General Physics Lab 6

Magnetic Fields

Objectives:

- To map the magnetic field of a permanent bar magnet
- To show that the magnetic field strength of an electromagnet is directly proportional to the current
- Measure the value of the permeability of free space (magnetic constant), μ_0

Equipment:

Part 1 – Magnetic Field Mapping

- Neodymium Permanent Bar Magnet
- Compass
- White Paper (1 sheet)
- Tape
- Wood/Graphite Pencil

Part 2 – Magnetic Field of a Current Loop

- Multimeter with Probes
- Breadboard
- Jumper Wire Kit
- 3 Alligator Clip Wires
- 9V Battery
- 9V Battery Connector
- 82 Ω Resistor
- 120 Ω Resistor
- 160 Ω Resistor
- Circular Coil of Wire (50 turns)
- Neodymium Permanent Bar Magnet
- Ruler
- Tape
- Smartphone with Phyphox App

Physical Principles:

Magnetic Field Direction

Magnetic monopoles have never been observed. A permanent bar magnet always has both North and South magnetic poles, leading to a dipole magnetic field surrounding the magnet (see Fig. 1). The magnetic field will be strongest near the North or South magnetic poles where the density of the field lines is greatest.

If a compass needle (a small, test, permanent magnetic dipole) is placed in the magnetic field, there is no net force on the needle, but a torque will align the needle with the field such that the North (red) side of the compass needle aims in the direction of the magnetic field line (see Fig. 1).

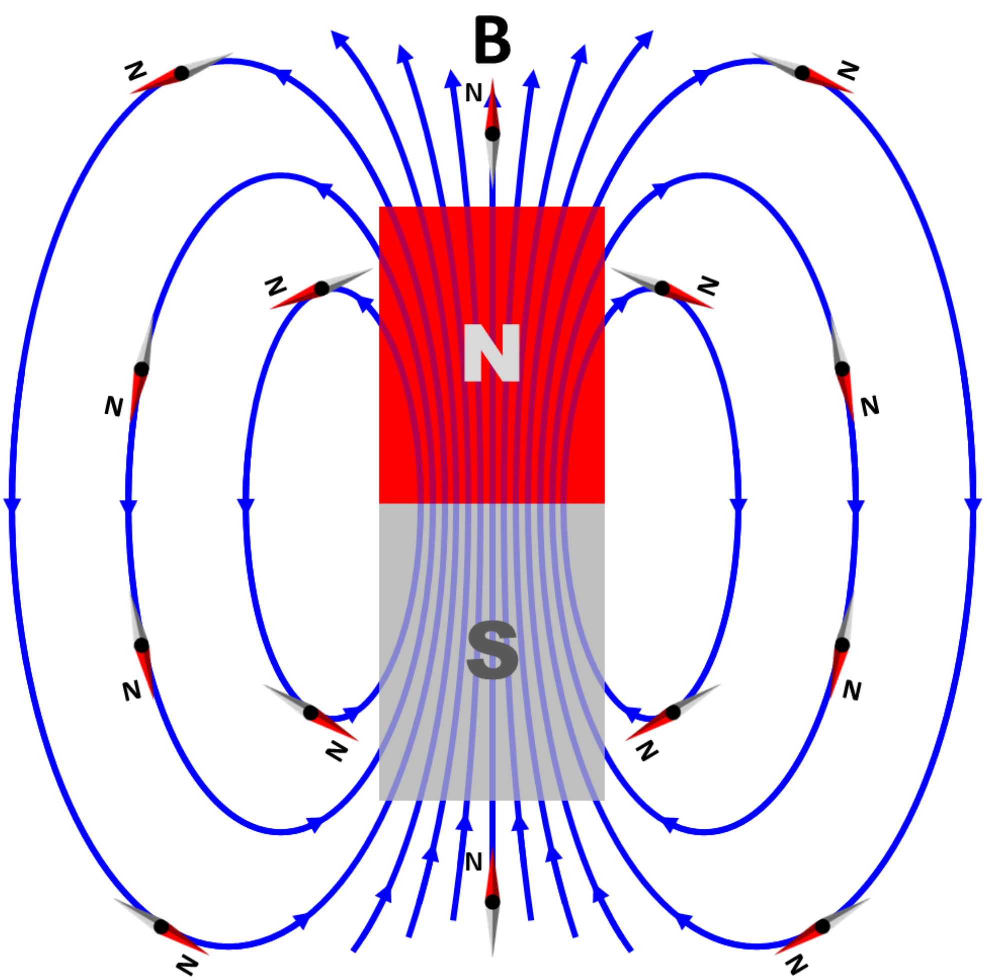


Fig. 1: A permanent bar magnet has both N- and S-magnetic poles. Magnetic field lines leave the N pole, circulate around and enter the magnet at the S pole. By convention, the magnetic field points in the direction of the North point of a compass needle (indicated as red and with a small "N").

