Physics 15b PSI Week 4: Magnetic Fields

Chapter 5 of Purcell consists of an extended theoretical treatment of electric fields in moving reference frames, and the logical consequences of electricity when combined with special relativity. Although it is a beautiful treatment, in practice we generally treat magnetic fields as a separate entity, subject to different laws, from electric fields, as opposed to treating them as electric fields in a different reference frame. (Chapter 6 of Purcell treats magnetic fields in this way, on their own footing.) In this week’s lab, we’ll investigate some of the laws governing magnetic fields, in particular those relating magnetism with steady (DC) currents.

The magnetic field $\vec{B}$ is defined such that the magnetic force on a charged particle $q$ moving with velocity $\vec{v}$ is given by the Lorentz force law:

$$\vec{F} = q\vec{v} \times \vec{B}.$$  

In the lab, we will be more concerned with steady currents than with individual moving charges. In this case the Lorentz force law becomes:

$$\vec{F} = I\vec{L} \times \vec{B},$$

where $I$ is the current and $\vec{L}$ is the vector whose magnitude is the length of the wire carrying the current, and whose direction is in the direction of the current. This is the magnetic force on a straight wire in a uniform external magnetic field. It is also the case that a current generates its own magnetic field in its vicinity, which can exert magnetic forces on permanent magnets (such as a compass needle) or other currents placed nearby.

Speaking of permanent magnets, they are not treated in Purcell until Chapter 11, but we will explore the magnetic fields of permanent magnets and consider the similarities between permanent magnets and steady currents.
Outline for Physics 15b Week 4: Magnetic Fields

A. Plotting the Magnetic Field
   1. Magnetic field near a permanent magnet
   2. Magnetic field near a current loop
   3. Relationship between currents and permanent magnets

B. Magnetic Fields and Magnetic Forces
   1. What is the relationship between current and the magnetic field generated by that current?
   2. What is the relationship between current and the magnetic force exerted on that current?

C. Magnetism Challenge
   1. How can you create a motor using only a battery, a permanent magnet, and a short piece of wire?

Lab Goals
   A. Increase understanding of the relationship between currents and magnetic fields
   B. Understand the relationship between magnetic fields and magnetic forces
   C. Understand the magnetic effects associated with permanent magnets and their interactions with currents and with each other

Prelab Question for PSI Week 4: Magnetic Fields

*Please write out your answer to this question on a separate sheet of paper and bring it with you to PSI.*

You would like to use a DC power supply to put current through a coil of unknown resistance (but on the order of tens of ohms) in such a way that you can measure the current through the coil at all times. You have an ammeter which can support a maximum current of 0.6 A, and a voltmeter which can measure a maximum of 6 V. The power supply can put out an adjustable current of anywhere from 0 to 5 A. You also have a resistor with a known resistance of 1 Ω, which can support 5 A of current without blowing out.

How should you connect your components if you would like to be able to vary (and measure) the current all the way up to the maximum of 5 A, without destroying any components? Draw a diagram and explain your circuit.
A. Plotting the Magnetic Field

Goals: Qualitatively investigate the magnetic fields produced by permanent magnets and current loops

1. Magnetic field near a permanent magnet

Materials: Graph paper; rare-earth magnet; small compass

Objective: Trace out the magnetic field lines surrounding a permanent magnet.

In this activity, you will use a small compass to investigate the magnetic field in the vicinity of a strong permanent magnet. The permanent magnet is roughly the size and shape of a nickel; it produces a much stronger magnetic field than the Earth’s, up to a distance of tens of centimeters away. The Earth’s magnetic field points north(ish) and has a magnitude on the order of 0.5 Gauss (1 G = 10⁻⁴ Tesla).

SAFETY WARNING: The rare-earth magnet is a very strong permanent magnet. It can easily pull other nearby metal objects to itself, or leap several inches to attach itself to a large metal object. Take care that you don’t let it snap up your fingers. Be especially careful any time you are dealing with two such magnets, which will want to come together with great force.

