Magnetic Fields

Solar coronal loops observed by NASA's Transition Region And Coronal Explorer (TRACE). The bright loops are generated by particles accelerated along the Sun's magnetic field lines.
Activity A: Signing in

(1) Before starting this experiment you must sign in. All students working with this piece of apparatus MUST enter their names in the boxes on this page.

(2) IMPORTANT If you want to clear data from a graph (for example, to redo a measurement) DO NOT use the command under the "EXPERIMENT" menu ... "DELETE ALL DATA RUNS". If you do you will LOSE ALL YOUR DATA and you, and your partners will have to redo the ENTIRE experiment. Instead use the command "DELETE LAST DATA RUN" under the "EXPERIMENT" menu or, more safely, type "alt-".
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Magnetic forces are all around us. They are at work at the core of our electric motors, loudspeakers, power plants, hard drives, medical devices, even our planet. The most familiar type of magnet is probably the permanent magnet, such as you may have on your refrigerator door at home.

First, you will directly observe magnetic field patterns generated by permanent bar magnets. Before moving on to part C, complete the iron filings worksheet on the center tables. Once you have completed your field line sketches, bring the sketches and bar magnets back, but leave the filings behind.

Activity C: Mapping field lines with an electronic sensor

Now that you have a feel for what the magnetic field lines of bar magnets look like, let’s see how to interpret what those field lines actually mean.

1. Place the long straight track (top shelf) into holes A and B on the gray plastic table, with the numerical scale facing to the right. Secure the track by screwing in thumb screws (drawer 4) underneath the gray table.

2. Align the bar magnet stand with the white line on the gray table, and secure it with thumb screws.

3. Place the magnetic field sensor cart (drawer 3) on the long straight track, with the wheel facing to the right.

4. Connect the black and yellow plugs coming from the sensor cart into digital channels 1 and 2 on the ScienceWorkshop 750, respectively.

5. Connect the magnetic field sensor to Analog Channel A on the ScienceWorkshop 750, using the long black analog port cords hanging on the wire rack.

Your completed setup should look like the picture to the left.
The magnetic field sensor is capable of measuring both the magnitude and direction of the magnetic field at any point in a plane. To do this, there are two separate sensors at the tip of the probe - one for measuring the field's radial component and one for measuring the axial component. These directions are defined in the picture at right.

As an example, if the probe is placed in a magnetic field like the example 1 below, the radial field would be positive, the axial field would be positive, and the radial component would be larger than the axial field component.

**Example 1**

B

As another example, if the probe is placed in a magnetic field like the example 2 below, the radial field would be negative, the axial field would be positive, and the axial component would be larger than the radial field component.

**Example 2**

B

1. In example 2, the radial field would be __________ the axial field would be __________

2. Make sure there are no magnets near the sensor. Align the wheel of the magnetic field sensor cart with the 21 cm mark on the scale, as shown at right (top). Select "Radial" and press "Tare" on the magnetic field sensor, this will zero the radial sensor.

**NOTE!** It is critical that you zero the sensor (Tare) before EACH measurement. You must move any source of magnetic field far (at least arm's length) from the sensor when you Tare. Do not forget, or your results will be incorrect!

(3) Pull a magnet into the left-hand cradle of the bar magnet stand, with the north pole (red) pointing to the right, as shown below.

(4) In this orientation, PREDICT the sign of the radial and axial components (write "+" or "-" in the left hand boxes, and if you think one of the components will be zero, write "0"). Repeat your predictions for 23 and 25 cm. Refer to your magnetic field line sketch if you need help. Don't worry! You will NEVER lose credit for incorrect predictions!

(5) After you have made your predictions, click Start above, with the wheel at the desired location. The relevant component will appear in the box below, right. Click Stop after a second or two.

(6) Repeat step (5) for both components, axial and radial, for all three positions (5 measurements total). Record the numerical values in the right hand column. After each measurement, don't forget to Tare, and select "Delete Last Data Run" from the experiment menu to clear the meter.

(21 cm) Prediction (+/-0):

Radial __________
Axial __________

(23 cm) Prediction (+/-0):

Radial __________
Axial __________

(25 cm) Prediction (+/-0):

Radial __________
Axial __________

(21 cm) Measurement (Gauss):

Radial __________
Axial __________

(23 cm) Measurement (Gauss):

Radial __________
Axial __________

(25 cm) Measurement (Gauss):

Radial __________
Axial __________
Before continuing, select "Delete All Data Runs" from the experiment menu.

Let's take this one step further, and study the shape of each component as a function of position.

1. Align the magnetic field sensor cart wheel with the 0 cm mark on the scale. Set the magnetic field sensor to "Radial." As always, remove the magnet from the left-hand cradle, and Tare the sensor.