Magnetic Field of a Current Loop

Fundamentally, all magnetic fields (even permanent magnets) are generated by electrical currents. One of the most common and simplest geometric shapes for a magnetic-field-generating current is a circular loop. The right hand rule for magnetic field directions gives the field direction through a loop of current as shown in Fig. 2.

The magnitude of the field at the center of a circular coil with N loops of radius, R, and current, I, is found from electromagnetic theory to be,

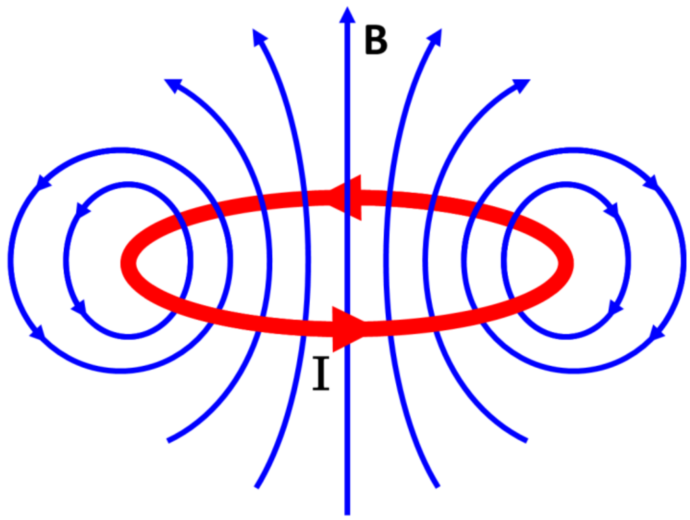


Fig. 2: Magnetic field, B, due to a circulating current, I.

$$B_{z\,coil} = N\frac{\mu_0}{2R}I \quad , \tag{1}$$

where μ_0 is the permeability of free space (magnetic constant) with value $4\pi \times 10^{-7}\ T \cdot m/A$.

Here, we are assuming that the coil is lying in the horizontal plane so that the magnetic field at the center only has a vertical, z-component.

If there is a background magnetic field – say the Earth's – with a component in the vertical direction, B_{z0}, then the total z-component of the magnetic field will be the sum,

$$B_z = B_{z\,coil} + B_{z0} = N\frac{\mu_0}{2R}I + B_{z0} \quad . \tag{2}$$

A comparison between Eq. (2) and the general equation of a straight line,

$$y = mx + b \quad , \tag{3}$$

suggests that a plot of B_z vs. I will yield a straight line with slope,

$$m = N\frac{\mu_0}{2R} \quad , \tag{4}$$

and y-intercept,

$$b = B_{z0} \quad . \tag{5}$$

Note: Both parts of the lab need to be completed. Work with your lab partner to divide up the work appropriately (ex. one could do Part 1 and the other could do Part 2).

Procedure (Part 1):

Magnetic Field Mapping

1. Lay a blank piece of paper on a table with no significant iron or steel components nearby.
2. Tape down the paper to prevent it from rotating relative to the Earth's magnetic field.
3. Tape your neodymium permanent bar magnet to the center of the paper and trace its outline with a pencil.
4. Locate the N end of the bar magnet by placing the compass near (but not touching) either end and observing the alignment of the needle (the N/red end of the compass needle points away from the N-pole and towards the S-pole – see Fig. 1b and Fig. 3). Mark the N and S poles of the magnet on the paper.

