Name ______________________ Date __________ Partners ______________________

The Magnetic Field in a Slinky

A CBL lab.

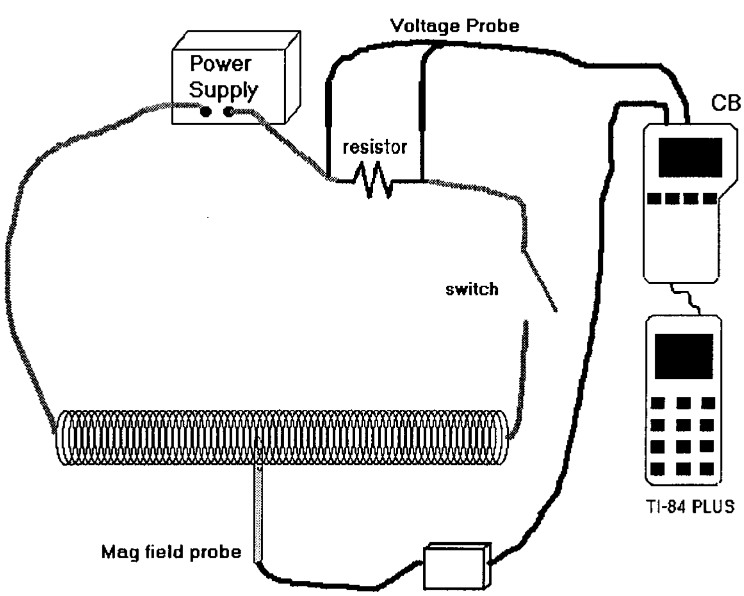
A solenoid is made by taking a tube and wrapping it with many turns of wire. A metal Slinky™ is the same shape and will serve as our solenoid. When a current passes through the wire, a magnetic field is present inside the solenoid. Solenoids are used in electronic circuits or as part of an electromagnet.

In this lab we will explore factors that affect the magnetic field inside the solenoid and study how the field varies in different parts of the solenoid. By inserting a Magnetic Field Sensor between the coils of the Slinky™, you can measure the magnetic field inside the coil. You will also measure μ_0, the permeability constant. The permeability constant is a fundamental constant of physics.

To determine the current through the solenoid you will measure the voltage across a 1-Ω resistor in series with the solenoid. Using Ohm's law, $I = V/R$, we find, for example, that a voltage of 2 V across the resistor will correspond to a current of 2 A through the resistor.

OBJECTIVES

Determine the relationship between magnetic field and the current in a solenoid.
Determine the relationship between magnetic field and the number of turns per meter in a solenoid.
Study how the field varies inside and outside a solenoid.
Determine the value of μ_0, the permeability constant.



Modified from John E. Gastineau, Kenneth Appel, Clarence Bakken, Richard Sorensen, and David L. Vernier, *Physics with a CBL,* 1998. 29-1 – 29-4T.

Figure 1

MATERIALS

- TI-82, **83**, 86, 89, 92, 92 Plus, or 84 plus
- CBL System
- PHYSICS program loaded in calculator
- Vernier Magnetic Field Sensor
- TI Voltage Probe
- Slinky™
- graph paper
- Vernier adapter cable
- meter stick
- DC power supply
- 1-Ω power resistor
- cardboard spacers
- clip-lead connecting wires
- momentary-contact switch
- tape and cardboard

INITIAL SETUP

1. Stretch the Slinky until it is about 1 m in length. The distance between the coils should be about 1 cm. Use a non-conducting tape to hold the Slinky™ at this length.
2. Set up the circuit and equipment as shown in Figure 1. Connect the TI Voltage Probe across the resistor, with the positive (red) lead on the side of the resistor connecting to the positive side of the power supply. Wires with clips on the end should be used to connect to the Slinky™.
3. Connect the TI Voltage Probe to the CH 1 port of the CBL unit. Connect the Vernier Magnetic Field Sensor to the CH 2 port of the CBL unit. Set the switch on the sensor to *High*.
4. Turn on the CBL unit and the calculator. Start the PHYSICS program and proceed to the MAIN MENU.
5. Set up the calculator and CBL for the Voltage Probe and the Magnetic Field Sensor.
   - Select SET UP PROBES from the MAIN MENU.
   - Select TWO as the number of probes.
   - Select VOLTAGE from the SELECT PROBE menu.
   - Confirm that it is connected to CH 1, and press ENTER.
   - Select MAGNETIC FIELD from the SELECT PROBE menu.
   - Confirm that it is connected to CH 2, and press ENTER.
   - Select USE STORED from the CALIBRATION menu.
   - Select HIGH(MTESLA) from the MG FIELD SETTING menu.
6. Monitor the magnetic field from the calculator screen. The reading is updated about once a second.
   - Select COLLECT DATA from the MAIN MENU.
   - Select MONITOR INPUT from the DATA COLLECTION menu.
   - The voltage across the 1-Ω resistor will be displayed on the CH 1 line of the calculator screen. 1 V corresponds to 1 A, 2 V corresponds to 2 A, and so forth.
   - The magnetic field reading will be displayed on the CH2 line of the calculator.
7. Turn on the power supply and adjust it so that the current reads 2.0 A on the calculator screen when the switch is held closed. Make sure the current limitation on the power supply does not limit you to a value below 2.0 A. Open the switch after you make the adjustment.

