

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.

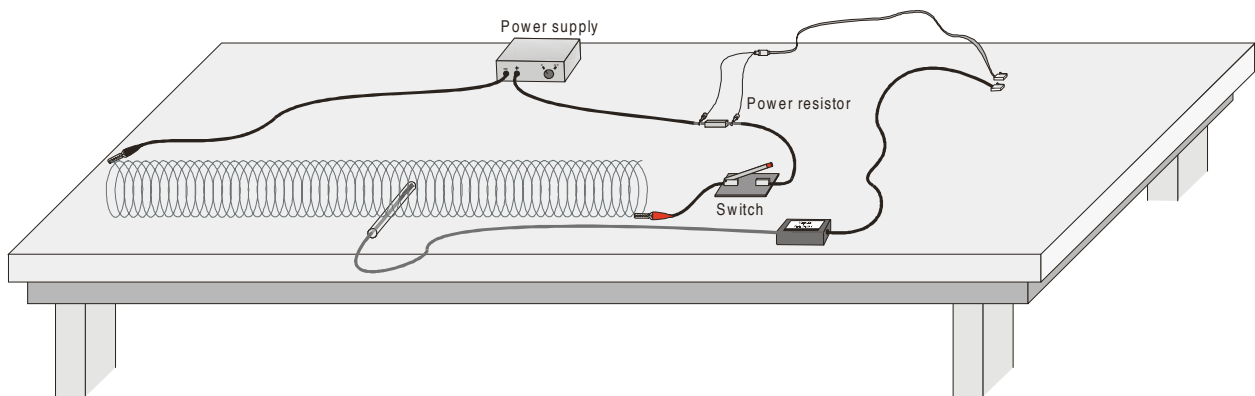


Figure 1

MATERIALS

- | | |
|--|----------------------------|
| LabPro or CBL 2 interface | meter stick |
| TI Graphing Calculator | DC power supply |
| DataMate program | 1- Ω power resistor |
| Vernier Magnetic Field Sensor | cardboard spacers |
| Voltage Probe | clip-lead connecting wires |
| Slinky® | momentary-contact switch |
| Graphical Analysis or graph paper (optional) | tape and cardboard |

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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. Connect the Voltage Probe to Channel 1 of the LabPro or CBL 2 interface. Connect the Vernier Magnetic Field Sensor to Channel 2 of the interface. Set the switch on the sensor to *High*.
4. Turn on the calculator. Start the DATAMATE program and press **CLEAR** to reset the program.
5. If CH 1 and CH 2 display the Voltage and Magnetic Field Sensors and their current readings, skip the remainder of this step. If not, set up DATAMATE for the sensors manually. To do this,
 - a. Select SETUP from the main screen.
 - b. Press **ENTER** to select CH1.
 - c. Choose the Voltage Probe you are using from the SELECT SENSOR list.
 - d. Press **▼** to select CH2 and press **ENTER**.
 - e. Choose MAGNETIC FIELD from the SELECT SENSOR list.
 - f. Choose of HI MAGNET FLD(MT) from the MAGNETIC FIELD list.
 - g. Select OK to return to the main screen.
6. Monitor the magnetic field from the calculator screen. The reading is updated about once a second. 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 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.
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.
 - b. Select ZERO.
 - c. Select CH2-MAGNET F(MT) from the SELECT CHANNEL screen.
 - d. Once the reading is stable press **ENTER** to zero.
4. Set up the calculator for data collection.
 - a. Select SETUP from the main screen.
 - b. Press **▲** to select MODE and press **ENTER**.
 - c. Select SELECTED EVENTS from the SELECT MODE screen.
 - d. Select OK to return to the main screen.
5. 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. Press **ENTER** to record the current and the magnetic field.
6. 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. Press **ENTER** to record the current and the magnetic field.
7. Repeat Step 6 up to a maximum current of 2.0A, in steps of 0.5 A. After recording the last point, select **STO▶**. Open the switch to turn off the current.
8. Press **▲** to select CH2 VS CH1 and press **ENTER**. Print or 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.

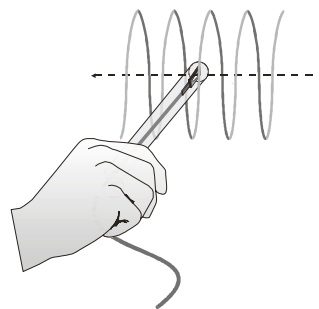


Figure 2

9. If the graph appears linear, fit a straight line to your data.
 - a. Press **ENTER** and select MAIN SCREEN.
 - b. Select ANALYZE from main screen.
 - c. Select CURVE FIT from the ANALYZE OPTIONS.
 - d. Select LINEAR(CH2 VS CH1) from the CURVE FIT menu.
 - e. Record the slope and intercept in your Data Table, including any units for these values.
 - f. Press **ENTER** to see the fitted line with your data.
 - g. Press **ENTER** to return to the ANALYZE OPTIONS.
 - h. Select RETURN TO MAIN SCREEN.
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.

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.

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.
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.
 - a. Select SETUP from the main screen.
 - b. Select ZERO.
 - c. Select CH2-MAGNET F(MT) from the SELECT CHANNEL screen.
 - d. Once the reading is stable press **ENTER** to zero.
13. 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 is on the CH1 line of the calculator display.
 - b. Read the magnetic field from the CH2 line of the calculator screen when the reading is stable.
 - c. Record the field value in your Data Table.
 - d. Turn off the switch to stop the current.
14. Repeat Steps 12 and 13 after changing the length of the Slinky to 0.5 m, 1.5 m, and 2.0 m. Record the length in the Data Table. 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 in the Data Table.
4. Plot a graph of magnetic field B vs. the turns per meter of the solenoid (n). Use your calculator, Graphical Analysis, 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 in your Data Table.