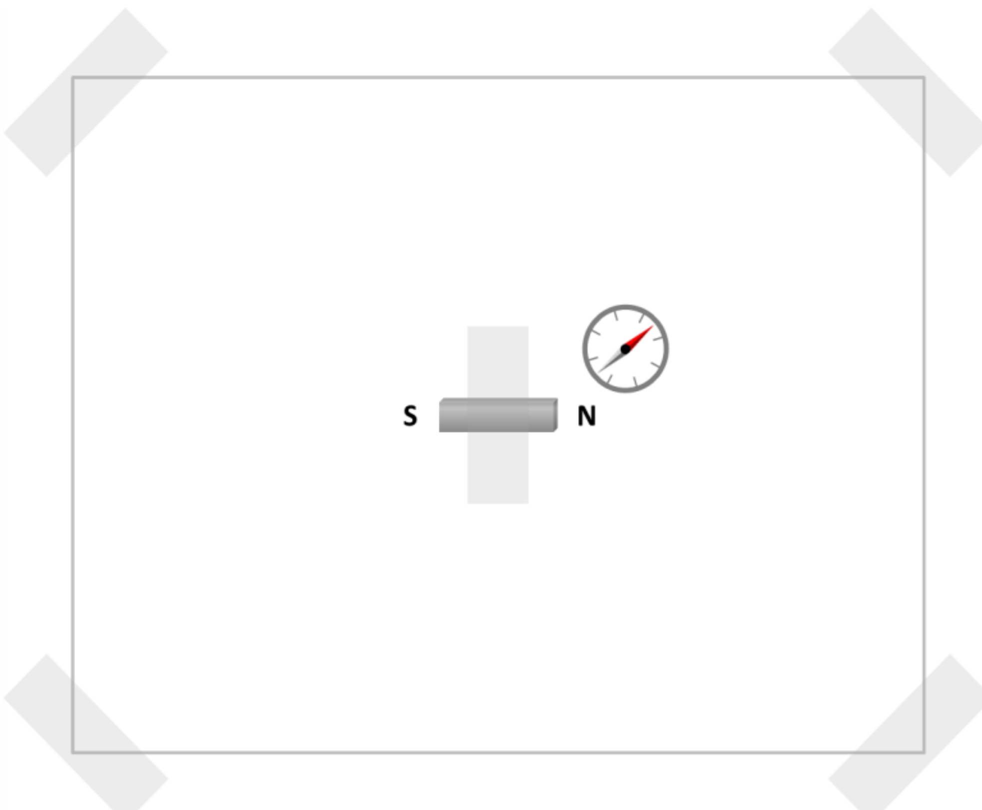


Fig. 3: Tape a sheet of plain, white paper down to a table or other surface without significant steel or iron objects nearby. Tape the bar magnet to the center of the paper, oriented with the paper along either axis. Trace the outline of the magnet on the paper. Place the compass nearby to check the orientation of the magnet's poles. Label the North and South poles on the paper.

5. With the compass resting on the paper near the N end of the bar magnet, put a pencil dot at both ends of the compass needle (see Fig. 4a). Disregard the NSEW headings of the compass casing and consider only the needle direction.
   Note: A pen or mechanical pencil could have some ferromagnetic material that distorts the bar magnet field - if the compass needle twitches as you bring in your pen/pencil, you will know to try something else, such as a wooden/graphite pencil or a marker.
6. Reposition the compass so that the S end of the needle is at the previous N pencil mark, and plot another point where the N end of the needle points (see Fig. 4b).
7. Continue marking N end-points of the compass needle and follow the magnetic field line until it either wraps into the S end of the permanent magnet or exits the page.
8. Connect the dots with a line including arrows to indicate the field direction (see Fig. 4c).
9. Start the compass needle at another point near the N end of the bar magnet and repeat the process of following a magnetic field line (see Fig. 4d).
10. Continue mapping the field lines until you have enough of the page filled (as in Fig. 1a) such that – if necessary – you could interpolate by eye and approximately sketch field lines anywhere on the page without the aid of a compass.

