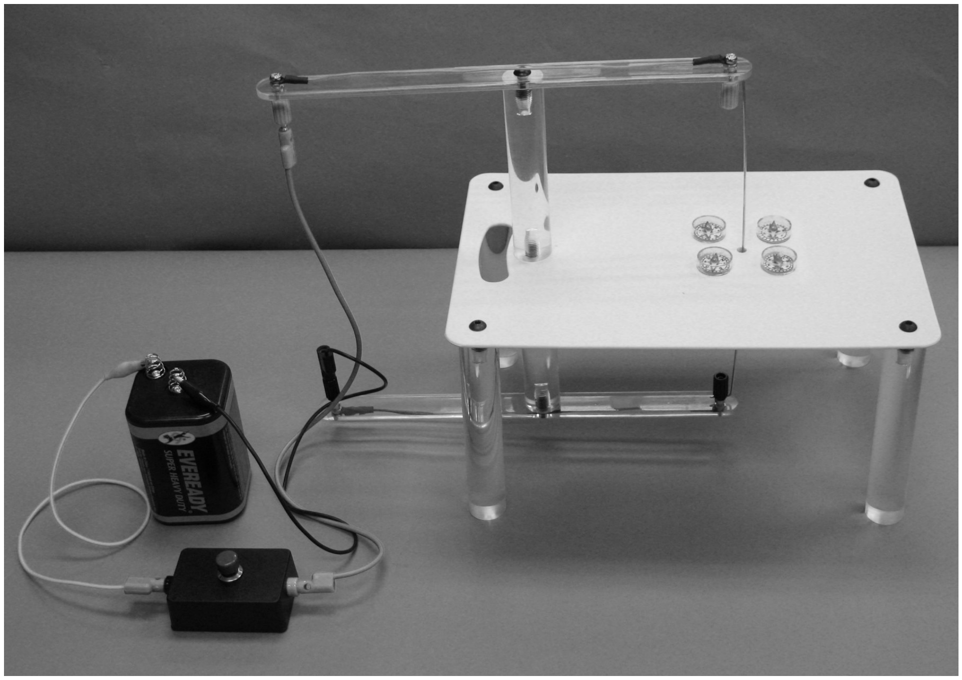


Figure 5.4: Oersted apparatus to study the magnetic field of a straight wire.

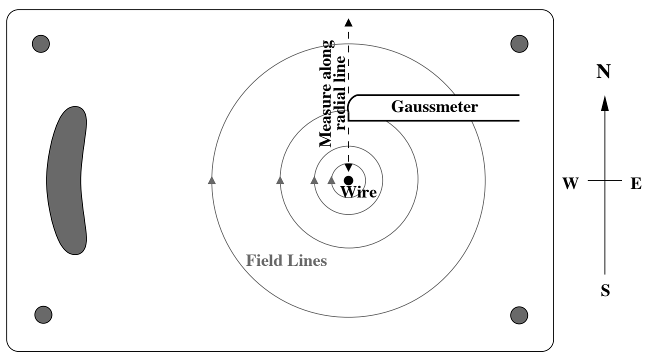


Figure 5.5: Determining the radial dependence of the magnetic field of a straight wire.

will drain the battery. Be sure to note which way the compass needles move, and what happens when the current is turned on and off. Reverse the leads on the battery and again note the change in the compasses.

You have just seen that the field lines generated by the current are circles centered on the wire. You will now determine the radial dependence of the field – how quickly the field weakens as you move away from the wire. Position the gaussmeter so that the sensitive portion of the probe is perpendicular to the field lines generated by the current. Place the probe handle along the east-west direction so that as little of the earth's field as possible is entering the probe, as in figure 5.5. Depress the switch and measure the magnetic field at distances of 1-5 cm from the wire in 0.5 cm increments, being careful not to leave the switch closed for more than a few seconds. ***Remember to take into account the position of the sensitive spot of the probe. It is not located at the very tip of the probe – see section 5.2.2.***

