

## Magnetic Fields with Oral Presentations (10-12 min presentation)

### General instructions to all groups

This lab will take place over three weeks.

- The first week you acquire all possible data you can think of. Some of it may end up being useless, but better to get extra stuff and not use it than to re-build your apparatus to take data in week 2.
- The second week you get any data you missed and prepare your presentation.
- The third week you present to the class.
- Missing any of these three weeks negatively significantly impacts other students in your lab group. As such, extra penalties may be imposed for any tardiness or absence during these three weeks.

**Take photos AND videos of yourself doing the experiment.** While videos are often much more useful for explaining things, they can add a level of headache in terms building your presentation. The videos might help you write up your talk even if you end up using only photos later on. *Include a ruler in every photo for scale!*

### If you can do an experiment, you should be able to plot SOMETHING.

A single data point is pretty darn meaningless to other scientists. To create a plot, typically you try to design an experiment wherein you vary one parameter (say mass) and only one other parameter is affected (say current). Ideally, you should have a theoretical prediction of how changing the mass causes the current to vary. You then create a table of values that looks like the one at right.

$m$ (g)	$I_{th}$ (mA)	$I_{exp}$ (mA)
10.0	51.5	62.3
20.0	103.0	115.2
50.0	257.5	291.8

**Choosing the correct prefix is crucial to looking good.** Looking good is almost as important as being good in terms of getting a job. It's all marketing these days. When you present info to others you are selling yourself as a product. The labels on your data are like the packaging. Compare the tables below. I think you will agree the third version looks better AND is easier for a reader to understand at a glance.

Scientific	Engr w/o prefix	Engr w/ prefix
$x$ (m)	$x$ (m)	$x$ (km)
2.00E+03	2.00E+03	2.00
5.00E+03	5.00E+03	5.00
1.000E+04	10.00E+03	10.00
2.000E+04	20.00E+03	20.00
5.000E+04	50.00E+03	50.00
1.0000E+05	100.00E+03	100.00

**Tip:** while doing your work/calculations in a spreadsheet, it is easiest to use *scientific* notation.

After doing all the work, make copies of each data column using *engineering* notation *with appropriate prefix*.

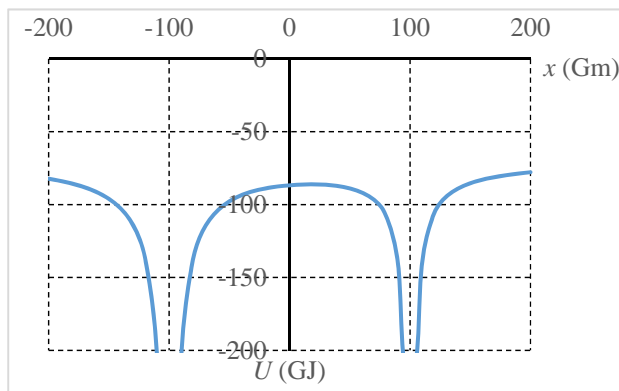
**Any time you take data, always think about how many sig figs you should show.** Always write down an estimate for the error/uncertainty for every measurement. Every once in a while this can make the difference between understanding your experiment and being completely clueless.

### Summary:

1. Always think about sig figs on every measurement/calculation.
2. Always record some kind of error estimate for every measurement/calculation.
3. Take photos and videos of your work as you go (including a ruler for scale in each shot).
4. Use *scientific* notation for *calculations*; use *engineering* notation (*with prefix*) for final *presentation*.

**Scientists, and everyone else, hate reading data tables.** It is much better to present your data *graphically*. General trends are more easily internalized by the audience. Plots show the audience you tested a particular scenario under a wide range of conditions.

Note: A wise choice of prefix keeps the numbers on your axes easy to read. If you chose prefixes wisely for your final data table, the plot should look great! As an example, I created a plot for gravitational potential energy versus position for a set of masses. Think how messy the axes would be had I not used gigameters and giga-Joules...



**Your plots will likely look like the one shown in your lab manual appendices entitled Sample Graph Type II.**

This type of graph is useful because it shows both the theoretically predicted values and the experimentally determined values. The audience can instantly recognize how well theory matches experiment. If theory is in good *qualitative* agreement with experiment, the experimental dots take on the same *shape* as the theoretical smooth line. If theory is in good *quantitative* agreement with experiment, for this class we assume 70% (or more) of the experimental error bars are in contact with the theoretical smooth line. This topic relates to confidence intervals...

Each group must produce **at least one plot** (not a table) of some experimental data compared to theoretical data. Most groups will have several plots. Usually, but not always, having more plots makes for an easier talk. Each plot will take several minutes to explain and rapidly chews up the required time.

**Questions to ask yourself while preparing your presentation slides with a plot:**

- Is the plot as big as possible? Use an entire slide (no border) for each plot to make them easy to read.
- Can we read the numbers on your graph? Is every font size at least 18 pt?
- Are you using the same font as the rest of the presentation? Or are you doing your best to use at most three fonts throughout your talk? Excessive font changes distract from content.
- Are the sig figs used in the axis labels comparable to the sig figs of the underlying data?
- **Units are NOT italicized.**
- **Variables ARE italicized.**
- I prefer you to use variables (instead of words) in your axis labels. Other instructors differ on this.
- Note: I sometimes make axes in a thicker black line and gridlines, if useful, in a thinner dotted line.
- Only include a legend if two or more data sets are shown on a single plot. You will *probably* have two sets (experimental & theoretical) on the same plot. You should *probably* have a legend.
- Typically, experimental data is shown as points (or just error bars) while a theoretical data set is shown as a smoothed line. Exception: a *large* experimental data set (>20 points?) is often shown as a solid line.