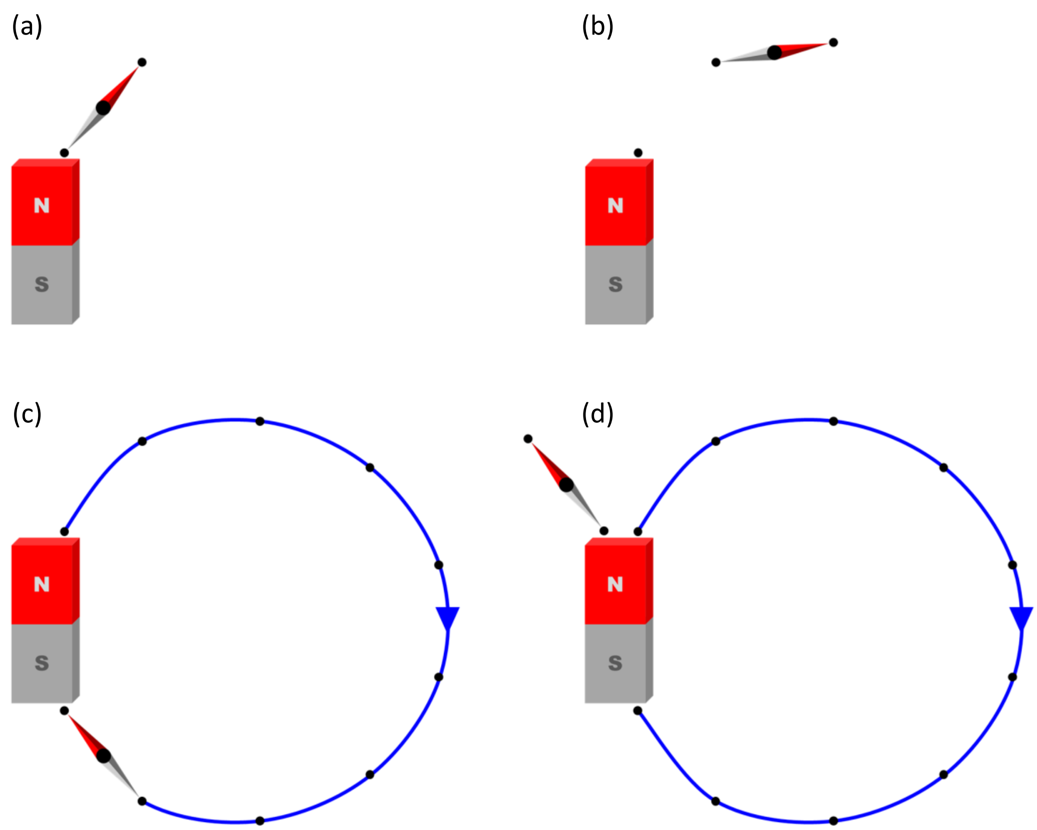


Fig. 4: Sketching the magnetic field of a permanent bar magnet – (a) Place compass near the N end of the magnet and place a dot at each end. (b) Move compass to find the next point. (c) Follow the magnetic field around a complete loop, connect the points, and draw an arrow on the field line. (d) Place the compass in another position near the N end of the magnet to plot a new field line.

Procedure (Part 2):
Magnetic Field of a Current Loop

Setup

1. Locate the 82 Ω, 120 Ω, and 160 Ω resistors from your lab kit.

   You can tell the resistor's nominal value from the 4 or 5-band color code printed on the resistor. To interpret this code, look up a resistor color code table or use an online calculator such as this one: https://resistorcolorcodecalc.com/.

2. Turn the multimeter dial to measure DC voltage (V ⎓), set it to the 20V range, insert the probes in the appropriate ports (black in COM, red in V), and measure the battery voltage by touching one probe to each pole of the battery (see Fig. 5).
   If the battery voltage has dropped below 8.5V, replace it with a different battery.

WARNING: Never attempt to measure across the poles of a battery or other power source while the multimeter is in current mode (A). Doing so will blow the internal fuse or even destroy the multimeter.

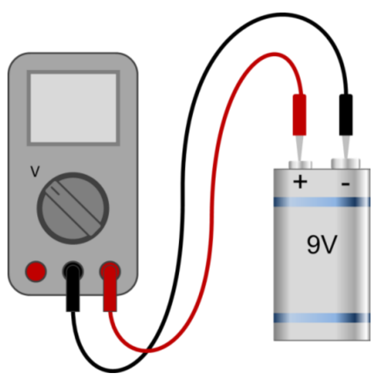


Fig. 5: Set multimeter dial to measure voltage (20V range), black probe in COM port, red probe in V port. Touch red probe to positive battery pole and black probe to negative battery pole.

3. Remove the multimeter from the battery and turn the dial to measure DC current (200 mA range). If the red probe is not already in the mA port, move it to that port.
4. Build the circuit shown in Fig. 6.
5. Start with the 160 Ω resistor for R. The resistors are used to limit current – preventing the battery from overheating. By using different resistors, we can vary the current flowing through the coil and thereby vary the magnetic field strength.
6. Measure and record the diameter, D, of your coil in meters. Measure it in several directions to check how circular it is. If it is stretched in one direction, just stretch it the other way so that it has the same diameter all the way around, then tape it down so it won't change. Divide the diameter by 2 to get the radius, R.
7. Record the number, N, of turns in the coil (see equipment list).
8. Check the resistance of the coil (should be very low) to make sure the insulation was removed from the wire ends. If it wasn't, use sandpaper, a flame, or knife/scissors to remove the insulation from the last centimeter of each end.

