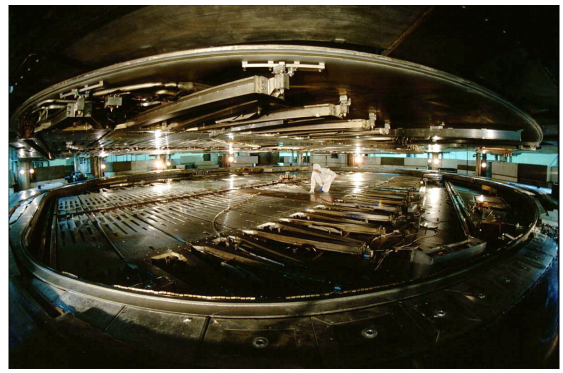
University of Calgary
Department of Physics and Astronomy
PHYS 259, Winter 2017

Labatorial 8: Magnetic Fields and Magnetic Force



The figures above show two technical applications of magnetic fields: The image on the left shows the MRI scanner (General Electric, Waukesha, Wisconsin) at the Seaman Family MR Research Centre of the University of Calgary, located at Foothills Medical Centre. This machine is used for medical imaging research and generates a field strength of 3T. To put this in perspective, the average strength of the magnetic field of the Earth is about 50 microtesla.

The image on the right shows the TRIUMF cyclotron, open for maintenance. The cyclotron was one of the earliest types of particle accelerators and was used as a source of high-energy beams for nuclear physics experiments for several decades. Today, cyclotrons still play a role in research as the first stage of multi-stage accelerators. In medical physics, they are used for isotope production for imaging and diagnostics. TRIUMF, Canada's national laboratory for particle and nuclear physics is operated by a consortium of 15 Canadian University, including the University of Calgary, and is located on the UBC campus. It houses the world's largest superconducting cyclotron, a source of 500 MeV protons. The magnet of the main cyclotron has a diameter of 18 m and produces a field of 0.46 T.

Learning Goals:

To understand the properties of magnetic fields, and how they are similar to or different from electric fields. To understand how a magnetic field affects the motion of charged particles, as compared to the effects of an electric field.

Preparation:

Halliday, Resnick, and Walker, "Fundamentals of Physics" 10th edition, Wiley: 28.1–28.5.

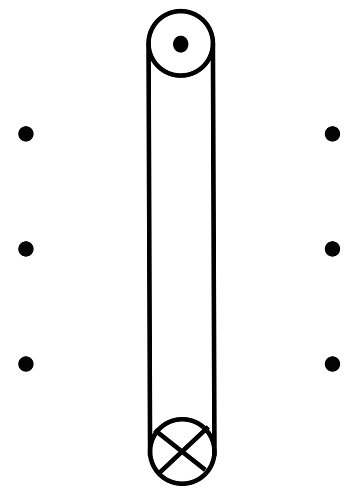
Equipment:

Slinky, table clamps, meter stick, ring stand with clamps, connecting wires, digital multimeter, DC power supply, Vernier magnetic field probe, Vernier LabPro Data Logger, Computer with Vernier Logger Pro.

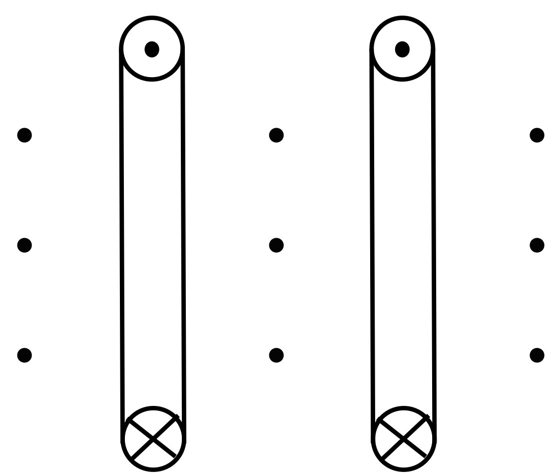
Note that there is an equation sheet at the end of this worksheet.