2. Let's first predict what the graph of Radial field strength vs. position will look like on the graph to the right. On this graph, the 0.00 position corresponds to the 28 cm mark on the scale, which you'll notice is right next to the north pole of the magnet.

Talk it over with your labmates, and once you've come to an agreement, click the "x" button on the graph, and draw your prediction! Be careful, there is no undoing your prediction!

3. Press Start and push the cart from 0 cm to 42 cm along the long straight track. The graph to the right will update as you go. Press Stop when complete.

4. How did you do? Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?
Let's do the same thing with the axial component.

(1) Align the magnetic field sensor cart wheel with the 0 cm mark on the scale. Set the magnetic field sensor to "axial". As always, remove the magnet from the left-hand cradle, and Tare the sensor.

(2) Draw on your prediction of what the graph of Axial field strength vs. position will look like on the graph to the right.

(3) Now, do the measurement. Press Stop when complete.

(4) Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?
Now we will do a measurement with the probe passing between two magnets, **south** pole to the left of the probe, and **north** pole to the right, as shown in this picture.

Refer to your field line sketch to answer this question:

1. When the probe tip lies **anywhere** along the line that is equidistant from the two magnets, one of the two magnetic field components should be zero. Which one?

2. Place the probe tip about 3 cm below the axis of the magnets, as shown in the picture. If you look from above, you'll notice that the left hand magnet is actually a bit farther away from the probe than the right hand magnet. We need to fix that before we can continue, but we can't simply do it with the naked eye.

On the **magnetic field sensor**, select the component of the E-field that you chose in part (1). Remove the magnets from their cradles, and **Tare the sensor**.

Press **Start**. Move the left hand magnet as shown in the picture until the value in the box is zero. Press **Stop** when complete. If you cannot find 0 this way, rethink your prediction in (1) and start over!

Once you have found 0, you have correctly positioned the sensor between the magnets! **Do not touch the magnets again until page 11.**

Before continuing, select "Delete Last Data Run" from the experiment menu, and save your work.

Save work then proceed to next page
(1) Select the "Radial" component on the magnetic field sensor, and align the wheel with the 0 cm mark on the long straight track's scale.

(2) Do not move the magnets, but press "Tare" on the magnetic field sensor. (Don't worry, the sensor is far enough away from the magnets.)

(3) Let's first predict what the graph of Radial field strength vs. position will look like on the graph to the right. On this graph, the 0.00 position corresponds to the 23 cm mark on the scale, which, you'll notice, is coincident with the axis of the magnets.

Talk it over with your labmates, and once you've come to an agreement, click the button on the graph, and draw your prediction directly on the graph!

(4) Press Start and push the cart from 0 cm to 42 cm along the long straight track. The graph to the right will update as you go. Press Stop when complete.

(5) Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?
Let's do the same thing with the axial component.

1. Align the magnetic field sensor cart wheel with the 0 cm mark on the scale. Set the magnetic field sensor to "axial." Leave the magnets where they are, and zero the sensor.

2. Draw (2x) your prediction for what the graph of Axial field strength vs. position will look like on the graph to the right. (Hint: think about your calibration on page 5.)

4. Now, do the measurement. Press Stop when complete.

5. OOPS! You may notice some surprising "wobbles" near the 0.00 Position. Use the smart tool to measure the height of the largest "wobble".

6. How does the size of this "wobble" compare to the size of the structure on the previous page?

7. Other than this surprising "wobble," how did you do? Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?

8. If we agree that this "wobble" was an unanticipated result, what do you think could have caused it? Hint: what would happen if the magnets were tilted slightly, like this?
N - N alignment

Now, let's do a final measurement with the probe passing between two magnets, this time with north pole to the left of the probe, and north pole to the right, as shown in this picture.

Refer to your field line sketch to answer this question:

(1) When the probe tip lies directly between the magnets, as in the picture, what should the radial component of the magnetic field be? [ ]

(2) Align the wheel of the magnetic field sensor cart with 23 cm on the long straight track's scale. This will center the probe tip between the magnets. Again, you'll notice that the left hand magnet is actually a bit farther away from the probe than the right hand magnet. We need to fix that before we can continue, but we need to proceed carefully.

On the magnetic field sensor, select "Radial." Remove the magnets from their cradles, Tare the sensor, and then put the magnets back.

Press Start. Move the left hand magnet as shown in the picture until the value in the box is zero. Press Stop when complete.

Once you have found 0, you have correctly positioned the sensor between the magnets! Do not touch the magnets again until page 14.

Before continuing, select "Delete Last Data Run" from the experiment menu, and save your work.
1. Select the "Axial" component on the magnetic field sensor, and align the wheel with the 0 cm mark on the long straight track's scale.