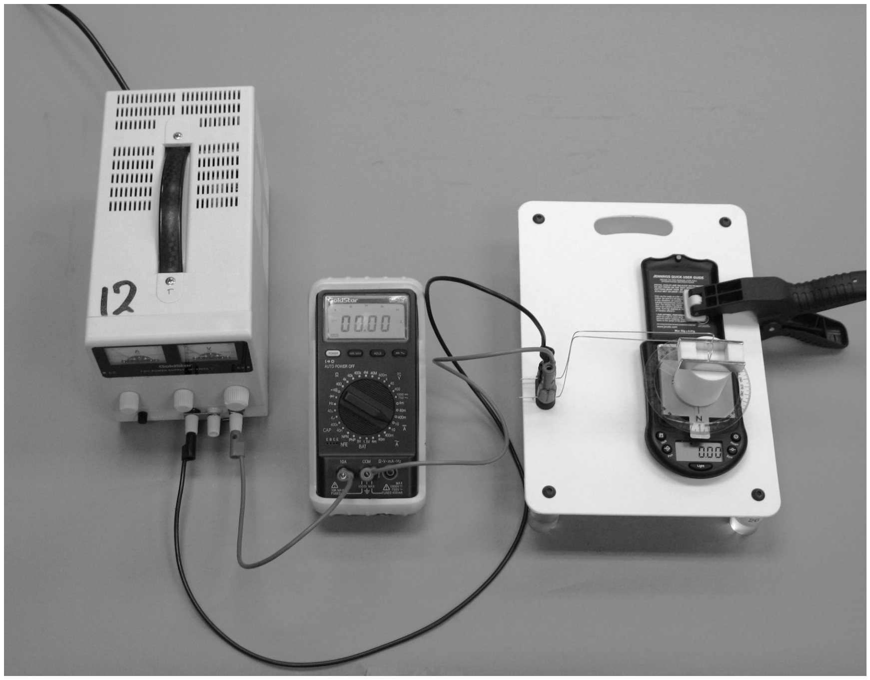


Figure 5.6: Setup to study the force on a current-carrying wire.

Analysis

Record your observations of the compasses on your worksheet. Why are the compass needles oriented the way they are when the battery is disconnected? What happens to the compasses when there is current in the wire? What was the effect of reversing the leads? Apply the "right hand rule" to the system. Which direction do you expect the field to point? Do your observations agree with this expectation?

Using what you know, predict the relationship between the magnetic field strength and distance from the wire. Make a plot of the magnetic field strength (in gauss) as a function of the distance from the wire. What is the shape of your graph? Does it agree with your prediction?

5.3.3 Magnetic Force Balance

Procedure

Next you will investigate how the force experienced by a current-carrying wire in a magnetic field depends on the current in the wire and the angle between the current and the field. **The apparatus you will use is fragile, and designed to be operated with minimal adjustment. Do not disassemble the apparatus after the experiment. If your setup does not look like that in figure 5.6, ask your GSI for assistance.**

Set up the Magnetic Force Balance apparatus shown in Figure 5.6. This device consists of a pocket digital scale, a pair of strong permanent magnets arranged to produce a roughly constant field, and a short segment of wire. The magnets can rotate on a small turntable. Make sure that the wire does not touch the magnets and that it is in the center of the gap. **If the wire is touching the magnet, DO NOT try to adjust the wires themselves.**

Figure 5.7: The magnetic field *between the magnets* points from one magnet to another, toward the "N" on the compass. Here the current and the magnetic field are parallel, so the net force is zero.

Instead, gently slide the magnet stand until the wires are no longer touching the magnet. If you aren't sure what to do, ask your GSI for assistance. Turn on the scale and zero it using the button on the lower right corner. Set the dial on the magnet stand to be at 90°, re-zeroing the scale if neccessary. Adjust the current on the power supply to 2.0 A and record the force (in grams) on the scale. Notice the way that the wire moves when the power supply is turned on and off. Turn off the power supply and reverse the leads going to it. Re-zero the scale, turn on the power supply, and record the force. Again note the direction the wire moves when the power supply is turned on and off. This process is a nice illustration of Newton's Third Law. We actually measure the force that the magnets exert on the wire by measuring the equal and opposite force that the wire exerts on the magnets (which then exert a force on the scale).

With the dial on the scale set to 90° and the scale properly zeroed, measure the force as a function of the current for values of 0.5-3.0 A at 0.5 A increments. Be sure to re-zero the scale if neccessary between measurements.

With the power supply off, set the dial on the scale to 0°. Make sure that the wire does not touch the magnets and that it is in the center of the gap. Re-zero the scale and adjust the power supply to 2.0 A. Record the force on the scale. Turn off the power supply and rotate the dial to 30°. Again check the orientation of the wire and re-zero the scale. Turn on the power supply and record the force. Repeat this measurement at angles of 45°, 60°, 90°, and 270°, being careful to re-zero the scale and check the orientation of the wire between measurements.

Analysis

Describe the movement of the wire when the power supply is turned on and off. How did reversing the leads affect this?

For a wire element l carrying a current I in a magnetic field $\mathbf{B}$, the resulting magnetic force on the vector current $\mathbf{I}$ is given by

$$\mathbf{F} = \mathbf{I}L \times \mathbf{B}. \tag{5.2}$$

The magnitude of the force is therefore given by

$$F = ILB\sin\theta, \tag{5.3}$$

where θ is the angle between the current and magnetic field directions. The direction of this force is determined by the right hand rule.