1 From a single loop to a solenoid

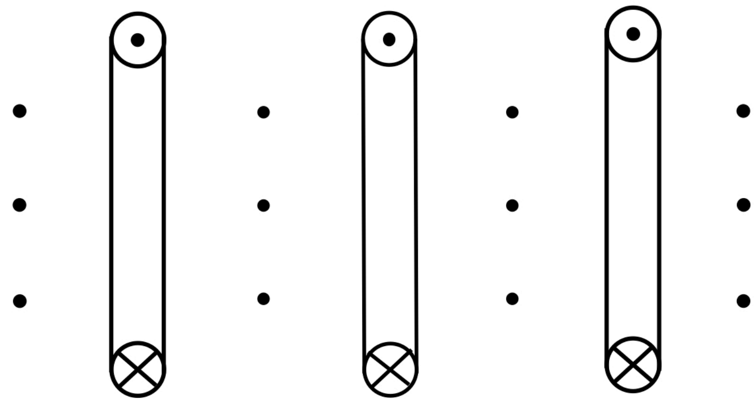
Question 1: This figure shows a cut through a current-carrying loop, seen from the side. The current comes out of the page at the top and flows into the page at the bottom. At each point indicated by a solid dot, sketch and label
a) the magnetic field vector generated by the top of the loop,
b) the magnetic field vector generated by the bottom of the loop, and
c) the net magnetic field generated by the loop.



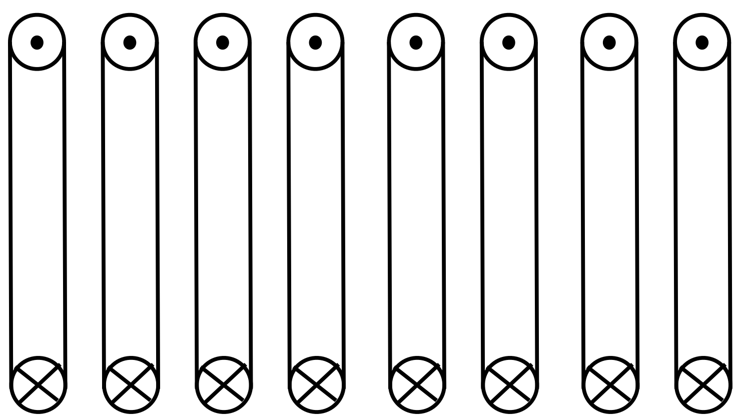
Question 2: Just as in the case of electric fields, we can start from simple magnetic field configurations and construct more complicated fields using superposition. At each point indicated by a solid dot, sketch and label the magnetic field vectors for the field generated by the loop on the left, for the field generated by the loop on the right, and the net magnetic field vector.



Question 3: Consider the magnetic field of three loops of current using the principle of superposition. At each point indicated by a solid dot, sketch and label the magnetic field vectors for the fields generated by each loop, and the net magnetic field vector.



Question 4: Now extrapolate your answer from the previous questions to the magnetic field of a solenoid: a coil that has many turns and is tightly wound. What do you expect for the direction of the magnetic field inside the solenoid? How do you expect the magnetic field strength to vary from point to point inside the solenoid? What do you expect the magnetic field to look like near the edges of the solenoid? Sketch your answer in the figure using field lines.