2. Do not move the magnets, but press 'Tare' on the magnetic field sensor. (Again, the sensor is far enough away from the magnets for this to be OK.)

3. Let's first predict what the graph of Axial field strength vs. position will look like on the graph to the right. On this graph, the 0.00 position corresponds to the 23 cm mark on the scale, which, you'll notice, is coincident with the axis of the magnets.

Talk it over with your labmates, and once you've come to an agreement, click the 'X' button on the graph, and draw your prediction! Be careful, there is no undoing this!

4. Press Start and push the cart from 0 cm to 42 cm along the long straight track. The graph to the right will update as you go. Press Stop when complete.

5. Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?
Let's do the same thing with the **radial** component.

1. Align the **magnetic field sensor cart** wheel with the 0 cm mark on the scale. Set the **magnetic field sensor** to "radial." Leave the magnets where they are, and **Tare** the sensor.

2. Draw your prediction for what the graph of **Radial field strength vs. position** will look like on the graph to the right.

4. Now, do the measurement. Press **Stop** when complete.

5. Again, you may notice some surprising "wobbles" near the 0.00 Position. Use the smart tool to measure the height of the largest "wobble.

6. How does the size of this "wobble" compare to the size of the structure on the previous page?

7. Other than this surprising "wobble," how did you do? Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?

8. If we agree that this "wobble" was an unanticipated result, what do you think could have caused it?

9. Why do you suppose we observed an unexpected wobble on this page, and not the last page?

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**Save work then proceed to next page**
Activity D: Magnetic field of current-carrying coils

1. Return the bar magnets to their case and store them on the lower shelf.
2. Unscrew the bar magnet stand and return it to the top shelf.
3. Remove the long straight track from the gray table.
4. Take the two 500-turn coils, and screw them into holes 1 and 7 on the gray table using thumb screws.
5. Carefully return the long straight track to holes A and B (the track will run through the coils).
6. Using red and black jumper wires from the rack, connect wires from the white and black ports on the coil 1 (front coil, in hole 1) to the red and black ports on the DC power supply.

After setup, your table should look like this:

(7) Align the magnetic field sensor cart wheel with 0 cm on the long straight track's scale.

(8) Make sure the DC power supply is turned OFF, set the magnetic field sensor to "Axial" and press "Tare."

(9) Turn on the DC power supply, and adjust the voltage until the current in coil 1 is 0.8 Amperes.

Which way is current flowing through this coil (when viewed from the front)?

[Box: clockwise (CW), counterclockwise (CCW)]

Save work then proceed to next page
Let's measure the axial field strength as a function of position.

(10) Press Start, and push the magnetic field sensor cart from 0 cm to 42 cm along the long straight track. Press Stop when complete.

Now let's measure the radial field strength as a function of position.

(11) Turn OFF the DC power supply, set the magnetic field sensor to 'Radial,' align the wheel to 0 cm, and press "Tare."

(12) Turn the DC power supply back on, and do the radial measurement. Press Stop when complete.

(13) Which of the pictures shown below depicts a magnetic field consistent with the two graphs we just recorded?

(14) Is the direction of this coil's magnetic field consistent with the right-hand rule you learned in class? This will be important for you to understand on an exam!
(1) Turn the DC power supply off, and reconnect coil 1 so that the current will flow Counterclockwise. Which way will the magnetic field point in this case?

(2) Align the wheel to 0 cm. Tare the axial sensor, turn the DC power supply back on, press Start, and push the magnetic field sensor cart from 0 cm to 42 cm. Press Stop when complete.

(3) Without deleting your last data run, repeat steps (1) and (2) for coil 2. (Coil 1 should no longer be connected. There should now be two graphs visible).

(4) Now that you've seen the results for each coil independently, predict what the axial magnetic field vs. position graph would look like if we had current flowing counterclockwise through both coils simultaneously. (Use the tool to draw your prediction.)

(5) Now to take the measurement. Turn the DC power supply off, and connect the 2 coils in series so that the current will flow Counterclockwise through both of them, as shown here.

(6) Align the wheel to 0 cm. Tare the sensor, turn the DC power supply back on, double-check that the current is still 0.8 Amperes, and take the measurement. Press Stop when complete. (There should now be three graphs visible).

(7) How did you do? Which aspects of your prediction were correct? Incorrect? How does the third graph compare to the first two?
Finally, let's imagine what would happen if the current were flowing in opposite directions in each coil.

1. Turn the DC power supply off, and connect the coils in series so that the current is flowing counterclockwise through coil 1, and clockwise through coil 2.

2. With the DC power supply OFF, align the wheel to 0 cm, and Tara the Axial sensor.

3. Predict what the graph of Axial field strength vs. position will look like on the graph to the right.

4. Turn the DC power supply back on, align the wheel to 0 cm, press Start, and push the magnetic field sensor cart from 0 cm to 42 cm. Press Stop when complete.