Using these equations and your measurement of the force at 90°, calculate the strength of the magnetic field between the magnets. How does it compare to the strength of the Earth's field measured earlier in the lab?

Using your observations of the wire movement and the direction of the force, verify the *right hand rule*. Using what you know about forces, explain why the sign of the force changes in certain situations.

Plot your data of the Force (in grams) as a function of the current. Is the graph *linear*? What is its slope? Is this what you would expect? Why or why not?

Using what you know about magnetic force, what do you expect the graph of the Magnetic Field vs. angle to look like? Graph your data. Does it agree with your prediction? What do you notice about the magnetic field at 270° in comparison with that of your other data points? Why is this the case?

5.3.4 Magnetic Field of a Coil

Procedure

Place one of the $N = 320$ turn coils in the coil stand as shown in Figure 5.8. With the power supply turned off and the current knob turned all the way down, connect the coil to the power supply. Mount the probe on the probe stand and position it 10 cm from the center of the coil, on the axis of the coil. Turn on the power supply and adjust the current to 0.5 A. Measure the magnetic field strength along the axis in 1.0 cm increments from −10 cm to 10 cm (take 0 cm to be at the center of the coil).

Analysis

Plot your data of the magnetic field strength (in gauss) as a function of the distance along the axis.

It can be shown that the magnetic field along the axis of a circular coil such as this is

$$B(z) = \frac{\mu_0 N R^2 I}{2(R^2 + z^2)^{3/2}}, \tag{5.4}$$

where N is the number of turns, R is the radius of the coil, and z is the distance from the observation point to the center of the coil. Evaluate this expression for $z = 0, 3, 6$ cm. How well do your measurements agree with the prediction? You can also try graphing this expression on your calculator and comparing the shape with the graph from your own data.

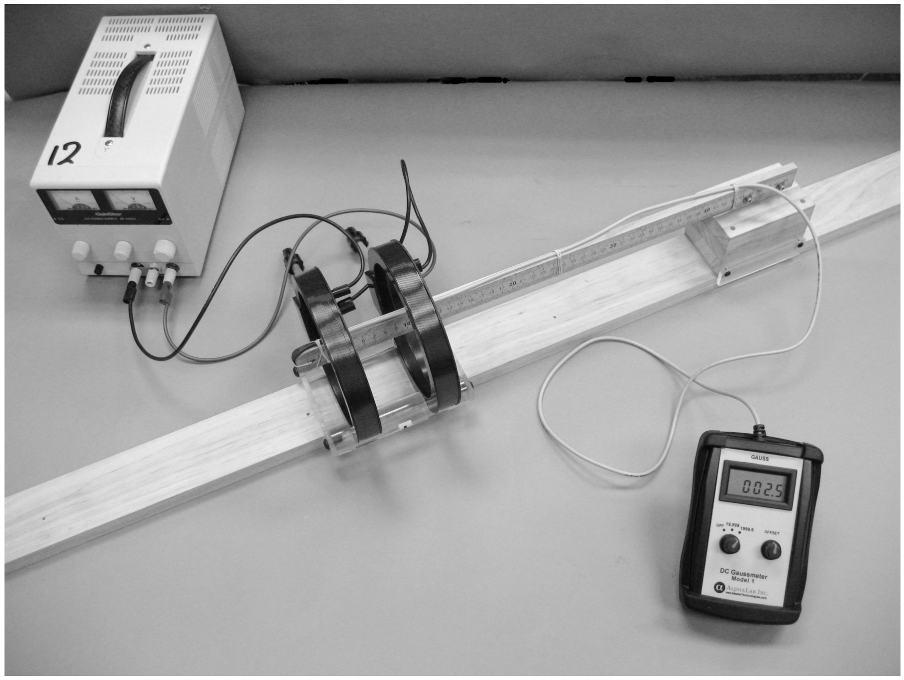


Figure 5.8: Setup for measuring the magnetic field of one and two coils.

5.3.5 Magnetic Field of Helmholtz Coils

Procedure

Now that you know what the magnetic field of a single coil looks like, you will test what the field of two coils connected in series looks like. Helmholtz coils are two identical coils that are separated by a distance equal to the radius of the coils, in this case 7 cm. Using the same equipment as in the previous experiment you will map the magnetic field of these coils.

Place the second coil in the stand. (The stand ensures that the coils are aligned and separated by the correct distance.) With the power supply turned off, connect the added coil in series with the other coil. Position the probe in the probe stand 10 cm outside one of the coils. Measure the magnetic field strength along the axis of the coils at 1.0 cm increments from 10 cm outside one coil to 10 cm outside the other (Take 0 cm to be at the center of the two coils. This should make your measurements go from -13.5 cm to 13.5 cm).

