The Magnetic Field in a Slinky

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 electromagnets.

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.
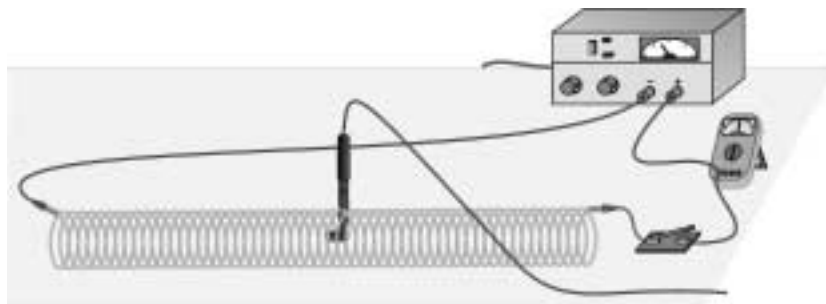- Determine the value of μ_0, the permeability constant.

Figure 1

MATERIALS

TI-83 Plus or TI-84 Plus graphing calculator	meter stick
EasyData application	DC power supply
data-collection interface	1 Ω power resistor
Vernier Magnetic Field Sensor	cardboard spacers
Voltage Probe	clip-lead connecting wires
Slinky®	momentary-contact switch
Logger *Pro* or graph paper (optional)	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 material (tape, cardboard, *etc.*) to hold the Slinky at this length.

2. Set up the circuit and equipment as shown in Figure 1. Connect the 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. Set up the Voltage Probe and Magnetic Field Sensor.

    a. Turn on the calculator and connect it to the data-collection interface.
    b. Connect the Voltage Probe to Channel 1 of the interface.
    c. Set the switch of the Magnetic Field Sensor to the 0.3 mT position and bend the tip so it is perpendicular to the sensor.
    d. Connect the Magnetic Field Sensor to Channel 2 of the interface.

4. Set up EasyData for data collection.

    a. Start the EasyData application, if it is not already running.
    b. Select ⌈File⌉ from the Main screen, and then select **New** to reset the application.
    c. Select ⌈Setup⌉ from the Main screen, then select **Selected Events**.

5. Monitor the magnetic field from the screen. The voltage across the 1 Ω resistor will be displayed for CH 1 on the screen. 1 V corresponds to 1 A, 2 V corresponds to 2 A, and so forth. The magnetic field reading will be displayed in CH2 on the screen.

6. Turn on the power supply and adjust it so that the current is 2.0 A when the switch is held closed. 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 overheat if left on continuously.

PRELIMINARY QUESTIONS

1. Hold the switch closed. Set the current to 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. What direction is the white dot on the sensor pointing?

2. What happens if you rotate the white dot to point the opposite way? What happens if you rotate the white dot so it points perpendicular to the axis of the solenoid?

3. 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. How does the magnetic field inside the solenoid seem to vary along its length?

4. Check the magnetic field intensity just outside the solenoid. Is it 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.

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.

Figure 2

3. To remove readings due to the Earth's magnetic field, any magnetism in the metal of the Slinky, or the table,

   a. Select 〔Setup〕 from the Main screen, and then select **Zero…**
   b. Select 〔CHs〕, and then select **CH2:Magnet F**.
   c. When the reading on the screen is stable, select 〔Zero〕 to record the zero condition.

4. You will take data of the magnetic field for a series of currents. The first point will be for zero current.

   a. Select 〔Start〕 from the Main screen.
   b. Select 〔Keep〕 to record the current and the magnetic field.

5. Now take additional points with the current flowing.

   a. Close the switch for the rest of this run.
   b. Set the current to 0.5 A.
   c. Select 〔Keep〕 to record the current and the magnetic field.

6. Repeat Step 5 up to a maximum current of 2.0A, in steps of 0.5 A. After recording the last point, select 〔Stop〕. Open the switch to turn off the current.

7. Select 〔Adv〕 and then **L3 vs L2** to see a graph of magnetic field *vs.* current. Print or sketch your graph. 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.

8. If the graph appears linear, fit a straight line to your data.

   a. Select 〔Anlyz〕, and then select **Linear Fit**.
   b. Record the slope and intercept in your data table, including any units for these values.
   c. Select 〔OK〕 to see your graph and the fitted line.
   d. Select 〔Main〕 to return to the Main screen.

9. 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.

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 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 0.5 to 2.0 m to change the number of turns per meter.

10. 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.

11. 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.

    a. Select ⟨Setup⟩ from the Main screen, and then select **Zero…**
    b. Select ⟨CHs⟩, and then select **CH2:Magnet F**.
    c. Once the reading is stable select ⟨Zero⟩ to zero.

12. Set the current and measure the magnetic field.

    a. Close the switch to turn on the current, and adjust the current to 1.0 A. The current reading for CH1 is displayed on the screen.
    b. Read the magnetic field from the screen when the reading is stable.
    c. Record the field value.
    d. Turn off the switch to stop the current.

13. Repeat Steps 11 and 12 after changing the length of the Slinky to 0.5 m, 1.5 m, and 2.0 m. Record the length. Keep the number of turns and the current the same each time. Each time, zero the Magnetic Field Sensor with the current off.

DATA TABLE

Part I

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

Part II

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

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

ANALYSIS

1. 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?

2. 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?