**Once you know the plot(s) you plan to explain, form a 10-12 min presentation around it.**

Your presentation should include slides for the following:

- Title slide with awesome picture, title of experiment, and your full names
- Goal slide
- Theory slides
- Procedure slides
- Plot(s)
- Conclusions

For a 40 minute video on slide design, try a web search for “giving an effective presentation Stanford”. Otherwise, continue reading below.

Title slide: Maybe you took a picture that really exemplifies your topic. Or consider a funny cartoon that relates to your topic (cite the website you get it from). Try to keep the joke funny but inoffensive.

Goal slide: Tell us what you plan to cover, no more than three items if possible.

Theory and procedure slides often get blended together. You might show a picture of what you hope to do, then show an FBD or other calculation supporting what you just talked about. Then show another picture of what happens next, then explain some more math, etc. No matter how you organize it, make sure it flows logically.

Usually it helps a lot to have photos AND a simplified drawing. Sometimes photos get too busy and the drawing can help the audience see what is really important. Word or ppt graphics should work just fine; I can help you as well. You could also sketch a simplified drawing and scan it in (or use your phone to snap a photo).

**Regarding cut and paste of my work:**

- Don't do it.
- One goal of making you do this is to improve your ability to make figures and use the equation editor

**Regarding videos:**

- If you are showing a video you made, have multiple ways to show it (embedded, online & flash drive).
- Be careful when embedding it in the talk. Test the embedding to verify it works.
- Have it saved on a flash drive and load it up ready to go BEFORE you start talking as a back-up.
- Know the best time to start/stop the clip so you do not waste time.

**Regarding calculations/derivations/equations:**

- Don't show every little step of algebra. Show the starting point and explain how it relates to your pictures, your drawings, or both if it helps. Skip to the final result. Perhaps, if one step is particularly counter-intuitive/tricky/important, show that sub-step.
- Have the full calculation worked out in your notes with all the gory details just in case I ask. Note: usually I can see if it is wrong right away so make sure you double check with me before presenting to make sure you get it right!
- USE THE EQUATION EDITOR for all equations AND any time you put a variable in a figure. It should automatically get all your italics and fonts correct. It will make your equations look professional and make the audience think you pay attention to detail!

**Regarding plots:**

- Correctly use engineering notation to clean up your plots
- Include theory and experiment on the same plot whenever possible
- Don't put the plot slide up and say, "Here is our plot. Moving on...". Work up some things to say about it!
- Compare the plot to the theoretical equations whenever possible. You may end up flipping back and forth between the final result of your theory and the plots. Perhaps you say stuff like "Here the mass is small so we expect the current to be large. As the mass increases we expect the current to decrease. Our equations predict current is inversely proportional to the square root of mass. This smooth line shows what the theory predicts while the dots indicate our experimental parameters. We see the data does not agree well with the theory for small masses but seems to match up quite well (within about \_\_\_%) for most of the large masses."
- Point out interesting spots where things don't match your predictions.
- If your data doesn't match theory well, explain why the data is noisy or has large errors.
- Have the data *table* on your flash drive just in case (but don't include it in the presentation).

**Conclusions:**

- Remind us of what you wanted to do in your original goal slide
- Summarize super-briefly how
- Propose future experiments that could elucidate related topics or further clarify your own experiment

**Regarding the scoring of your presentation:**

- 40 points total (10 points for data day, 10 points for prep day, 20 points for presentation day)
- Show up to all meetings for the next three weeks.
- If you miss a day you will lose AT LEAST 10 points per day missed.
- If you miss more than one day additional penalties to your *overall course grade* are incurred.
- If you do not participate fully on any day, your score is reduced.
- Each group member must do an equal portion of the talking or all group members lose points.
- **Stay within the time limits or you will lose points.**
- **Practice your talk and time it at least twice as a group prior to presenting.**
- Follow the slide design guidelines. I reduce points for using too many words, formatting/style, inappropriate use of italics (or lack thereof), subscripts, superscripts, font size, color schemes, excessive clutter, slides too sparse, etc. Basically, if something distracts the audience (me) from focusing on the content, you lose points.
- If the content is wrong, you also lose points.
- Being a decent speaker (eye contact, loud enough, keeping us awake, etc) is worth a few points as well.
- Work hard, show me several rough drafts, verify your equations are correct (and formatted correctly).
- Test drive your talk on the big screen in advance to make sure it shows up well.

### General tips on Measurement Settings for Mag Field Sensor

**TIP:** Expect only 1-2 sig figs for your mag field measurements. On 100x precision is 0.1 G; on 10x it's 1 G.

**TIP:** For fields larger than 10 G use 10x; for fields less than 10 G use 100x.

### MEASUREMENT SETTINGS FOR SOLENOIDS:

Use 1.5A current as measured by the power supply display. Set magnetic force sensor on 100x sensitivity and leave it. Open DataStudio and install a "Magnetic Field Sensor". Look on the upper left side of the screen. Drag the 100x setting to "DIGITS" (on lower left side of screen). If for some reason you reach 9-10 G, switch to 10x on the probe and in Data Studio. **Watch out! If the sensor locks up you might need to re-boot DataStudio and restart the probe.**

### MEASUREMENT SETTINGS FOR COIL:

Use 1.5A current as measured by the power supply display. Set magnetic force sensor on 10x sensitivity and leave it. Open DataStudio and install a "Magnetic Field Sensor". Look on the upper left side of the screen. Drag the 10x setting to "DIGITS" (on lower left side of screen). When your magnetic field drops below 10 G you can switch to 100x sensitivity. **Watch out! If the sensor locks up you might need to re-boot DataStudio and restart the probe.**

### MEASUREMENT SETTINGS FOR LONG STRIGHT WIRE:

Use 1.7A current as measured by the power supply display. Remember your experimental current is effectively  $44(1.7A) = 75A$ . Open DataStudio and install a "Magnetic Field Sensor". You will need to use 10x sensitivity close to the wire and 100x sensitivity a few cm away. You must ensure the sensor switches are visible from above while you take data. At each grid point you must take both radial and axial measurements to get both components of the magnetic field. Historically the sensor has not stayed well-zeroed (tared) over all measurements. At the end we can subtract off any unusual offsets and add that to error.