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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 Graphical Analysis 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.

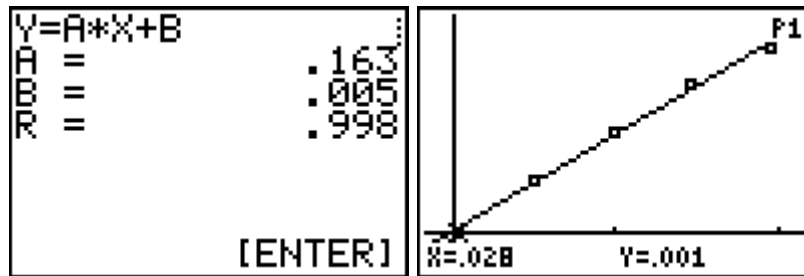
TEACHER INFORMATION**The Magnetic Field in a Slinky**

1. 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. One power supply that could be used is the Protek Model 303, available from RadioShack.com. The exposed wires of the Slinky are not a safety problem, because only a small voltage is needed to create a 2-A current through the low-resistance path of a Slinky.
6. The 1- Ω resistor must dissipate at least 4W. A good choice is the Radio Shack #271-131 10W 1 Ω power resistor. Cost is about \$0.50.
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. One such switch is available from TechAmerica, their catalog number 900-6519. Cost is about \$2.00.
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.
9. The permeability constant μ_0 is sometimes called the permeability of free space.
10. If students only perform Part II of the experiment, eight D cells in series with an 8-ohm power resistor (10W) 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 .

SAMPLE RESULTS

Part I

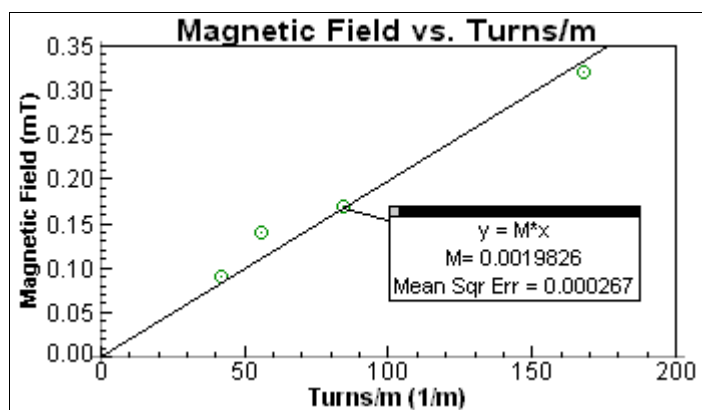
Magnetic field vs. Current	
Slope	0.163 mT/A
Intercept	0.005 mT
Length of solenoid (m)	0.59
Number of turns	84
Turns/m (m^{-1})	142



Part II

Length of solenoid (m)	Turns/Meter n (m^{-1})	Magnetic field B (mT)
0.5	168	0.32
1.0	84	0.17
1.5	56	0.14
2.0	42	0.09

Magnetic field vs. Turns/meter n	
Slope	$1.98 \times 10^{-6} \text{ T m}$
Number of turns in Slinky	84
Current (A)	1.50 A



Magnetic field strength vs. turns per meter in a Slinky

ANSWERS TO PRELIMINARY QUESTIONS

1. The sensor gives the largest readings with the white dot pointing along the long axis of the solenoid.
2. When the dot is pointed in the opposite direction along the long axis, the field measurement changes sign. This is to be expected, since the sensor is measuring a vector component.
3. The field is quite uniform near the middle of the solenoid and decreases near the ends.
4. Just outside the coils, the magnetic field is directly opposite the field inside and is much smaller. A few cm farther outside the coils, the field is very small.

ANSWERS TO ANALYSIS QUESTIONS

1. Magnetic field vs. current graph is shown above. The graph shows that the magnetic field increases linearly with current.
2. Using these data, the slope is 0.16 mT/A, and the intercept 0.005 mT. The intercept is near zero compared to the measurements. The slope measures how rapidly the field increases with current.
3. See Data Table.
4. Magnetic field vs. turns/m graph is shown above.
5. The magnetic field is proportional to the number of turns/m.
6. Using these data, the slope is 0.00198 mT-m.
7. The relation $B = (\mu_0 n)I$ suggests that B is proportional to I . The graph in Part I is consistent with this prediction. The relation also suggests that B is proportional to n . The graph in Part II is consistent with this prediction.
8. From $B = (\mu_0 n)I$, we see that the slope of a graph of B vs. n is equal to $\mu_0 I$. Using the slope of 0.00198 mT•m, or $1.98 \times 10^{-6} \text{ T}\cdot\text{m} = \mu_0 I$, and a value for I of 1.50 A, we get μ_0 of $1.32 \times 10^{-6} \text{ T}\cdot\text{m/A}$.

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9. The defined value of μ_0 is exactly $4\pi \times 10^{-7} \text{ T}\cdot\text{m/A}$, or approximately $1.26 \times 10^{-6} \text{ T}\cdot\text{m/A}$. The experimental value agrees well with the defined value.
10. In this activity the sensor was zeroed before each series of measurements, so the Earth's field, or any other magnetic field, will not change the results.

EXTENSION NOTES

1. Since $B = (\mu_0 I) n$, the slope of the best-fit regression line should be equal to $\mu_0 I$.
2. The value at the end of the coil should be half the value in the center.
5. Henry = 1 telsa-meter²/ampere, so (henry/meter) \times (telsa-meter²/ampere)/henry = tesla meter/ampere.
7. The lab extension with the metal rod added to the Slinky will greatly increase magnetic field intensity. You may have to switch to the low-gain setting and calibration to read the field.