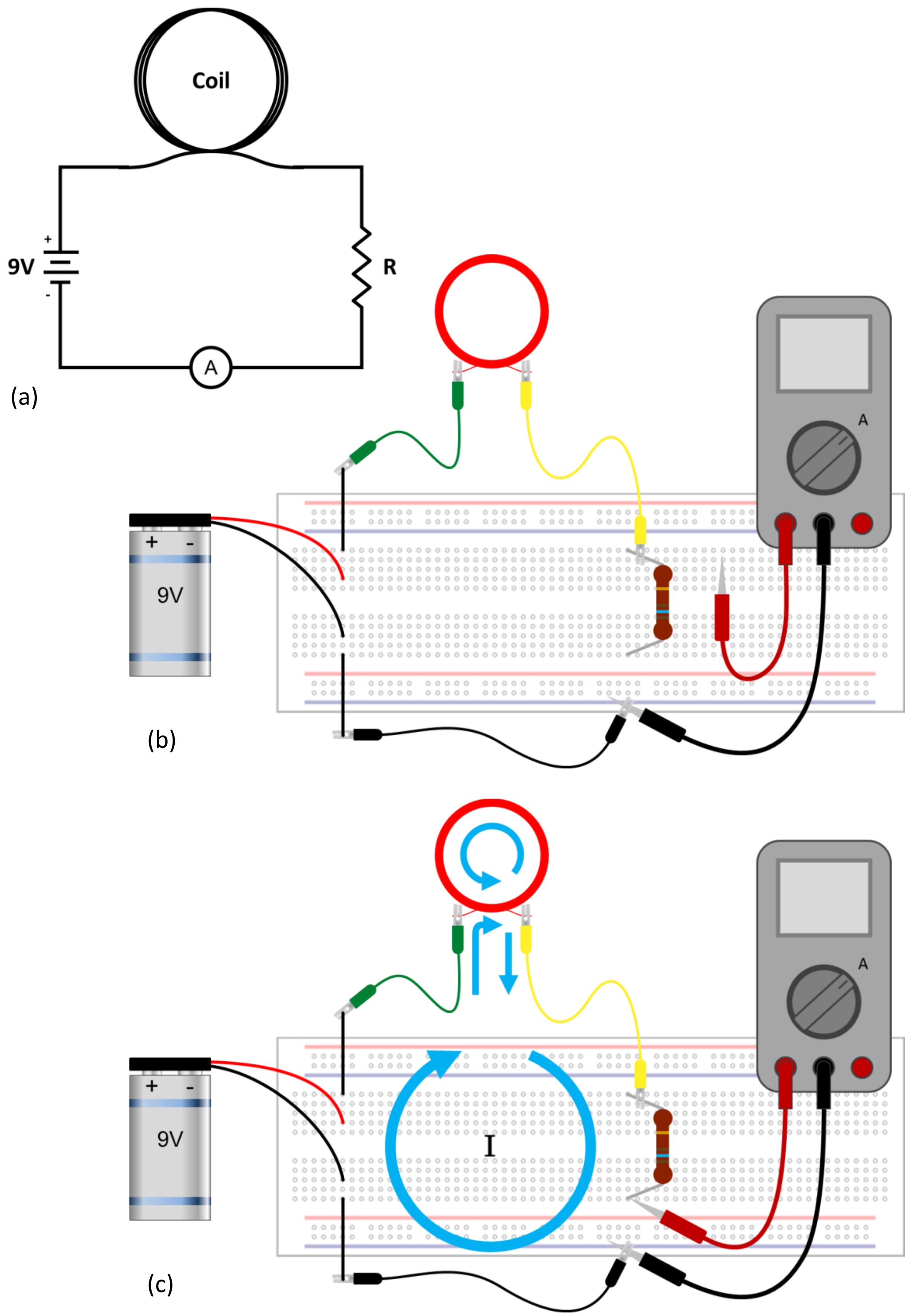


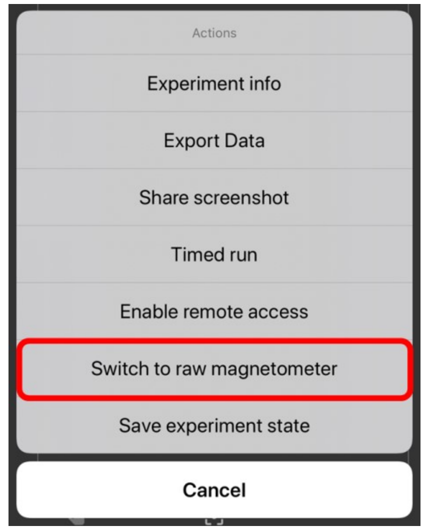
Fig. 6: Circuit providing current through the coil – (a) Circuit diagram, (b) Breadboard diagram (no current is flowing yet), (c) When the red probe touches the resistor, the circuit is completed and current flows in the direction indicated.

9. On your smartphone, open the Phyphox app, then choose the Magnetometer tool. Go to the tool's menu (three dots) and switch from "calibrated magnetometer" to "raw magnetometer" (this option is available on most phones).

(a)

Fig. 7: Set the magnetometer to "Raw Magnetometer"
(a) Tap the menu button.
(b) Tap "Switch to raw magnetometer".