### MEASUREMENT SETTINGS FOR NEODYMIUM MAGNET:

Set magnetic force sensor on 1x sensitivity and leave it. Open DataStudio and install a "Magnetic Field Sensor". Look on the upper left side of the screen. Drag the 1x setting to "DIGITS" (on lower left side of screen).

**WATCH OUT!** The most common error is using 10x on the probes and 100x in DataStudio (or vice versa).

Before each set of measurements, ensure the setting on the probe and the screen match.

Just prior to each set of measurements, move the sensor far away from the coil/solenoid *without changing the probe orientation*. Then zero the sensor using the TARE button.

After taking measurements on the 10x setting, you might try for more sig figs on any measurement less than 10 G.

**WATCH OUT!** In many instances it appears changing the sensitivity settings will cause the mag field sensors to malfunction. If you change the sensitivity setting, move the probe around a bit to verify it is working properly (verify the probe reading is large close to the wire and small far from the wire). If a malfunction occurs, try closing Data Studio and setting up the sensor from scratch. Several times this has fixed this problem for me.

**WATCH OUT!** Earth's mag field is about 0.5 Gauss where  $10^4$  Gauss = 1 Tesla. For magnetic field measurements smaller than 5 G the earth's field is potentially a 10% error! **For on axis data**, one way to reduce this error is to take a first set of data ( $\vec{B}_{measured1}$ ). Next reverse the current direction and retake the data ( $\vec{B}_{measured2}$ ). By subtracting your two measurements and dividing by two the contribution from the earth's field should drop out and you should get higher precision measurements. **No one ever has time to do this...**

$$\begin{aligned}\vec{B}_{measured1} &= B_{coil}(+\hat{k}) + \vec{B}_{earth} \\ \vec{B}_{measured2} &= B_{coil}(-\hat{k}) + \vec{B}_{earth} \\ \frac{\vec{B}_{measured1} - \vec{B}_{measured2}}{2} &= B_{coil}(+\hat{k})\end{aligned}$$

**Option 1:** Compare solenoids to coils.

Determine  $B$  vs  $z$  along the axis of a coil. See Sample Graph Type II in lab manual appendices.

Determine  $B$  vs  $z$  along three different solenoids. Compare each solenoid to both the coil and to other solenoids.

The magnetic field along the central axis of a *solenoid* is given by

$$B_{sol} = \frac{\mu_0 n I}{2} \left( \frac{z + \frac{L}{2}}{\sqrt{\left(z + \frac{L}{2}\right)^2 + r^2}} - \frac{z - \frac{L}{2}}{\sqrt{\left(z - \frac{L}{2}\right)^2 + r^2}} \right)$$

where  $n = \frac{N}{L}$  is the number of turns *per unit length*,  $I$  is current,  $L$  is total length of the solenoid,  $r$  is the radius of the solenoid, and  $z$  is the distance (on-axis) from the center of the solenoid. You should be able to derive the above result for  $B_{sol}$  (in terms of  $z$ ) by finding the appropriate problem in the workbook. The trick is to take your long solenoid and slice it into coils...

We already derived the mag field along the axis of a *coil*

$$B_{coil} = \frac{N\mu_0 I r^2}{2(r^2 + z^2)^{3/2}}$$

where  $r$  is the radius of the coil,  $N$  is the number of turns,  $I$  is current, and  $z$  is distance from the center of the coil. To compare the coil to the solenoid, modify the current such that the product  $NI$  for *each solenoid* equals  $NI$  for *the coil*. I think you need to cut the current in half for the coil, if I remember correctly, because the solenoids each have 100 turns while the coil has 200 turns.

Be careful: carefully distinguish between  $N$  and  $n$ .

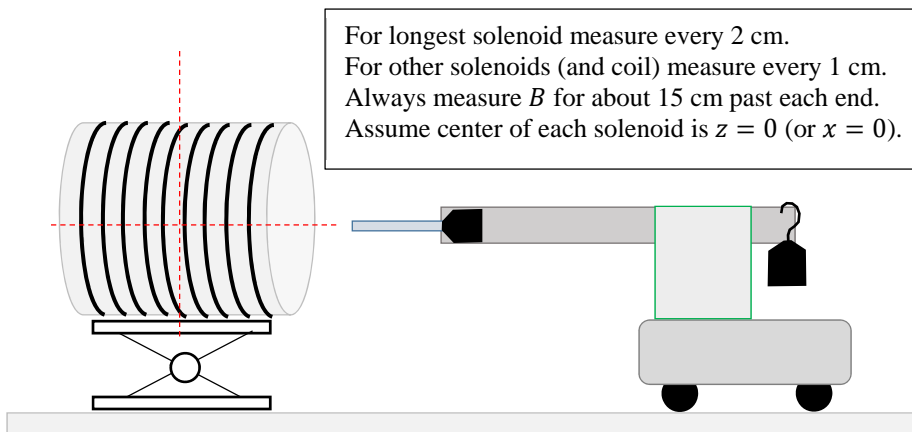
Plot  $B$  vs  $z$  showing both experimental and theory values on the same plot.

Perhaps show an additional version with all data sets on the same plot for easy comparison?

Discuss which solenoids, large  $n$  vs small  $n$ , have the worst problems with fringing fields. Support your conclusion by showing the fringing fields on the plots. Compare experiment to theory with a percent difference.