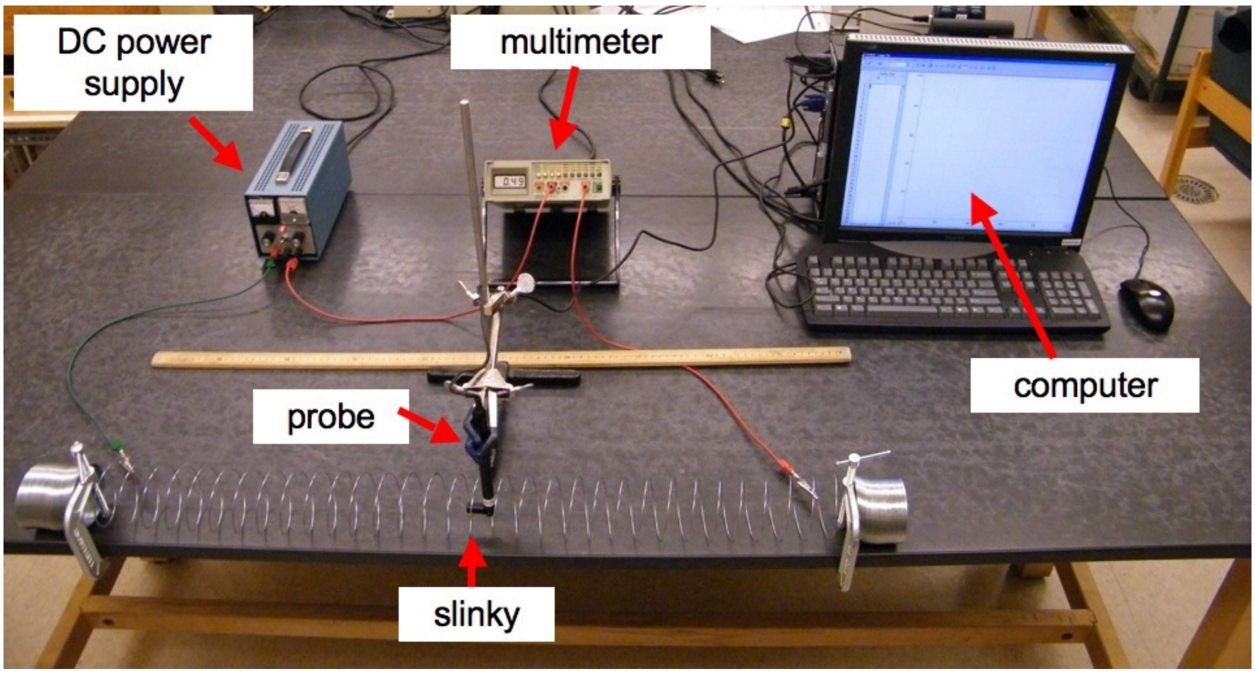


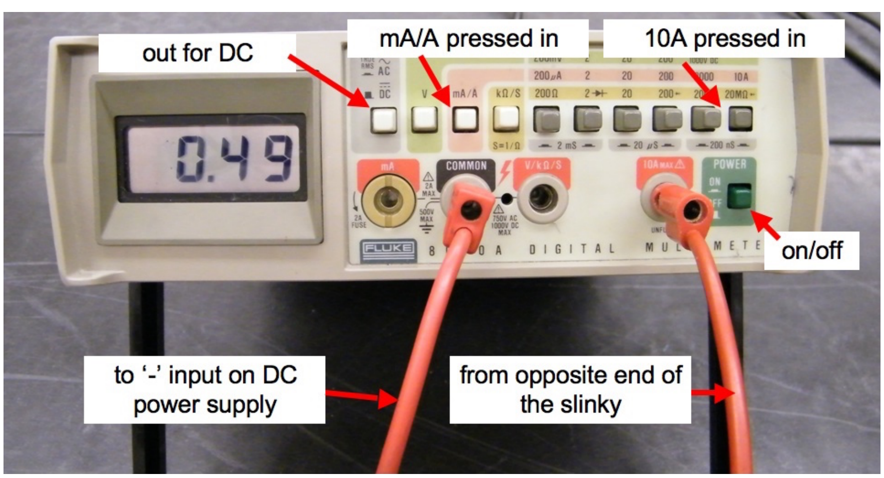
STOP **CHECKPOINT 1: Before moving on to the next part, have your TA check the results you obtained so far.**

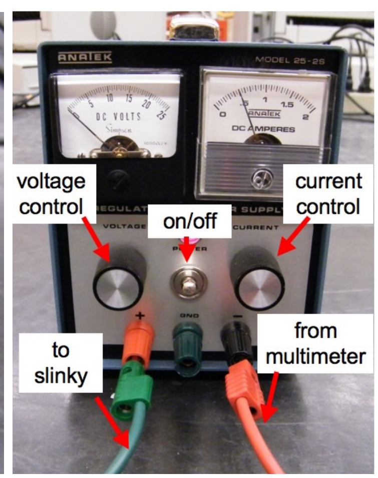
2 Magnetic Field of a Solenoid

Many technical applications require a uniform magnetic field, i.e. a field with the same strength and direction at every point in a certain region of space. This can be achieved with a solenoid, which is a tightly wound coil with many turns. The superposition of the magnetic fields of the single loops creates a strong, nearly uniform field in the center of the solenoid, whereas the field on the outside is weak and not homogeneous. The magnetic field strength in an ideal solenoid is given by $B = \mu_0 n I$, where I is the current that runs through the solenoid, and n is the number of turns per unit length. Note that the magnetic field of the solenoid does not depend on the radius of the solenoid, in contrast to the magnetic field of a coil.