3. For each of the measurements of Part II, calculate the number of turns per meter. Enter these values.

4. Plot a graph of magnetic field B *vs.* the turns per meter of the solenoid (n). Use your calculator, Logger *Pro*, or graph paper.

5. How is magnetic field related to the turns/meter of the solenoid?

6. 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.

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

$$B = \mu_0 nI$$

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

8. 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.

9. 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.

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

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. If you have studied calculus, refer to a calculus-based physics text to see how the equation for the field of a solenoid can be derived from Ampere's law.

5. If you look up the permeability 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 either Logger *Pro* or 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.

TEACHER INFORMATION

The Magnetic Field in a Slinky

1. This activity can be performed with calculators from the TI-83 Plus or TI-84 Plus families and a LabPro or CBL 2. It can not be performed with Easy products because the EasyLink can not support two sensors simultaneously.

1. We purchased a Slinky for about $2 at a toy store. Be sure to use a metal Slinky, not a plastic one. The name Slinky is a trademark of James Industries, the manufacturer of the toy.

2. This lab is based on an idea in *The Physics Teacher*, October 1995 magazine by Colin Terry, Ventura College, Ventura, CA. It was developed and tested by Lowell Herr, The Catlin Gabel School, Portland, Oregon.

3. Some students initially find the Magnetic Field Sensor a confusing tool. The Magnetic Field Sensor measures a component of the magnetic field along one direction. A magnetic field may be large, but if the sensitive direction of the sensor is perpendicular to the field, the sensor will read zero. You may want to have your students explore the behavior of the sensor by rotating it near a bar magnet.

4. This experiment should be done with the Magnetic Field Sensor in the High switch ("high" meaning high sensitivity, not high field strength) setting. In this range, the sensor can read only to about 0.3 mT. If you use larger currents or larger n values, you will need to use the Low range to get useful measurements.

5. A power supply capable of delivering a current of 2.0 A is required to perform this experiment. For best results and safety to the equipment, use a current-controlled power supply. A current-controlled power supply will not be damaged by operating into the direct short of the slinky.

6. The 1 Ω resistor must dissipate at least 4W. A good choice is the Radio Shack 10 W, 1 Ω power resistor.

7. The switch should be a momentary contact normally open switch capable of handling currents of 2 A. We recommend this type of switch since some power supplies may become hot if operated continuously. We recommend a power supply such as the Extech Digital DC Power Supply, available from Vernier Software & Technology.

8. Stress to your students that they must turn off the current to the Slinky when not making measurements. The Slinky or power supply may overheat if the current is left on indefinitely.

10. The permeability constant μ_0 is sometimes called the permeability of free space.

11. If students only perform Part II of the experiment, eight D cells in series with an 8 ohm power resistor (10 W) can be substituted for a power supply. Generally the current will be about an ampere. The current must be measured to obtain a value for μ_0.

12. If you are using a clear, plastic Magnetic Field Sensor with an amplifier box, set the switch to the High X 100 position.

SAMPLE RESULTS

Part I

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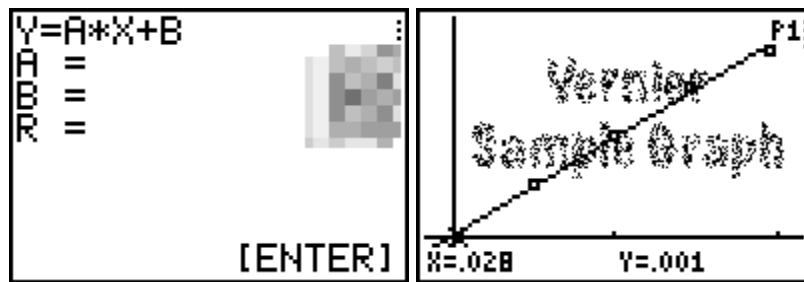
Part II

Length of solenoid (m)	Turns/Meter n (m^{-1})	Magnetic field B (mT)
0.5	xxxx	xxxx
1.0	xxxx	xxxx
1.5	xxxx	xxxx
2.0	xxxx	xxxx

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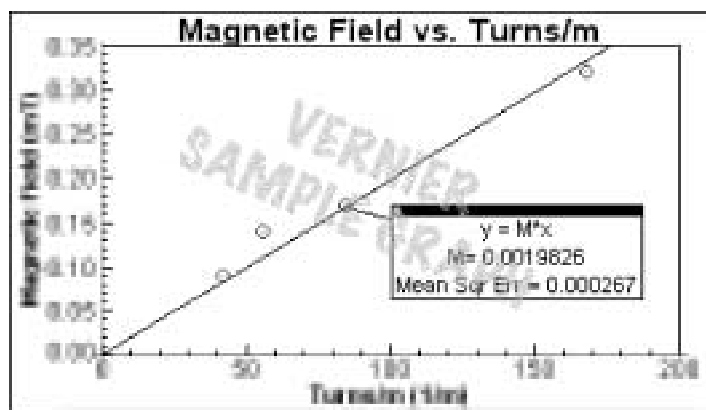
Magnetic field strength vs. *turns per meter in a Slinky*

ANSWERS TO PRELIMINARY QUESTIONS

ANSWERS TO ANALYSIS QUESTIONS

EXTENSION NOTES

Answers have been removed from the online versions of Vernier curriculum material in order to prevent inappropriate student use. Graphs and data tables have also been obscured. Full answers and sample data are available in the print versions of these labs.