Now measure  $B$  vs  $(x, y)$  in the plane of the coil and in the plane at the end of your largest diameter solenoid. Use Matlab to make a contour plot. I'm basically curious to see how uniform the field at the end of the big radius solenoid is compared to the coil. **Include points both inside and outside the coil/solenoid!** See option 2 in-plane measuring procedure for more detailed instructions on this. Think: the solenoid mag field *should* or *shouldn't* change much as you vary the location in plane?

Continues next page...



To address:

- Two of your solenoids have the *same radius* & number of turns but one is twice as long. Should they have the same magnetic field strength or no? Does your data support your reasoning?
- Two of your solenoids have the *same length* & number of turns but one has twice the radius. Should they have the same magnetic field strength or no? Does your data support your reasoning?
- Magnetic energy *density* in your air core solenoids is given by  $u = \frac{B^2}{2\mu_0}$ . Rank the solenoids according to magnetic energy density clearly indicating any approximate ties.
- Consider the two solenoids with *same length* & number of turns but *differing radii*. The magnetic field inside a solenoid is not supposed to depend on the length if each solenoid uses the same current. That means for the same input current they should also have the same magnetic field energy density. Since the larger radius solenoid encloses more volume that implies you have more total magnetic field energy for the larger radius solenoid for the same current input. Is this a contradiction? Let's discuss...

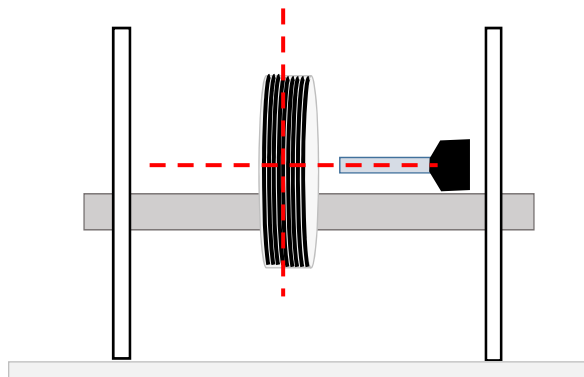
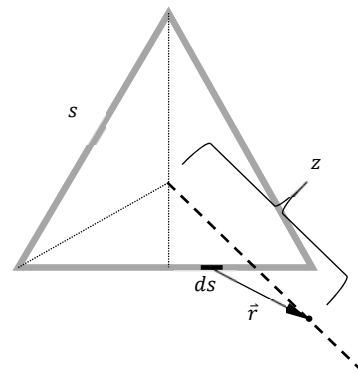
**Option 2:** Circular vs *triangular* coil of equal perimeter.

Before you do anything, take a guess: if circular coil and triangular coil have same number of turns and equal perimeter, which should have the larger mag field at the center?

Use the workbook to determine  $B$  on the axis of the coil and the triangle distance  $z$  from the center. Relate side length  $s$  of the triangle to coil radius  $r$ .

Hint: they have equal perimeter.

$$\vec{B} = \frac{\sqrt{3}\mu_0 I}{8\pi} \frac{s^2}{\left(\frac{s^2}{12} + z^2\right)\sqrt{\frac{s^2}{3} + z^2}} \hat{k}$$

**On-axis measuring procedure:**

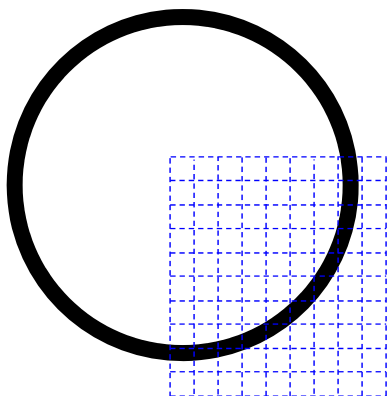
Support a ruler along the axis of the coil.

Ensure the field sensor is centered on the axis (not the ruler).

Measure  $B$  every 1 cm along the axis.

Measure  $B$  15 cm from the center in either direction.

Assume center is  $z = 0$  (or  $x = 0$ ).

**In-plane measuring procedure:**

Lay the coil flat on the 1 cm by 1 cm grid.

Measure  $B$  at every intersection for a quadrant of the coil.

Include the sign of each measurement.

Tabulate your data in Excel without any column headings.

Save the file as a csv (comma delimited) file.

Import the csv file to Matlab and make a contour plot.

Your grid should cover half the triangle but only a quarter of the circle or square.

**Include points both inside and outside each coil!**

**ON-AXIS:** Plot  $B$  vs  $z$  along axis of both the circular and triangular coils. See Sample Graph Type II in lab manual appendices.

**IN-PLANE:** Plot  $B$  vs  $(x, y)$  of both coils and show contour plots using Matlab.

Plan on explaining your derivation in detail to the class. You might have a few more intermediate steps on your theory slides than other people.

Note: when before you start explaining your derivation, ask the class to take a vote and ask them your initial question: if circular coil and triangular coil have same number of turns and equal perimeter, which should have the larger mag field at the center?

At the end of your derivation, state which one should win. If possible, try to think of a heuristic argument (one that requires no calculation) for which one should win. I might be able to help.



**Option 3:** Circular vs *square* coil of equal perimeter. Similar to Option 2 but use a *square* coil. Before you do anything, take a guess: if circular coil and square coil have same number of turns and equal perimeter, which should have the larger mag field at the center?