5. How did you do? Which aspects of your prediction were correct? Incorrect? Can you explain any differences that you observe?
Activity E: Ampere's Law

An important feature of magnetic fields is summarized by **Ampere's Law**. This law, along with Faraday's Law, which we will study next week, represent deep and fundamental links between electricity and magnetism, links that paved the way for enormous technological breakthroughs in the 19th and 20th centuries. Since Ampere's law may not be covered in detail in your 107 class, we will first state it as a postulate, and then aim to demonstrate it:

**Postulate:** The area underneath an axial magnetic field vs distance graph as the sensor traverses a CLOSED LOOP is proportional to the current passing through that loop.

While you take some time to absorb this law, let's setup this last experiment.

1. Remove the **long straight track** from the gray table and store it on the top shelf.
2. Remove the **2 coils** from holes 1 and 7, and screw them tightly into holes 9 and 10 (fronts still facing towards you).
3. Screw the 3 table legs into holes C, D, and E on the gray table.
4. Carefully weave the **small circular track** (underneath gray table) between both coils, and securely rest it on the table legs, with the gap facing toward you.
5. Screw the **small wedge** (drawer 4) into the gap of the small circular track (two thumb screws are enough).
6. Align the **magnetic field sensor cart** with the white tick on the small wedge.

Your setup should now look like the picture to the right.
Single coil

Let's start by running current through **just** the right hand coil.

(7) Connect the right hand coil to the DC power supply so that the current flows **counterclockwise**.

In this configuration, the field lines from our single coil are sketched here. Notice that along the **small circular track**, they are nearly circular and coincident with the track.

(8) As you move the **magnetic field sensor cart** along the track, which component would you expect to be bigger, the **radial** component or the **axial** component?

(9) Write the reason for your choice.

(11) Which diagram shows (with a red dot) the location where the **axial** component will have a maximum magnitude?

(12) Take the axial sensor, turn the DC power supply ON, press **Start**, and move the cart 360 degrees around the **small circular track**. **Stop** when the cart reaches its start position.

(13) Record the value of the area under the curve here.

(14) How much current was passing through the inside of the closed loop defined by the **small circular track**? (Remember, each coil has 300 windings!)

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**Save work then proceed to next page**
2 coils, counterclockwise

(1) Now, connect the coils to the DC power supply so that the current flows counterclockwise through BOTH coils.

(2) Repeat the measurement you made on the last page with this new coil configuration.

(3) Record the value of the area under the curve here: \[ \text{[ ]} \text{ Gm} \]

(4) How much current was passing through the inside of the closed loop defined by the small circular track? (This one is trickier! The direction of the current matters. If the current pokes up through the loop, call it positive. If down, call it negative.)

\[ \text{[ ]} \text{ A} \]
2 coils, opposite directions

(1) Now, connect the coils to the DC power supply so that the current flows counterclockwise through the right hand coil, and clockwise through the left hand coil.

(2) Repeat the measurement you made on the last page with this new coil configuration.

(3) Record the value of the area under the curve here: $G m$

(4) How much current was passing through the inside of the closed loop defined by the small circular track?

$A$,
Recall Ampere's Law: The area underneath an axial magnetic field vs distance graph as the sensor traverses a CLOSED LOOP is proportional to the current passing through that loop.

1. Let's see if it worked! Copy your results, repeated here, into the table at right:

<table>
<thead>
<tr>
<th>Current through loop (A)</th>
<th>Area under curve (G m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 coil (CW)</td>
<td></td>
</tr>
<tr>
<td>2 coils (CCW)</td>
<td></td>
</tr>
<tr>
<td>2 coils (CCW, CW)</td>
<td></td>
</tr>
</tbody>
</table>

2. Select "Proportional Fit" from the fit menu on the graph. Record your "A (Scale Factor)" parameter here: 

\[ A = \text{G m/A} \]

3. You've actually just measured a fundamental quantity of electromagnetism, known as the permeability of free space, \( \mu_0 \). In this set of units, \( \mu_0 = 1.26 \times 10^{-2} \) G m/A.

4. Calculate the % difference between your experimental value of \( \mu_0 \), and the actual value given above. Show your work in the box below.
Activity F: Cleaning up

1. Turn off the DC power supply, and return all wires to the wire rack.
2. Disconnect the magnetic field sensor cart from the ScienceWorkshop 750, and return it to its drawer. Return the black wire to the wire rack.
3. Carefully remove the small circular track from the coils, and place it underneath the gray table.
4. Unscrew the 3 legs, and return them to drawer 4.
5. Log off from UCLAB.

Thank you for leaving your station tidy!