   Warning: This lab requires fairly large currents to flow through the wires and Slinky™. Only close the switch so the current flows when you are taking a measurement. The Slinky™, wires, and possibly the power supply may get hot if left on continuously.

PRELIMINARY QUESTIONS

1. Hold the switch closed. The current should be 2.0 A. Place the Magnetic Field Sensor between the turns of the Slinky™ near its center. Rotate the sensor and determine which direction gives the largest positive magnetic field reading.

   Question 1: What direction is the white dot on the sensor pointing when you have the maximum reading for the magnetic field?

   Question 2: What happens if you rotate the white dot to point the opposite way?

   Question 3: What happens if you rotate the white dot so it points perpendicular to the axis of the solenoid?

2. Insert the Magnetic Field Sensor through different locations along the Slinky to explore how the field varies along the length. Always orient the sensor to read the maximum magnetic field at that point along the Slinky.

   Question 4: How does the magnetic field inside the solenoid seem to vary along its length?

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3. Check the magnetic field intensity just outside the solenoid.

Question 5: How is the magnetic field outside different from the field inside the solenoid?

Open the switch when you are done.

PROCEDURE

Part I How Is The Magnetic Field in a Solenoid Related to the Current?

For the first part of the experiment you will determine the relationship between the magnetic field at the center of a solenoid and the current flowing through the solenoid. **As before, leave the current off except when making a measurement.**

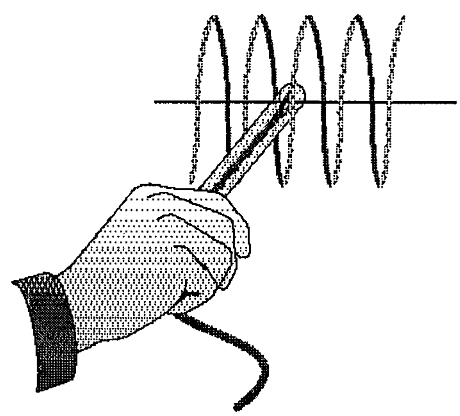

Figure 2

1. Place the Magnetic Field Sensor between the turns of the Slinky™ near its center.
2. Close the switch and rotate the sensor so that the white dot points directly down the long axis of the solenoid, in the direction that gives the maximum positive reading. This will be the position for all of the magnetic field measurements for the rest of this lab. Open the switch to turn off the current.
3. To remove readings due to the Earth's magnetic field, any magnetism in the metal of the Slinky, or the table,
   - Press [+] and select RETURN TO MAIN.
   - Select ZERO PROBES from the MAIN MENU.
   - Select CHANNEL 2 from the SELECT CHANNEL menu.
   - Press and release [CH VIEW] on the CBL until the CH2 indicator is flashing. This displays the magnetic field reading on the CBL.
   - Once the reading is stable, press [TRIGGER] on the CBL.
4. Set up the calculator and CBL for data collection.
   - Select COLLECT DATA from the MAIN MENU.
   - Select TRIGGER from the DATA COLLECTION menu.
5. You will take data of the magnetic field for a series of currents. The first point will be for zero current. The current is off, and the switch is open.
   - Press [TRIGGER] on the CBL unit to record the current and the magnetic field.
   - Select CONTINUE from the TRIGGER menu.