The compass needle will align itself in the direction of the local magnetic field. The red end points in the direction of \( \vec{B} \). However, be sure to note that the needle is free to swing only in a plane; therefore, if \( \vec{B} \) is perpendicular to the plane of the compass, the needle cannot and will not point in the correct direction. If the needle seems to tilt or get stuck, try tilting the plane of the compass.

Which end of the lab is north?

Your intuition for the direction of the magnetic field near the permanent magnet may not be very good yet, so take some time to play around with different compass orientations with respect to the magnet. When you think you know what is going on, place the magnet in the center of a sheet of graph paper (tear one out of the lab book at your table) and use the compass to trace out a few field lines around it. Since the compass is quite small, one technique that works well is to put the compass on the paper and place a dot at the north
tip of the needle. Then move the compass so that the south tip is at the dot, and put another dot at the new position of the north tip. Keep going in this fashion until the field line you are tracing out either curves back in on itself or goes off the edge of the paper. Then connect the dots with a smooth line or curve and draw an arrow in the appropriate (S to N) direction.

**How do you have to orient the permanent magnet relative to the page if you want the field lines to be in the plane of the graph paper?**

**When you have finished tracing out a few field lines, show your work to an instructor.**

### 2. Magnetic field near a current loop

**Materials:** Graph paper; DC power supply; banana cables; alligator clips; small current loop; small compass

![DC Regulator Power Supply](image1.png)

![Small Compass](image2.png)

**Objective:** Trace out the magnetic field lines surrounding a current-carrying loop.

We will now try to repeat this exercise using a current loop as the source of the magnetic field instead of the permanent magnet. Recall that the permanent magnet has a very strong magnetic field, so when you are done with it, put it far away from the area where you plan to work on this next task. (I recommend sticking it to the top of the ring stand.)

**SAFETY WARNING:** The current loop will heat up as you put a large current through it. For safety, do not exceed 0.5 A of current through the loop. This much current will cause the loop to get warm but not hot. Larger currents run the risk of burning your fingers or melting the wires in the loop. Follow the instructions carefully to make sure the current is limited.
Apparatus Assembly and Measurement Directions

a. Make sure the DC power supply is off (orange button in the lower left).
b. Plug one banana cable into the + (red) banana jack and another into the – (black) jack. Don’t connect the other end of either cable to anything yet.
c. Turn the power supply on.
d. Use the coarse voltage adjust (far right knob) to set the voltage to 10 V.
e. Touch the two free ends of the banana cables together. You should see a current reading on the left digital display (and the voltage will drop to near zero). Use the coarse current adjust to cap the current at 0.5 amps. Once you do this, **don’t touch the current knob again** until you are done with this part of the lab. As long as you leave the current knob the way it is, nothing else you do can cause the current to exceed 0.5 A.
f. Turn the voltage down to 0.
g. Un-link the two free ends of the banana cables and attach an alligator clip to each of them. Connect them to the two leads on the current loop.

When you are ready to begin mapping out the magnetic field near the loop, use the coarse voltage adjust knob (not the current adjust!) to turn on the power. You will only have to give it a little bit of voltage before the current tops out at 0.5 A (you’ll hear a little click and the “C.C.” light on the power supply will come on). You can leave the current running at 0.5 A while you investigate the magnetic field, but please **remember to turn it off when you are not working**. Do this either by turning the voltage down to 0 or by pressing the orange power button (which will leave the current and voltage settings where they are).

Again, you will use the compass to map out the magnetic field lines near the current loop and plot them on a sheet of graph paper.

**How do you have to orient the current loop relative to the page if you want the field lines to be in the plane of the graph paper?**

**When you have finished tracing out a few field lines, show your work to an instructor. How would you compare the results of this part to the same exercise using the permanent magnet?**

When you are done with this part, please turn the power off, but you can leave everything connected since you’ll be using it again in the next part.

### 3. Relationship between currents and permanent magnets

**Materials:** DC power supply; banana cables; alligator clips; small current loop; rare-earth magnet; Gaussmeter

**Objective:** Explore the relationship between current loops and permanent magnets, and quantitatively measure the “strength” of the rare-earth magnet.
At the microscopic level, magnetic fields in matter are generated essentially by a quantum mechanical property of electrons called magnetic spin. Magnetic spin causes electrons to act as little current loops even when they are not actually going in loops. Thus, a permanent magnet can be considered to be equivalent to the superposition of many, many current loops, which in turn can be considered to be equivalent to a single current loop.