Use the workbook to determine  $B$  on the axis of the coil and the square distance  $z$  from the center. You will want to follow a derivation similar to the one shown for the triangle in option 2. The derivation is nearly identical with the following exceptions:

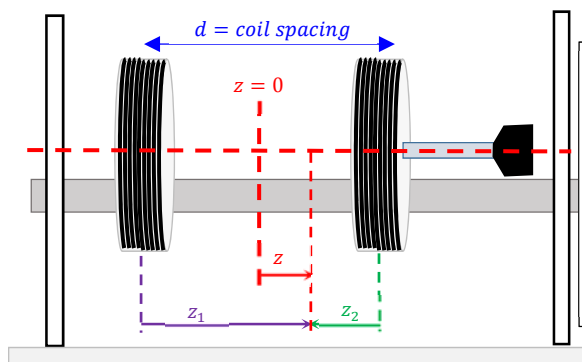
1. Make a new figure.
2. Use  $h = \frac{L}{2}$ .
3. Use  $\vec{B}_{NET} = 4\vec{B}_{segment1}$  instead of  $\vec{B}_{NET} = 3\vec{B}_{segment1}$ .
4. Relate side length  $s$  of the square to coil radius  $r$ . Hint: they have equal perimeter.

From several web sources I found

$$\vec{B}_{square} = \frac{\mu_0 I}{2\pi} \frac{s^2}{\left(\frac{s^2}{4} + z^2\right) \sqrt{\frac{s^2}{2} + z^2}} \hat{k}$$

Do all the same things described in Option 2.

#### Option 4: Helmholtz coils



##### On-axis measuring procedure:

Support a ruler along the axis of the coil.

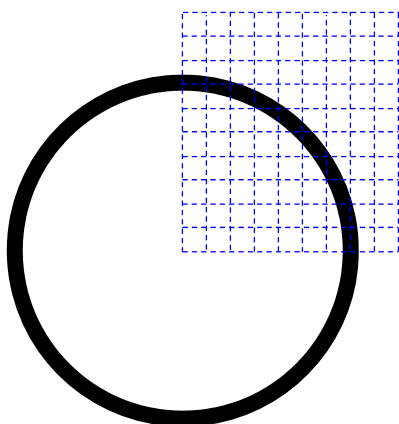
Ensure the field sensor is centered on the axis (not the ruler).

Measure  $B$  every 1 cm along the axis.

Measure  $B$  15 cm from the center in either direction.

Assume center is  $z = 0$  (or  $x = 0$ ).

Do the experiment a total of five times:  $d = 0, \frac{R}{2}, R, 1.5R$  and  $2R$ .



##### In-plane measuring procedure (only for $d = R$ case):

Suspend the 1 cm by 1 cm grid halfway between the two coils, parallel to the plane of the coils, covering 1 full quadrant of the coils.

Measure  $B_z$  at every grid intersection for a 15 by 15 grid.

Tabulate your data in Excel without any column headings.

Save the file as a csv (comma delimited) file.

Import the csv file to Matlab and make a contour plot.

**ON-AXIS:** Plot  $B$  vs  $z$  for two coils (current both running same direction) with each of five spacings:  $0, 0.5R, R, 1.5R$ , and  $2R$ . Perhaps it is best to first show  $B$  vs  $z$  for each data set separately then show all curves on a single plot of  $B$  vs  $z$ . Color code the experimental dots to match each smooth theoretical line to make your presentation more clear. Assuming the current in each coil is running down on the front side (and to the right is  $\hat{k}$ ) one finds:

$$\vec{B}_{total} = \vec{B}_1 + \vec{B}_2$$

$$\vec{B}_{total} = \frac{\mu_0 N I r^2}{2(r^2 + z_1^2)^{3/2}} \hat{k} + \frac{\mu_0 N I r^2}{2(r^2 + z_2^2)^{3/2}} \hat{k}$$

$$\vec{B}_{total} = \frac{\mu_0 N I r^2 \hat{k}}{2} \left\{ \frac{1}{(r^2 + z_1^2)^{3/2}} + \frac{1}{(r^2 + z_2^2)^{3/2}} \right\}$$

$$\vec{B}_{total} = \frac{\mu_0 N I r^2 \hat{k}}{2} \left\{ \frac{1}{\left( r^2 + \left( \frac{d}{2} + z \right)^2 \right)^{3/2}} + \frac{1}{\left( r^2 + \left( \frac{d}{2} - z \right)^2 \right)^{3/2}} \right\}$$

**IN-PLANE:** Plot  $B_z$  vs  $(x, y)$  and do a contour plot in Matlab. Use the plane halfway between your Helmholtz coils. You do not need to do this for other coil spacings...just the Helmholtz coils. This plot shows the uniformity of the field (or lack thereof) as you get away from the central axis. It gives an idea of the practical usable space that has constant  $B$  in between the coils. This will contrast nicely with the talk from Option 1.

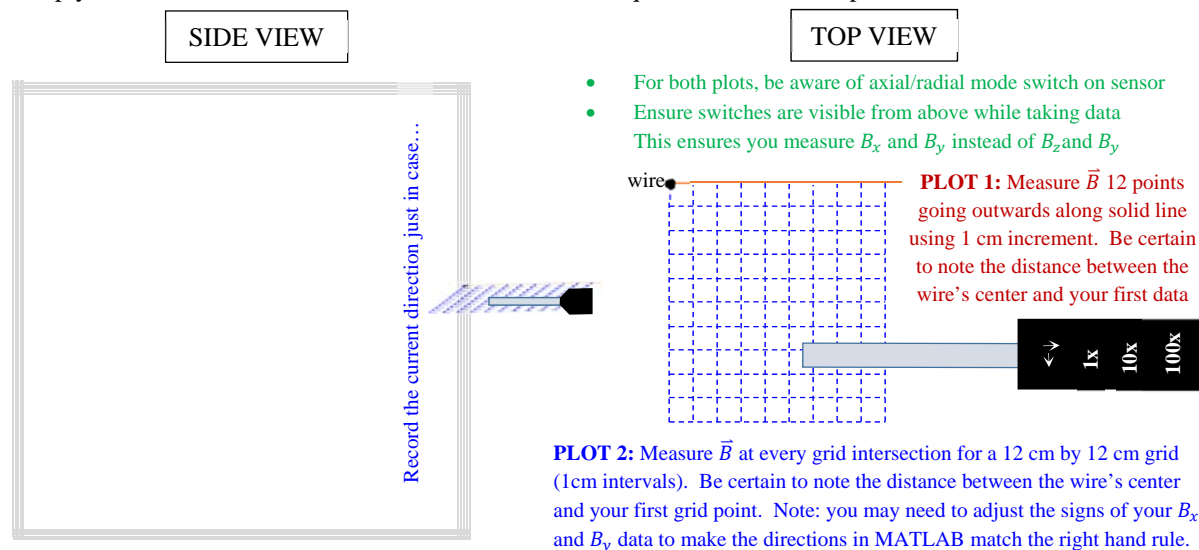
More on next page...