(b)



10. On the main graph screen (Magnetometer x, Magnetometer y, Magnetometer z), touch the Magnetometer z graph to see only the z-component of the magnetic field. This should be the direction coming out of your phone screen. If you find that a different axis is coming out of your screen, use that graph instead.

Before continuing, you need to identify the location of the magnetometer (magnetic field sensor) in your phone. It is not located in the same place in every phone so this step is **very important** to find where it is in your phone. To do this we will use the permanent magnet.

11. Tape the permanent magnet to a ruler so that one end of the magnet is about 12 cm from the end of the ruler (see Fig. 8). It doesn't matter if the magnet is oriented N-S or S-N.

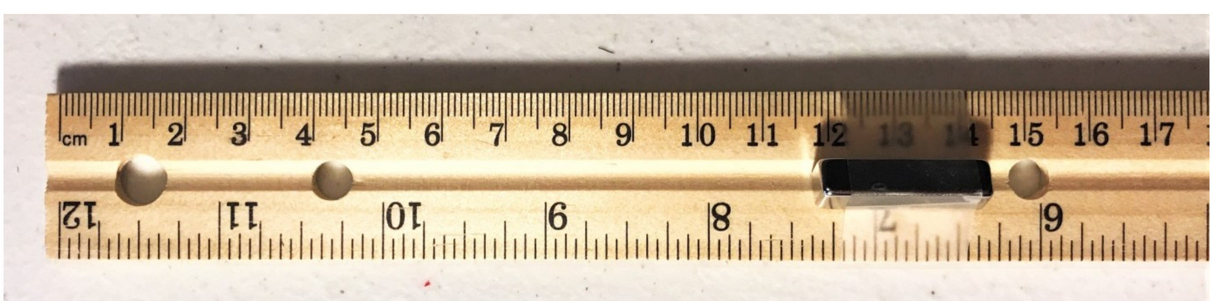


Fig. 8: Place the permanent magnet on the ruler so that one end of the magnet is at 12 cm and the magnet is aligned with the ruler as shown. Then tape the magnet to the ruler.

12. Place the phone face up on a flat surface (do not move it while identifying the sensor) and start recording magnetometer z data with the Phyphox app.
13. Hold the magnet away from the phone and record for a few seconds.
14. Place the ruler vertically with the zero cm end resting on the phone screen. This will keep the magnet the same distance (12 cm) from the phone, without getting it too close to the phone where it might damage the electronics. This also allows you to move it around above the phone screen without any change in vertical position.
15. Move the ruler with the magnet around over the phone and watch the magnetometer reading to see where the most extreme (highest/lowest) value occurs relative to the starting value (see Fig. 9). When you identify the spot that gives the most extreme reading, you have found the magnetometer in your phone. Depending on which way you oriented the magnet (N-S or S-N), the value will either increase or decrease dramatically as you move the magnet closer to the sensor.
16. Stop recording data and clear the graph. Then place the permanent magnet far away from your experiment setup so that it won't affect the magnetic field readings for the next part.

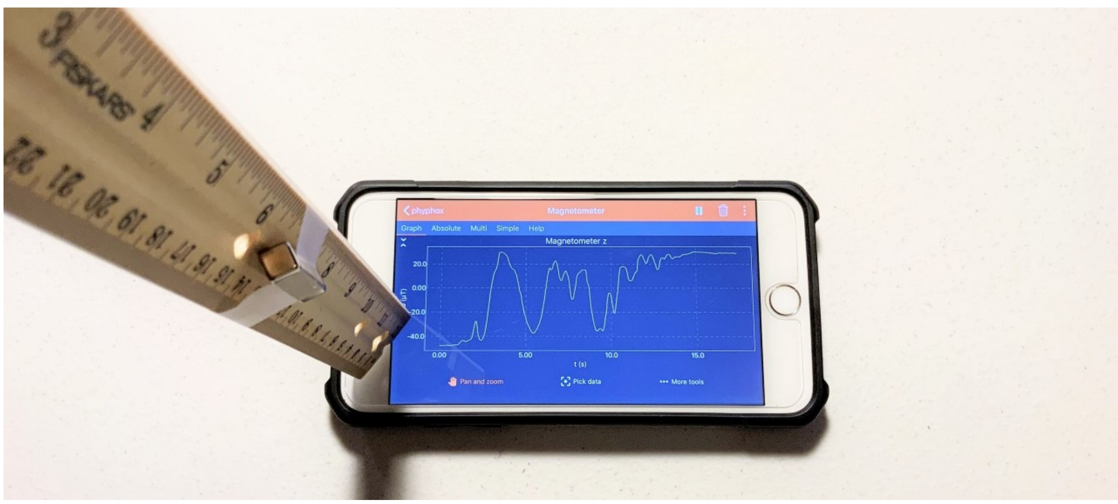


Fig. 9: Move the ruler with the magnet over the phone to find the magnetometer. When the magnet is directly above the sensor, the graph will show the highest (or lowest) value compared to the readings when it was away from the sensor. In this example, the magnet was oriented such that it gave the highest reading when above the sensor.