One consequence of this is that you can characterize the “strength” of a permanent magnet by asking what DC current would be required to produce the same magnetic field. In order to measure magnetic field strength, we’ll use the gaussmeter pictured below. To turn it on, turn the knob from OFF to DC.

How does the gaussmeter measure the magnetic field? Recall that the magnetic field is a vector, and the gaussmeter reads only a number. So the first thing to note is that the gaussmeter measures only one component of the magnetic field. To get the full magnetic field at a point, you have to orient the probe of the gaussmeter in different directions.

Look carefully at the probe (the flat black flexible piece at the end of the gray cable). The actual measuring device is located quite close to the very tip of this piece (maybe 1 mm short of the tip). It measures the component of the magnetic field perpendicular to the plane in which the tip lies. Notice that where the black piece meets the gray cable, on one side of the cable there are some black lines, and the other side is all gray. The side with black lines is the N side, and the gray side is the S side. The gaussmeter gives a positive reading when the magnetic field points from S to N. The units are in Gauss (remember, 1 G = 10^-4 T).

The gaussmeter also has a DC out, which converts the reading into a voltage (1 tesla = 1 volt), but for this part, we won’t need it, as we can just read the measurement off the display on the gaussmeter itself.

**Apparatus Assembly and Measurement Directions**

a. Measure the magnetic field strength as close as you can to the center of the permanent magnet.
b. Do the same for the current loop with a current of 0.5 A.

It turns out that the current loop is not actually one loop, but rather \( N = 100 \) loops wound tightly together. The orientation of the current is the same around each loop. Using superposition, explain how the magnetic field depends on \( N \).

Calculate how much current you would have to put through a single loop (of the same size) in order to generate the same strength of magnetic field as the rare-earth magnet.

Model the rare-earth magnet as an equally spaced lattice of atoms 1 nm apart. If each atom is a current loop, estimate how much “current” flows in each atom. (Hint: does the radius of the magnet matter? Does its thickness matter?)

c. Be sure to turn off the DC power supply when you are done.

**B. Magnetic Fields and Magnetic Forces**

**Goals:** Quantitatively investigate the relationships between current, magnetic fields, and magnetic forces

Note: this section has two independent exercises, which can be done in either order. #2 requires use of the Ohaus balance USB adapter, which we don’t have enough of, so groups will have to share. If you reach this part and you have a USB adapter available to you, do #2 first. If there is no USB adapter available, do #1 while you wait for one to free up. If you can’t tell whether you there a USB adapter connected, ask an instructor.

1. **What is the relationship between current and the magnetic field generated by that current?**

In this exercise, you’ll use Logger Pro to take simultaneous measurements of the current in a coil and the magnitude of the magnetic field produced by the coil. In order to get Logger Pro to do all the hard work for us, we’ll convert both the current and the magnetic field readings into voltages.

**Materials:** DC power supply; large current coil (below, left); small compass; Vernier differential voltage probe x2; banana cables; alligator clips; large 1-ohm resistor (below, right); LabQuest Mini
Objective: Explore the quantitative relationship between the current in a loop and the strength of the magnetic field generated by that current.

SAFETY WARNING: In this part, you will be running very large currents (up to 5 A) through both the coil and the large resistor. They can both handle it, but the metal casings of each will become warm to the touch. This is by design, as it helps the device to cool. Most importantly: make sure that you do not leave the current on at 5 A while you are not actively collecting data, which should only be for about 20 seconds at a time.