For the experiment in this labatorial, we will use a Slinky. It is not as tightly wound as a solenoid should be, but that gives us the chance to conveniently put a magnetic field probe at various points inside the coil.







Before starting the measurements, check the circuit:

1. Ensure that the positive input of the power supply is connected to the left end of the Slinky.
2. Ensure that the right end of the Slinky is connected to the "10A MAX" input of the multimeter.
3. Ensure that the "DC" and "mA" buttons on the multimeter are selected, along with the maximum allowable input range (10A, as shown in the photo of the multimeter).
4. Ensure that the ground input of the multimeter (labeled "common") is connected to the negative input of the DC power supply. Ask your TA to check your setup before turning on the power supply.
5. The magnetic field probe should be plugged into CH1 on the Vernier LabPro DataLogger.
6. Ensure that the DataLogger USB connector is plugged into the computer.
7. Open the Logger Pro Software using the icon on the Desktop. Ensure that the software recognizes that the magnetic field probe is plugged in. If you see a message that asks you to change the sensor setting, click the "use sensor setting" field.

Experiment 1

1. Make sure there are between 30 and 40 turns of the slinky between the clamps. Measure the length L of $N = 10$ turns of the Slinky. Enter the value in the appropriate fields of Table 1.
2. Place the magnetic field probe in the middle of the Slinky.
3. In LoggerPro, click the blue "zero" button at the top of the screen to zero the magnetic field probe.
4. Turn on the DC power supply. Using the reading on the multimeter as a guide, adjust the output to $I = 0.5A$. (This value is already entered in Table 1.)
5. In LoggerPro, click the "collect" button at the top of the screen. The computer will plot the magnetic field measured in the Slinky. Use the mouse to select a large area of the plot, and click on the "statistics" button at the top of the screen. The software will display the mean magnetic field for the part of the plot that you have selected. Record this mean value in the appropriate place in Table 1.
6. Now increase the output on the DC power supply to $I = 1.0A$, click the "collect" button, find the mean value of the magnetic field, and record this value in Table 1.
7. Finally, increase the output on the DC power supply to $I = 1.5A$, click the "collect" button, find the mean value of the magnetic field, and record this value in Table 1.
8. Turn off the power supply.

Table 1: Measurements for Experiment 1

N	length L(m)	current I(A)	B (mT)	n (1/m)	$I \cdot n(A/m)$
10		0.5			
10		1.0			
10		1.5			

Experiment 2

Make sure that the power supply is turned off. Carefully remove the magnetic field probe from the Slinky. Stretch the Slinky by grabbing a few extra coils at one end, and slide the excess coils around the table clamp. Measure the length L of $N = 10$ turns of the Slinky, and enter the value in the appropriate fields of Table 2. Place the magnetic field probe inside the Slinky. Click the "zero" button. Turn the power supply back on. Repeat the same steps as in Experiment 1, and record the new values in Table 2. After your measurements, turn off the power supply.

Table 2: Measurements for Experiment 2

N	length L(m)	current I(A)	B (mT)	n (1/m)	$I \cdot n(A/m)$
10		0.5			
10		1.0			
10		1.5			

Experiment 3

Make sure that the power supply is turned off. Carefully remove the magnetic field probe from the Slinky. Stretch the Slinky a little more by grabbing a few extra coils at one end and sliding them around the table clamp. Measure the length L of $N = 10$ turns of the Slinky, and enter the value in the appropriate fields of Table 3. Place the magnetic field probe inside the Slinky. Click the "zero" button. Turn the power supply back on. Repeat the same steps as in Experiment 1, and record the new values in Table 3. After your measurements, turn off the power supply.

Table 3: Measurements for Experiment 3

N	length L(m)	current I(A)	B (mT)	n (1/m)	$I \cdot n(A/m)$
10		0.5			
10		1.0			
10		1.5			

STOP

CHECKPOINT 2: Before moving on to the next part, have your TA check the results you obtained so far.