Note: be sure to look up Helmholtz coils. Only when the hoop-to-hoop spacing is  $R$  is this arrangement of two coils called Helmholtz coils. In your theory section, spend a little extra time explaining your theoretical equation for  $B$  vs  $z$ . Focus your energy on the Helmholtz equation case. Show the class  $\frac{dB}{dz}$  and  $\frac{d^2B}{dz^2}$  are both equal to zero midway between the two coils for Helmholtz coils. Also, think about why this might be a useful thing for an experiment. Or, consider teaching the class about a *Maxwell* Coil...you could build one if you are really crazy.

**As an easy variation**, you could instead reverse the current direction on one of the coils for  $d = R$ .

**This would make for a fun final question** to the audience to challenge their understanding. You could say “What should happen if I use spacing  $R$  but reverse the current in the left coil?” Then show a final type two graph for two coils with one current reversed.

**Option 5:** The magnetic field of a single straight wire is very small. To make the field larger, a single leg of a very large square coil can be considered as an infinite straight wire. This allows us to use the number of turns to safely multiply the current to a measureable level. Our massive square is about 1.0 m per side with 44 turns.



**PLOT 1:** Plot  $B$  vs  $r$  from the wire and compare to theory  $B = \frac{\mu_0 I}{2\pi r}$  (use radii of 1-12 cm in 1 cm increments). Read about Sample Graph Type 2 in the lab manual appendices.

**Watch out!** Remember your experimental current is  $44I_{DMM}$  because of the 44 turn multiplier previously discussed.

**PLOT 2:** Measure  $\vec{B}$  vs  $(x, y)$  for points on a 1-cm grid surrounding the wire. At each grid intersection, record both the axial and radial modes. These should be the values of  $B_x$  &  $B_y$ . determine the components of the magnetic field in the  $x$ - and  $y$ -directions (along the two axes of your grid). Use these components to determine the *magnitude* AND *direction* of the field at all points in space similar to what was done in the electric field mapping lab.

Create a graphic where the field at each location is drawn as an arrow to scale. Show an arrowhead indicating the field direction at each point. I think the best way to do this is to read the helpfile in Matlab on the “quiver” function.

Create a second plot with perfect theoretical values for comparison. One way to do this is to create a comma delimited file in Excel (called csv file). Another method might be to use the “meshgrid” function in Matlab. Better yet, use the technique described in Option 7. If another group is doing option 7, collaborate with them and farm out your theory work to them in exchange for giving them some experimental data.

Note: far from the wire the field components should be zero. Close to the wire the field components should be large. If you notice your mag field changing from positive to negative as you move away from the wire, it is probably not zeroed well. It is probably not your fault either.

Before taking data do the best you can to zero the sensor about 20-30 cm away from the wire, in the plane of the grid, in the orientation you expect to use with the grid. If you still end up recording both positive and negative values, determine the largest negative value for the  $x$ -component of the field. Add this amount to each  $B_x$ . Do a similar process for each  $B_y$ . By doing this all fields should be positive and the fields farthest from the wire should be zero.

**Is it reasonable to treat our system as an infinitely long wire?** Determine the theoretical magnitude and direction of the field produced by each of the big square wire's four segments at a point 10.0 cm from the midpoint of the right side of the square. Should any of the components cancel or no? Do the other three segments increase or decrease the theoretical magnetic field close to the wire? Also, compare the size of the field produced by the right 1.00 m segment to one produced by an infinite straight wire. What % error is introduced by treating the wire as infinite as opposed to only being 1.00 m long?

**Option 6: Transformer response versus frequency and core type (use new transformer equipment)**

One year I had some students build some air core transformers with turn ratios of 5:80, 10:80, 20:80, 40:80, 80:80. Note: there should be four wires sticking out of each tube; two for connecting to the first solenoid and two for the second solenoid. You will connect one of the solenoids to an AC power source (function generator) operating with the output cranked to max for a sine wave at 1.00 kHz.

I floated an oscilloscope to measure the max voltage across the primary coil while in operation. At the same time you can measure the max voltage on the secondary coil. Since the turns ratio is known, we can compare the voltage ratio to the turns ratio and use a percent difference to quantify any discrepancy.

The turns ratio ( $\frac{N_P}{N_S}$ ) is given the symbol  $\gamma = \frac{N_P}{N_S}$ . The transformer equation predicts

$$\frac{V_P}{V_S} = \gamma$$

Tip: Your instructor can show you how to use the measure button on our oscilloscopes to speed up data collection. Hopefully you can fill out the table below (or something comparable). Notice you will use most of the coils twice. Sometimes the smaller number of turns will be the primary (called a *step-up* transformer). Sometimes the larger number of turns will be the primary (*step-down* transformer).