Measure the Magnetic Field

1. Place the phone on the table, face up (z-axis up), with the magnetometer (which you just located) directly over the center of the wire coil (see Fig. 10).
2. For the rest of the experiment, do NOT move the phone.
   Keep it in the same place so that the position of the magnetometer relative to the coil is the same for each measurement.
3. Make sure the multimeter is set to measure current in the 200 mA range with the probes in the correct ports.
4. With the 160 Ω resistor present in the circuit, hit the record button on the Phyphox app.
5. Record for a few seconds, with no current flowing (do not touch the probe to the resistor), to capture the background magnetic field (see Fig. 10a).
6. Touch the red probe to the resistor (see Fig. 10b) and record data for a few seconds.
7. While the current is flowing, hit the “Hold” button on the multimeter to save the value. Then remove the probe, pause the Phyphox recording, and leave the phone in place.
8. Record the current displayed on the multimeter in units of mA. Then hit the “Hold” button again to return to the live value.
9. Swap out the 160 Ω resistor for the 120 Ω resistor, resume recording in the app, and repeat the previous 3 steps to measure the current and magnetic field for the 120 Ω resistor.
10. Swap out the 120 Ω resistor for the 82 Ω resistor and repeat the process to measure the current and magnetic field for the 82 Ω resistor.
11. When finished, you should have 4 measurements in a row, similar to Fig. 11.

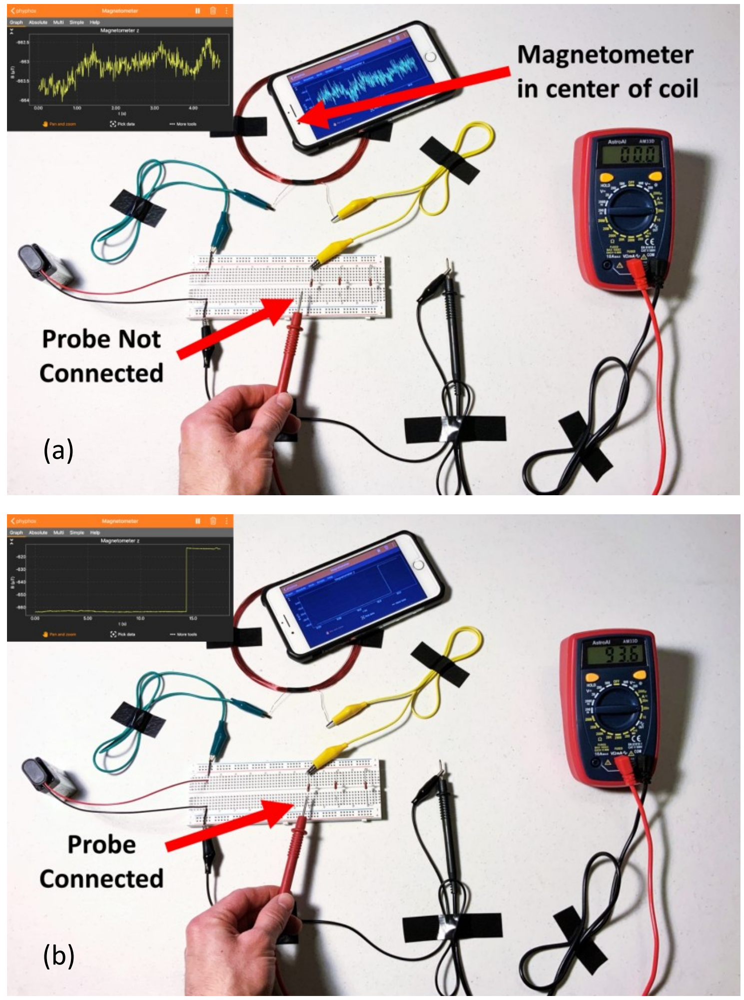


Fig. 10: Experiment setup (a) without current flowing and (b) with current flowing. Touch the red probe to the resistor to allow current to flow.

WARNING: Do not leave the current on (probe touching resistor) for too long or the resistor may overheat.