Question 5: From your data, calculate the values for $n = N/L$ and for $I \cdot n$. Record these values in Tables 1, 2, and 3. Then, use LoggerPro to plot a graph of B vs $I \cdot n$.

Question 6: a) Which kind of fit (linear, quadratic, exponential ...) best represents your data? Which parameter of the fit will give the value of μ_0? State how you know.

b) Do the appropriate fit and record the value found for μ_0.

Question 7: Compare your result for μ_0 with the value found on the formula sheet. Calculate this as a percent difference: $\frac{\mu_{0,exp} - \mu_{0,th}}{\mu_{0,th}} \times 100\%$, where $\mu_{0,exp}$ is your experimental value and $\mu_{0,th}$ is the actual value. What are possible reasons for any difference that you found between the measured and the actual values of μ_0?

Question 8: In the instructions for each experiment, you were asked to zero the magnetic field probe before taking your measurements. This is necessary to ensure that you measured only the field generated by the Slinky, and not other fields. Which other magnetic fields do you expect to be present in the lab?

Question 9: To find out whether the Slinky is a good realization of an ideal solenoid, we will explore the magnetic field in the Slinky qualitatively:

a) Remove the magnetic field probe carefully from its stand. Measure the magnetic field at four points along the axis of the Slinky and record these values:

b) Are the values that you recorded in part (a) nearly equal? If not, what could be the reason?

c) What do you find for the value of the magnetic field in the middle of the Slinky if you move the probe away from the axis of the Slinky, towards the sides? Does the result agree with your expectation for an ideal solenoid?

d) What do you expect to find for the value of the magnetic field if you rotate the probe so that it points perpendicular to the axis of the Slinky? Explain your answer.

e) Now do the measurement described in part (c) and record the value. What could be a reason for the difference between the theoretical expectation and the measured result?

Last Checkpoint! Clean up your area, and put the equipment back the way you found it. Call your TA over to check your work and your area before you can get credit for the labatorial.

Equations and constants

$$
\begin{aligned}
F_C(r) &= \frac{1}{4\pi\epsilon_0}\frac{|q_1q_2|}{r^2} \\
\vec{E} &= \frac{\vec{F}}{q} \\
\vec{E} &= -\vec{\nabla}V \\
\Delta V &= -\int \vec{E}\cdot d\vec{l} \\
\Delta U &= q\Delta V \\
Q(t) &= Q_{max}e^{-t/RC} \\
Q(t) &= Q_{max}(1-e^{-t/RC}) \\
C &= \frac{Q}{\Delta V} \\
C &= \frac{\epsilon_0 A}{d} \\
C &= KC_0 \\
U &= \frac{Q^2}{2C} \\
\Delta V &= RI \\
R &= \frac{\rho L}{A} \\
\rho &= \frac{E}{J} \\
P &= \Delta V I \\
\Delta V_{bat} &= \varepsilon - Ir \\
\vec{F} &= q\vec{v}\times\vec{B}
\end{aligned}
$$

$$
\begin{aligned}
F_g(r) &= G\frac{m_1m_2}{r^2} \\
U_{grav}(y) &= mgy \\
K &= \frac{1}{2}mv^2 \\
v_x(t) &= v_{0x} + a_xt \\
x(t) &= x_0 + v_{0x}t + \frac{1}{2}a_xt^2 \\
v_x^2(t) &= v_{0x}^2 + 2a_x(x(t)-x_0) \\
\omega &= \frac{d\theta}{dt} \\
v &= \frac{2\pi r}{T} = \omega r \\
a_{rad} &= \frac{v^2}{r} = \omega^2 r \\
g &= 9.81\frac{m}{s^2} \\
G &= 6.67\times 10^{-11}\frac{Nm^2}{kg^2} \\
\frac{1}{4\pi\epsilon_0} &= 8.99\times 10^{9}\, Nm^2C^{-2} \\
\epsilon_0 &= 8.85\times 10^{-12}\, C^2N^{-1}m^{-2} \\
e &= 1.60\times 10^{-19}\, C \\
m_e &= 9.11\times 10^{-31}\, kg \\
m_p &= 1.67\times 10^{-27}\, kg \\
m_n &= 1.67\times 10^{-27}\, kg \\
\mu_0 &= 4\pi\times 10^{-7}\, Wb/A\cdot m
\end{aligned}
$$