Analysis

Using what you know about the superposition of magnetic fields and your graph from the previous section, predict what the graph of the magnetic field (in gauss) vs. axial distance will look like for pair of coils. Plot your data and see if it agrees with your prediction. Do you notice anything special about the field between the two coils? Why might this arrangement be useful in real world applications? You will use these Helmholtz coils when you measure the charge-to-mass ratio of the electron later in this course.

Figure 5.9: You can study the magnetic field of a solenoid using a Slinky and the gaussmeter.

5.3.6 Magnetic Field of a Solenoid

Procedure

A solenoid is a very long coil of wire. We will use a Slinky to investigate how the magnetic field of a solenoid is different from the magnetic field of a typical coil, and how the magnetic field is affected by various factors.

Using the board and hooks, stretch the Slinky to 1.0 m in length (the distance between holes on the board is 25 cm) and lock it in place. Connect the power supply to the Slinky using alligator leads (See Figure 5.9) and count the number of turns between the leads. Turn on the power supply and adjust the current to 1.0 A. Using the gaussmeter, measure the magnetic field at various points along the axis of the solenoid. Be sure to include measurements on the inside of the coil, near the ends, and outside of the solenoid.

Adjust the length of the solenoid to 0.5 m. Lock the gaussmeter into the probe stand and position it at the end of the solenoid. With the current set to 1.0 A, measure the magnetic field strength. Using 1.0 cm increments measure the magnetic field strength along the axis toward the center of the coil, until it appears that the field has reached a constant value.

Position the probe near the center of the Slinky. Measure the strength of the magnetic field for currents of 1.0-3.0 A at 0.5 A increments.

With the power supply off, change the length of the solenoid to 0.5 m using the board and hooks. Be careful not to change the position of the alligator leads or you may change the number of turns that current passes through. Reposition the gaussmeter so that it is near the center of the Slinky. Again turn the power supply on and adjust the current to 2.0 A. Measure the strength of the magnetic field. Repeat this for lengths of 0.75 m, 1.25 m and 1.5 m as well, being careful not to change the location of the gaussmeter.

Analysis

Describe the strength of the magnetic field inside and outside of the solenoid. How strong do you expect the magnetic field to be near the ends of the solenoid in comparison with the field near the center of the solenoid? What did you measure the magnetic field to be like? Do your measurements agree with your prediction? Why or why not?

Make a plot of your data for the magnetic field of the solenoid, B, vs. the distance, z, along the axis. At what distance inside the solenoid does the magnetic field reach a constant value B_0? Using the radius of the Slinky, convert this distance to the number of radii into the solenoid one must be to have a constant magnetic field. This data can be used to find a universal relation between the strength of the magnetic field of a solenoid and the position in terms of the radius of the solenoid. Make a plot of B/B_0 vs. z/R where B_0 is the strength of the magnetic field when it reaches a constant value and R is the radius of the solenoid. What are the units for the graph? What does this graph show and how might it be used in further investigations of solenoids?

Plot your data of the magnetic field (in gauss) produced near the center of the coil as a function of the current in the coil. Does the data obey a *linear* relationship? Is the field *proportional* to the coil current? Determine the equation which describes your data, giving the field as a function of the solenoid current I (in amps).

For a solenoid (a very long coil of wire), the magnetic field at the center is given by $B = \mu_0 NI/L$, where N is the number of turns of wire in the coil, L is the length of the coil, and $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 is a constant. Are your results consistent with this equation? If not, why do you think this is the case?

Calculate the number of turns per unit length for each length of the Slinky. Plot your data of the magnetic field (in gauss) of the Slinky as a function of the turns per meter. Is this relationship *linear*? Draw a best-fit line and determine its slope. Using what you know about the magnetic field within a solenoid, calculate μ_0. How does this compare to the actual value? Why might your calculated value be different from the known value?

5.4 Test Your Understanding

1. A conducting loop lies in the plane of this page, and is wired to a battery that produces a constant clockwise current in the coil. Which of the following statements describes the field produced *by the coil*?

   (a) a constant magnetic field directed into the page;

   (b) a constant magnetic field directed out of the page;

   (c) an increasing magnetic field directed into the page;

   (d) a decreasing magnetic field directed into the page;

   (e) a decreasing magnetic field directed out of the page.

2. If the magnetic field vector is directed toward the north and a positively charged particle is moving toward the east, what is the direction of the magnetic force on the particle?

   (a) up;

(b) west;
(c) south;
(d) down;
(e) east.