Apparatus Assembly and Measurement Directions

a. If the Ohaus balance USB cable is plugged into your computer, unplug it.
b. Make sure both differential voltage probes are plugged into your LabQuest Mini.
c. On your computer, locate the week4 folder on your desktop, and double-click on the file IB_Template.cmbl (NB: not the one called IF_Template! That is for part 2). This will open Logger Pro.
d. Clip the red and black leads to each other on the voltage probe from channel 1. Do the same for the other voltage probe. Then zero both voltmeters in Logger Pro (click the “0” button on the toolbar or type command-0). Unclip the leads.
e. Connect the voltage probe from channel 1 to the DC out from your gaussmeter. The DC out ends in a split wire; clip the red lead from the probe to the wire with the stripe, and the black lead to the unstriped wire.
f. Connect the voltage probe from channel 2 across the 1-ohm resistor, where the wires attached to the resistor have been stripped bare.
g. Connect the large current coil in series with the 1-ohm resistor with a banana cable. (One end of the banana plug can slide easily into the clip on the coil, but if it doesn’t, you can use an alligator clip.)
h. That should leave one free end on both the current coil and the resistor. Connect a banana cable to each and plug them into the two jacks on the front of the DC power supply.
i. Remember: the voltage on channel 1 is actually a reading of the magnetic field strength from the gaussmeter, with a conversion factor of 1 volt per tesla. The voltage on channel 2 is actually a reading of the current in the circuit, with a conversion factor of 1 volt per ampere (i.e. 1 ohm).
j. Turn on the power supply. Turn the current all the way down to 0, and then turn the voltage knob all the way up.
k. Turn the current from the power supply up to 0.25 A. Check to make sure that your Logger Pro reading on channel 2 makes sense.
l. We would like to measure the magnitude of the magnetic field at its strongest point, which is exactly in the center of the large coil. In order to do that, we need to know the direction of the field there, so that we can orient the probe correctly.
Can you guess the orientation of the magnetic field at this point? Use the small compass to check your answer. (You won’t be able to put it all the way inside, but you can place it pretty close in different orientations to see if the field is what you think it is.)

m. Position the probe inside the coil in the correct orientation to measure the magnetic field. The black part of the probe is flexible, so you can bend it at a right angle if you want the tip—where the sensor is located—to be perpendicular to the cable. Have one group member hold it steadily in place.

n. Turn the current down to 0. Then click collect in Logger Pro.

o. Have another group member slowly turn the current up from 0 to 5 A (the maximum that the power supply can produce). Once the current maxes out, click Stop Data Collection.

p. Turn the current back down to 0.

q. On the right-hand side of the Logger Pro window, you should see a graph that displays voltage 1 against voltage 2. This is our proxy for $B$ vs $I$.

Does the shape of the graph look like what you expect?

For a tightly wound loop of $N$ turns and radius $r$, the $B$ field at the center of the loop is supposedly given by

$$B = \frac{\mu_0 NI}{2r},$$

where $\mu_0 = 4\pi \times 10^{-7}$ T · m/A is the magnetic permeability of free space.

Estimate the value of $r$ for your coil. Then using your data from Logger Pro, calculate the value of $N$ that would make the above equation true.

Examine your coil closely. Estimate the actual number of turns in the coil. How does this compare to your previous answer? If there is a discrepancy, can you think of an explanation for it?

2. What is the relationship between current and the magnetic force exerted on that current?

A current-carrying wire in an external magnetic field experiences a force. In this exercise, you’ll to try to quantify the relationship between the current, the field, and the force (both magnitude and direction).
**Materials:** DC power supply; permanent magnet array; small compass; current-carrying wire supported by plastic sheath; Vernier differential voltage probe; banana cables; alligator clips; large 1-ohm resistor; LabQuest Mini

**Objective:** Explore the quantitative relationship between the current in a wire, an external magnetic field, and the magnetic force felt by the current.

The setup is a bit complicated on this one. The idea is to use a permanent magnet array to approximate a uniform magnetic field, and then measure the magnetic force that it exerts on a known current. However, there are a few complicating factors. The first is that the force is quite small, so we are going to try to measure it by using a digital balance with a sensitivity of 0.01 grams. Any change in the apparent “weight” on the balance will be interpreted as an additional vertical force on the object. The second complicating factor is that the wire itself has some slack, which will render the weight measurement unreliable. As a result, we will do the measurement somewhat backwards: we will measure the magnetic force that the current exerts on the permanent magnet array (which has the advantage of being both rigid and unconnected to any circuit, so that it can be isolated from other forces), and then use Newton’s 3rd Law to determine the force that the magnet array exerts on the wire, which is what we’re interested in.