$f$ (Hz)	$N_P$	$N_S$	$\gamma$	$V_P$ (V)	$V_S$ (V)	$V_P/V_S$	% diff $= \frac{V_P/V_S - \gamma}{\gamma} \times 100\%$	% err Discuss with instructor...
	5	80						
	10	80						
	...							
	80	80						
	80	40						
	...							
	80	5						

Finally, try repeating the experiment using an *iron* core. Repeat again using an *aluminum* core. Now repeat with all three cores variations at 10.0 kHz, 100 Hz, and 10.0 Hz.

Compress this data table down using a plot of voltage ratio versus turns ratio. Show the theory as a smooth line and the experimental data as dots only (no line). Make a second version of this plot using logarithmic horizontal axis.

Note: the voltage across the primary will probably not be exactly the same for each case...I'm not sure so measure it (and the secondary voltage) for every trial just in case...

Look at real transformers, get some pictures and discuss practical design features/issues. Maybe just talk about the different types of transformers that exist in the real world. Perhaps read a discussion online about air core vs soft iron core vs steel. Make sure you cite any web resources. If at all possible, narrow the scope of what you discuss and try and give the class 1-3 simple takeaways about real life transformers at the end of your talk as a way to tie your data set into the real world. I'm thinking out loud here. Figure out why aluminum decreases the effectiveness of the transformer.

Describe how one might convert AC voltage from a standard outlet to 9 VDC for charging a phone. Basically, explain how a transformer is used in conjunction with diodes and capacitors to create an AC to DC converter. A sub step is learning about rectification.

More next page...

The information below comes from my workbook. Perhaps it will give you some ideas of things to discuss.

**Transformers:** A transformer is a device consisting of two coils of wire in close proximity. Many transformers have an iron core. This essentially means you have two coils of wire wrapped on a chunk of iron. One coil can be thought of as the input. The input coil is called the primary. The output coil is called the secondary. If the magnetic field created by the primary changes an induced emf is created in the secondary. In this manner electricity is transferred from the primary to the secondary without an electrical contact!

The equation relating coil voltages (for a lossless transformer) is

$$\frac{\Delta V_2}{\Delta V_1} = \frac{N_2}{N_1} = \gamma$$

where  $\Delta V_1$  is primary voltage,  $\Delta V_2$  is secondary voltage,  $N_1$  is number of turns in the primary,  $N_2$  is number of turns in the secondary, and  $\gamma$  is called the “turns ratio”.

**Q1:** Why do transformers require an AC signal (think function generator or wall socket) connected to the input instead of a DC signal (think battery or DC power supply)?

**Q2:** A step-up transformer has a secondary voltage greater than the primary voltage. Which coil, primary or secondary has more turns? Is the turns ratio greater than or less than 1?

**Q3:** Based on the previous question, what is the logical name for a transformer with turns ratio less than 1?

**Q4:** Assume energy losses in a transformer are minimal. We know power relates to energy via  $\mathcal{P} = I\Delta V$ . Use this information to determine a relationship between the *currents* in the primary & secondary.

**Q5:** Explain why the use of transformers with AC power helps power companies reduce energy waste along transmission lines.

**Q6:** In real life, our air core transformers do not transfer all of the energy from the input source to the output source. Explain why?

**Challenge/Going Further:** We will soon learn that a coil of wire (or solenoid) has *inductance*. For an oscillating source signal operating at frequency  $f$  the impedance ( $Z$ ) of a circuit with resistance  $R$  and inductance  $L$  is given by

$$Z = \sqrt{R^2 + (2\pi fL)^2}$$

Impedance is measured in ohms.

For an AC source, this impedance can be used to determine the current in the circuit (similar to Ohm’s law) using

$$V_{max} = I_{max}Z$$

Here  $V_{max}$  is the amplitude (or maximum value) of voltage. Similar for  $I_{max}$ .

The power delivered to such a circuit is given by

$$\mathcal{P}_{avg} = I_{rms}^2 R$$

where  $I_{rms} = \frac{1}{\sqrt{2}} I_{max} \approx 0.7071 I_{max}$ .

Rearrange this formula to determine the average power in terms of  $V_{max}$ ,  $R$ ,  $f$ , and  $L$ .

Look online to find a formula determine for the inductance of an air core solenoid (probably tightly wound for all but the low turns solenoids).

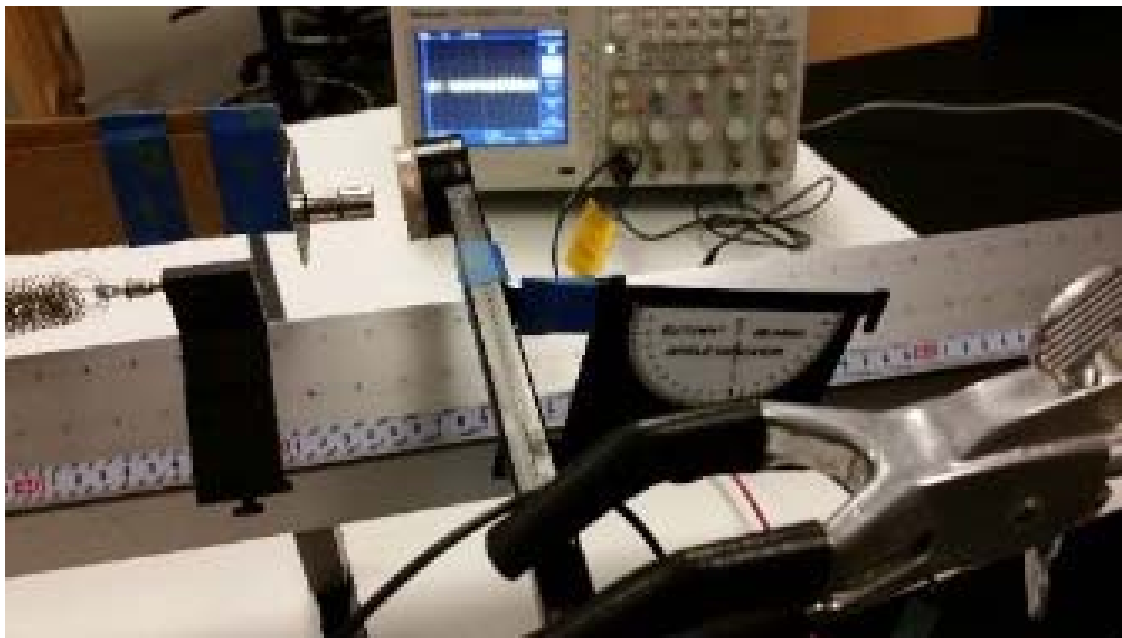
For each data point, use this rearranged formula to determine the power input to the solenoid.