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6. Now take additional points with the current flowing.
   - Close the switch for the rest of this run.
   - Press and release [CH VIEW] on the CBL until the CH1 indicator is flashing. This displays the voltage across the 1-Ω resistor (equivalent to the current through the resistor in amperes).
   - Set the current to 0.5 A. (You may have to use the CBL reading to set the current, but note the CBL and calculator read slightly different. We will end up using the values the calculator records.)
   - Press [TRIGGER] on the CBL unit to record the current and the magnetic field.
   - Select CONTINUE from the TRIGGER menu.

7. Repeat Step 6 up to a maximum current of 2.0A, in steps of 0.25 A. After the last current entry, select STOP instead of CONTINUE. Open the switch.

8. Sketch your graph of magnetic field *vs.* current. Note that although your calculator is plotting voltage on the x axis, the values correspond directly to current in amperes since you are using a 1-Ω resistor.

   Sketch of magnetic field vs. current from graphing calculator:

9. If the graph appears linear, fit a straight line to your data.
   - Press [ENTER], and select NO to return to the MAIN MENU.
   - Select ANALYZE from the MAIN MENU.
   - Select CURVE FIT from the ANALYZE MENU.
   - Select LINEAR L2, L3 from the CURVE FIT menu.
   - Record the slope and intercept in your Data Table, including any units for these values.
   - Press [ENTER] to see the fitted line with your data.
   - Press [ENTER] to return to the MAIN MENU.

   Note: You may find the zero current value results in a poor fit. If you record your values, you can do a fit in Excel with or without the zero value.

10. Count the number of turns of the Slinky and measure its length. If you have any unstretched part of the Slinky at the ends, do not count it for either the turns or the length. Calculate the number of turns per meter of the stretched portion. Record the length, turns, and the number of turns per meter in the Data Table 1.

Modified from John E. Gastineau, Kenneth Appel, Clarence Bakken, Richard Sorensen, and David L. Vernier, *Physics with a CBL,* 1998. 29-1 – 29-4T.

Data Table I

Magnetic field *vs.* Current	
Slope	
Intercept	
Length of solenoid (m)	
Number of turns	
Turns/m (m^{-1})	

Part II How is the Magnetic Field in a Solenoid Related to the Spacing of the Turns?

For the second part of the experiment, you will determine the relationship between the magnetic field in the center of a coil and the number of turns of wire per meter of the solenoid. You will keep the current constant. Leave the Slinky set up as shown in Figure 1. Position the sensor as it was before, so that it measures the field down the middle of the solenoid. You will be changing the length of the Slinky from 1.0 to 2.0 m to change the number of turns per meter.

11. Use the length and number of turns of your Slinky from Part I and record the values in the first line of the Data Table 2.

12. Since the Slinky is made of an iron alloy, it can be magnetized itself. Moving the Slinky around can cause a change in the field, even if no current is flowing. This means you will need to zero the reading *each* time you move or adjust the Slinky, even if the sensor does not move.
    - Select ZERO PROBES from the MAIN MENU.
    - Select CHANNEL 2 from the SELECT CHANNEL menu.
    - With the current off, press [TRIGGER] on the CBL.

13. Set the current and measure the magnetic field.
    - Select COLLECT DATA from the MAIN MENU.
    - Select MONITOR INPUT from the DATA COLLECTION menu.
    - Close the switch to turn on the current, and adjust the current to 1.0 A. The current reading is on the CH1 line of the calculator display.
    - Read the magnetic field from the CH2 line of the calculator screen when the reading is stable.
    - Record the field value in Data Table 2.
    - Turn off the switch.
    - Press [+] and then select RETURN TO MAIN.

14. Repeat Steps 12 and 13 after changing the length of the Slinky to 1.0 m, 1.5 m, and 2.0 m. Record the length in Data Table 2. Keep the number of turns and the current the same each time. Each time, zero the Magnetic Field Sensor with the current off.

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Data Table 2

Length of Solenoid (m)	Turns/meter n (m^{-1})	Magnetic Field B (mT)

DATA ANALYSIS

Question 6: Inspect your sketched or printed graph of magnetic field B *vs.* the current I through the solenoid. How is magnetic field related to the current through the solenoid?

Question 7:. Inspect the equation of the best-fit line to the field *vs.* current data. What are the units of the slope? What does the slope measure?

1. For each of the measurements of Part II, calculate the number of turns per meter. Enter these values in the Data Table 2.
2. Plot a graph of magnetic field B *vs.* the turns per meter of the solenoid (n). Use Excel to do this.