12. Once you have recorded the magnetic field and current for all three resistors, you can remove your phone from the coil.
13. Look at the Magnetometer Z graph in the Phyphox app. If you collected the data as instructed, then you should see a graph similar to Fig. 11 with 3 regions where the field increased or decreased relative to the background measurement. These correspond to the 3 resistors used in the circuit.

    Note: If you built the circuit as shown in Fig. 6, then the current will flow counter-clockwise through the coil, causing an increase in the magnetic field (see Fig. 11). If you wired the circuit backward such that the current flows clockwise through the coil, than the field strength will decrease. Either way is fine since we will use the absolute value of the slope during the analysis.

14. Use the “Pick data” tool to select a point in the region before current was flowing (see Fig. 11a). This is the background magnetic field (B_{z0}) at your location. Take a screenshot to save the value and record B_{z0} (in units of µT) as the magnetic field when I = 0.
15. Next, select a point in the region where the magnetic field changed (see Fig. 11b). This corresponds to the measurement with the first resistor.
    Take a screenshot to save the value and record the magnetic field, B_z, with the corresponding current measurement.
16. Continue using the “Pick data” tool to identify the magnetic field strength for the other two resistors, take screenshots, and record the B_z values with their corresponding current measurements.

Note that your phone will measure different magnetic field strengths than this example. This is caused by differences in the sensors, different phone brands and models, and geographic variation in Earth’s magnetic field. What should be consistent, regardless of these factors, is the change in field strength for a given current and coil geometry.

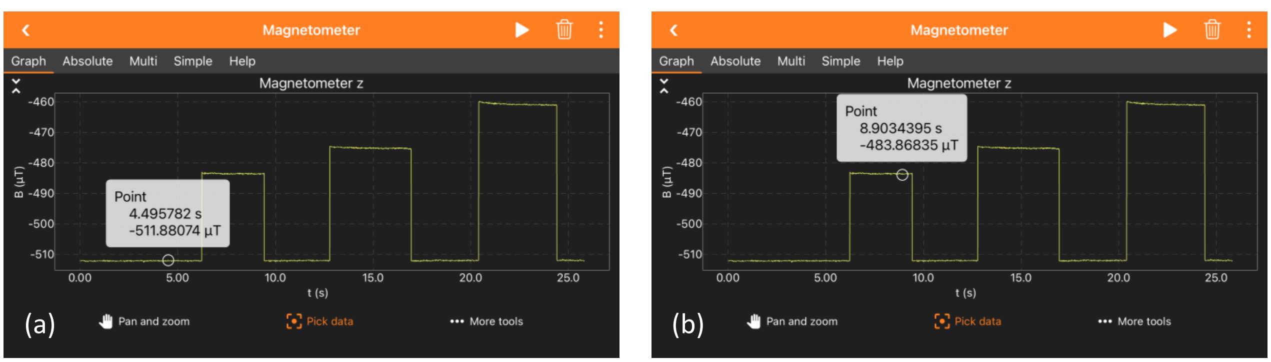


Fig. 11: Z-component of magnetic field with 4 measurements of several seconds each. First , the background measurement with I = 0, followed by measurements for each resistor (160 Ω, 120 Ω, 82 Ω) with currents approximately I ≈ 50 mA, 70 mA, and 100 mA.
(a) Data selected for B_{Z0} when I = 0. (b) Data selected for B_Z when I ≈ 50 mA.
Continue this process for the other two resistors. Your B_Z values will differ from these.

IMPORTANT: When you finish the experiment, turn off the multimeter to save the battery. The simpler inexpensive multimeters often do not shut off automatically.

Analysis (Part 1):

There is no analysis for Part 1.

Analysis (Part 2):

1. Plot B_z (in μT on the y-axis) vs. I (in mA on the x-axis), perform a linear fit, and record both the absolute value of the slope, |m|, and the y-intercept value, b.
   Note: The slope must be recorded as the absolute value to potentially correct for a clockwise coil current causing a negative slope.
2. Convert the slope from units of μT/mA into SI units of T/A.
3. Rearrange Eq. (4) and use the unit-converted slope with the radius, R, and number of turns, N, to solve for the measured permeability of free space, $\mu_{0\,meas}$.
4. Compare $\mu_{0\,meas}$ with the generally accepted value, $\mu_0 = 4\pi \times 10^{-7}\, T \cdot m/A$, by calculating the percent error.

$$\%Error = \frac{|\mu_0 - \mu_{0\,meas}|}{\mu_0} \times 100\%$$

5. Compare the measured background field strength, B_{z0}, with the y-intercept, b, by calculating the percent difference.

$$\%Diff = \frac{|b - B_{z0}|}{|b|} \times 100\%$$