**SAFETY WARNING:** The permanent magnets glued into the array are quite powerful, so again be cautious about your fingers, and definitely don’t bring any other magnets nearby. Also, we will once again be working with large currents, so don’t leave a large current running except while you are actively measuring something.

**Apparatus Assembly and Measurement Directions**

a. If Logger Pro is open, quit it.
b. Connect your digital balance to a USB port of your computer.
c. Take everything off the balance and then turn it on. Wait for it to read 0.00 g.
d. Place a wooden block on top of the balance, and put the other wooden block (the one with the nail in it) on top of that one.
e. Mount the permanent magnet array by sticking it to that top block (it attracts the nail) so that the red faces are horizontal.
f. Zero the balance.
g. Use a small compass to determine the direction of the magnetic field just outside the red-painted faces.

**The red faces are the N poles of the permanent magnets. Do the magnetic field lines go into or out of the N poles?**

h. On the LabQuest Mini, make sure there is exactly one voltage probe plugged in. If there are two, unplug the one from channel 2.

i. On your computer, locate the week4 folder on your desktop, and double-click on the file **IF_Template.cmbl** (NB: **not** the one called **IB_Template**! That is for part 1). This will open Logger Pro.

j. Clip the red and black leads to each other on the voltage probe. Then zero the voltmeter in Logger Pro (click the “0” button on the toolbar or type command-0). Unclip the leads.

k. Position the current-carrying wire and plastic tubing adjacent to the red face of the magnet array as shown:

l. You may have to adjust the height of either the wire (on the ring stand) or the magnet array (on its wooden block) to match the height of the wire to the center of the magnet array. Try to leave as little space between the wire and magnet faces as possible without actually having them touch each other.

**Why do we position the magnet array and wire so that they are horizontally adjacent, as opposed to running the wire above or below the face of the magnet?**

m. Connect the leads from the voltage probe across the 1-ohm resistor, where the wires attached to the resistor have been stripped bare.

n. Connect the wire in *series* with the 1-ohm resistor using banana cables and alligator clips. Connect the other end of the resistor and the other end of the wire to the DC power supply.

o. Turn on the power supply. Turn the current down to 0. Then turn the voltage all the way up.

p. Observe what happens to the reading on the balance if you turn up the current slightly. Then turn the current back down to 0.

**Explain your result and compare to the prediction of the Lorentz force law. You will need to think carefully about the direction of the current (trace it from the**
q. While the current is off, use the gaussmeter to measure the magnetic field due to the permanent magnet at the position of the wire.

r. In Logger Pro, make sure that both the mass and voltage are reading 0. If not, re-zero the mass by pressing the button on the balance itself. Re-zero the voltage by clipping the red and black leads to each other and clicking the 0 button in Logger Pro.

s. Click Collect. Logger Pro will begin to collect data at a rate of one measurement per second. As it is doing this, slowly turn the current up from 0 to its maximum value of 5 A.

t. When you reach the maximum current, click Stop Data Collection and then turn the current off.

u. The graph on the right in Logger Pro will show you mass vs voltage. Remember that we are using voltage as a proxy for the current, with a conversion factor of 1 volt per ampere (i.e. 1 ohm). We are also using mass as a proxy for the magnetic force.

What is the relationship between the mass reading and the magnitude of the magnetic force?

Does the graph of mass vs voltage have the shape you expect?

Does the graph have the slope you expect? You will need to do a calculation here involving the magnetic field $B$, the current $I$, the magnetic force $F$, the number of loops $N$ in your wire, and the length $L$ of the region containing the magnet field.

Which quantity in your calculation has the largest uncertainty? Is it large enough to explain any discrepancy between your predicted slope and your measured slope?