Question 8:. How is the magnetic field related to the number of turns/meter in the solenoid?

3. Determine the equation of the best-fit line to your graph of magnetic field *vs.* turns per meter. Record the fit parameters and their units in your Data Table 3.

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Data Table 3

Magnetic field *vs.* Turns/meter *n*	
Slope	
Number of turns in Slinky	
Current (A)	

Question 9:. From Ampere's law, it can be shown that the magnetic field B inside a long solenoid is

$$B = \mu_0 n I$$

where μ_0 is the permeability constant. Do your results agree with this equation? Explain.

4. Assuming the equation in the previous question applies for your solenoid, calculate the value of μ_0 using your graph of B *vs.* n. You will need to convert the slope to units of T•m from mT•m.

μ_0 ____________________

Question 10:. Look up the value of μ_0, the permeability constant. Compare it to your experimental value. Note that any error in the value of the resistor will influence your current measurements, and so your value of μ_0.

Question 11: Was your Slinky positioned along an east-west, north-south, or on some other axis? Will this have any effect on your readings?

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EXTENSIONS

1. Use the graph obtained in Part I to determine the value of μ_0.
2. Carefully measure the magnetic field at the end of the solenoid. How does it compare to the value at the center of the solenoid? Try to prove what the value at the end should be.
3. Study the magnetic field strength inside and around a toroid, a circular-shaped solenoid.
4. Ampère's law is

$$\oint_C B \bullet dl = \mu I \qquad \text{C, any closed curve}$$

where I is the net current that penetrates the area bounded by the curve C. Ampere's law holds for any curve C as long as the currents are continuous, that is, they do not begin or end at any finite point. Like Gauss' law, Ampere's law can be used to obtain an expression for the magnetic field in situations that have a high degree of symmetry. If the symmetry is great enough, the line integral $\oint_C B \bullet dl$ can be written as the product of B and some distance. Then if I is known, B can be determined. Also, like Gauss' law, Ampere's law is of no use in finding an expression for the magnetic field if there is no symmetry. It is, however, of considerable theoretical importance.

The simplest application of Ampere's law is to find the magnetic field of an infinitely long, straight, current-carrying wire. If we assume that we are far from the ends of the wire, we can use symmetry to rule out the possibility of any component of B parallel to the wire. We may then assume that the magnetic field is tangent to this circle and has the same magnitude B at any point on the circle. Ampere's law then gives

$$\oint_C B \bullet dl = B\oint_C dl = \mu I$$

where we have taken B out of the integral because it has the same value everywhere on the circle. The integral of dl around the circle equals $2\pi r$, the circumference of the circle. The current I is the current in the wire. We thus obtain

$$B(2\pi r) = \mu I$$

$$B = \mu I / 2\pi r$$

We can also use Ampere's law to find an expression for the magnetic field inside a long, tightly wound solenoid, assuming that the field is uniform inside the solenoid and zero outside. We chose the rectangle of sides a and b for our closed curve C. The current that passes through this curve is the current I in each turn times the number of turns in the length a. If the solenoid has n turns per unit length, the number of turns in the length a will be na, and the current through the rectangular curve will be $I_{enclosed} = naI$. The only contribution to the sum of $\oint_C B \bullet dl$ for this curve is along the long side of the rectangle inside the solenoid, which gives Ba. Ampere's law thus gives

$$\oint_C B \bullet dl = Ba = \mu I = \mu naI$$

The magnetic field inside the solenoid is thus

$$B = \mu nI$$

- this material is obtained from Tipler, Paul A., *Physics: For Scientists and Engineers,* 3rd ed. Vol. 2. Worth: New York, 1991. p. 828-31

5. If you look up the permeabilty constant in a reference, you may find it listed in units of henry/meter. Show that these units are the same as tesla-meter/ampere.

6. Take data on the magnetic field intensity *vs.* position along the length of the solenoid. Check the field intensity at several distances along the axis of the Slinky past the end. Note any patterns you see. Plot a graph of magnetic field (*B*) *vs.* distance from center. Use graph paper. How does the value at the end of the solenoid compare to that at the center? How does the value change as you move away from the end of the solenoid

7. Insert a steel or iron rod inside the solenoid and see what effect that has on the field intensity. Be careful that the rod does not short out with the coils of the Slinky. You may need to change the range of the Magnetic Field Sensor.

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