C. Magnetism Challenge

Goals: Think creatively about how to use magnetic forces and DC currents to create steady rotational motion

1. How can you create a motor using only a battery, a permanent magnet, and a short piece of wire?

Materials: AA battery; small rare-earth magnet; short length of copper wire; pliers

Objective: Construct a motor (i.e. a steadily rotating object) consisting of only a battery, a magnet, and a wire.
SAFETY WARNING: These magnets are also quite strong, so watch your fingers. The pliers you have been given are for bending the wire only, not cutting or stripping. You should not need to strip the copper wire, as it is uninsulated. If you would like to cut a different length of wire, consult an instructor and wear safety goggles to guard against flying bits of wire. For bending only, you do not need to wear goggles.

If you are able to successfully produce a motor, it will require large currents, so be mindful that if you leave it running, it will get hot.

This is a challenge task, so no apparatus instructions will be provided. You do not need, and will not be given, any adhesives. The magnet itself is coated in conducting metal.

When you get this working, show it to an instructor.

Everyone in the group is welcome to build their own motor and take it home with you when you’re done, but again, heed the warning about leaving it on because it can get quite hot. (Also, the battery will run down very quickly if you leave it on.) If you do want to take it with you, don’t put the magnet near your credit cards, Harvard ID, iPod, cell phone, etc., for obvious reasons.
Supplemental Information

More on Magnetic Fields

One can argue that magnetic fields play a much smaller role than electric fields: atoms and molecules are held together by electrical forces, with magnetism playing a negligible role. Similarly, electrical effects play a strong role in biology, whereas magnetic effects seem to be negligible with the possible exception of navigation. For purposes of this lab, particles with spin can be modeled as small current spools, where the current in the spool is an inherent property of the particle that cannot be changed and requires no energy to maintain.

The earth’s magnetic field provides some deflection of charged particles moving toward earth from space. Magnetic field control of particle velocities and positions also features prominently in high-energy physics experiments, fusion experiments, cold atom/ion experiments, and scanning electron microscopy.

http://news.bbc.co.uk/2/hi/science/nature/6522189.stm
http://public.web.cern.ch/Public/Welcome.html
http://www-project.slac.stanford.edu/ssrltxrf/bending_magnet.htm
http://www.slac.stanford.edu/
http://cerncourier.com/cws/article/cern/100577
http://www.iter.org/a/index_nav_4.htm
http://www.cmse.ed.ac.uk/AdvMat45/SEM.pdf

Magnetic fields are used to control the position and/or velocity of particles. Bose-Einstein condensation was achieved using magnetic traps and the Nobel Prize was awarded in 2001. http://www.colorado.edu/physics/2000/bec/mag_trap.html

It is hoped that magnetically levitated trains will make transport much more energy efficient, though these gains have not yet been realized. In biology and medicine magnetic tags with functionalized surfaces designed to specifically bind to biological targets are used to separate the targets from vast numbers of untagged particles.

http://www.lerner.ccf.org/bme/zborowski/lab/

Magnetic separation is much more desirable than electric field separation precisely because most biological material is not strongly affected by magnetic fields. Large-scale magnetic separation is used to isolate metallic ores from soils obtained through mining.

http://www.met.sgs.com/met_magnetic_separation

MRI imaging uses the gradient of magnetic fields to provide the three dimensional location of material inside people. Purcell won the Nobel Prize for inventing Nuclear Magnetic Resonance http://nobelprize.org/nobel_prizes/physics/laureates/1952/purcell-lecture.pdf which is the basis of MRI. http://en.wikipedia.org/wiki/Magnetic_resonance_imaging#2003_Nobel_Prize for which a Nobel Prize in medicine was awarded in 2003.

Most long-term computer memory uses magnetic fields, though current flash drives actually use electric fields. Old-style magnetic memory systems read the values stored in memory using Faraday’s Law, but most hard drives now use Giant Magneto-resistance instead. http://www.research.ibm.com/research/gmr.html Switching to GMR permitted an enormous decrease in the size of stored memory bits, and the Nobel Prize for 2007 was
awarded for the fundamental scientific discovery underlying this technology.  

Unfortunately, magnetic separation, MRI, and magnetic memory depend on the spin of particles, a topic that is not considered in 15b until Chapter 11 of Purcell. In Chapter 11 of Purcell it will be shown that the magnetic properties of ferromagnets are a consequence of electrical interactions rather than magnetic interactions.