For each data point, use the rearranged formula to determine the power output of the solenoid.

See if the ratio of power more closely matches the turns ratio.

**Option 7:** Attach a magnet to an oscillating glider. Allow the magnet to oscillate near a pick-up coil.

- 1) Plot pick up coil peak voltage versus angle comparing theory to experiment with a plot similar to Sample Graph Type II in lab manual appendix.
- 2) Create a theoretical model for the signal (voltage versus time) and compare theory to experiment with a plot similar to Sample Graph Type II in lab manual appendix.



First do the procedure outlined in the *numbered* bullets. Then do the math model described on the following four pages. Extremely confusing at first but, in my opinion, pretty amazing and cool.

1. Start with the coil area vector perpendicular to motion of the magnet (magnet goes towards edge of coil...not towards hole in the center). This orientation will be called 90 degrees. **The above picture shows 0 degrees...not 90 degrees.** Figure out the max distance you can stretch the glider on the air track without having the magnet smash into the edge of the coil.
2. Ensure the coil can rotate with its center always equidistant from the magnets closest approach.
3. Now set the coil to zero degrees. Oscillate the magnet. Record a video. From this video you can determine the period of the oscillation. Also record the amplitude of this oscillation. Use this same oscillation amplitude for all measurements.
4. **Using a Data Studio Voltage Sensor** the peak voltage in the pick up coil from the 1<sup>st</sup> oscillation. Call this peak voltage  $\mathcal{E}_{max}$ . Be sure to include the sign of the first peak.
5. Sweep the angle in 10 degree increments from 0 deg to 180 deg. For each angle, predict peak voltage (*relative* to peak voltage from 90 deg). We predict the measured voltage should be  $\pm\mathcal{E}_{max} \cos \theta$  depending on how the electrical cables are attached.
6. Record experimental peak voltage for each angle. For each measurement
  - a. Keep the center of the coil position unchanged.
  - b. Keep the oscillation identical.
  - c. Use the height of the first peak.
  - d. Be sure to include the sign of each measurement (first peak could be negative).
7. You should be able to plot peak voltage in the pick-up coil vs angle. You should have a theoretical and number and experimental number for each. In the lab manual appendices see Sample Graph type II for formatting tips.
8. Repeat experiment with a larger magnet, a longer period (add mass to glider), or a longer amplitude.
9. Measure the magnetic field strength versus distance in 1 cm increments for up to 15 cm from each magnet face. This data might be useful later.

Magnetic flux is  $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos \theta$ .

For a coil of wire, remember that  $\vec{A}$  points perpendicular to the plane of the coil.

Notice there is no flux when  $\vec{B}$  lies in the plane of the coil. Flux is maximum when  $\vec{B}$  is perpendicular to the coil.

A **changing** magnetic flux through a coil induces a voltage called induced emf ( $\mathcal{E}$ ).

The induced emf creates a current that opposes **the change** in flux. The equation is thus

$$\mathcal{E} = -\frac{d}{dt}(BA \cos \theta) = -\frac{d}{dt}(B\pi r^2 \cos \theta)$$

where, for a *circular* loop of wire,  $A = \pi r^2$ .

If you use a coil of wire instead of a single loop the equation becomes

$$\mathcal{E} = -\frac{d}{dt}(NB\pi r^2 \cos \theta)$$

where  $N$  is the number of turns. The coil of wire used to obtain the induced voltage is sometimes called a “pick-up” coil.

In our experiments today we will try various trials at various fixed angles. We will not be changing the angles *during* any given trial. The number of turns and radii of our coils will remain constant between all trials. Therefore, for our experiments today

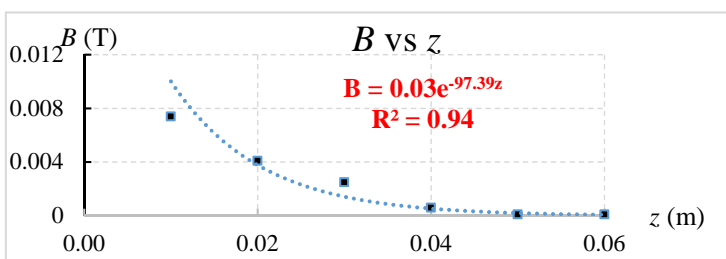
$$\mathcal{E} = -(N\pi r^2 \cos \theta) \frac{d}{dt} B$$

Using the chain rule, we can convert the time derivative to a spatial derivative

$$\begin{aligned} \mathcal{E} &= -(N\pi r^2 \cos \theta) \frac{dB}{dz} \frac{dz}{dt} \\ \mathcal{E} &= -(N\pi r^2 \cos \theta) \frac{dB}{dz} v \end{aligned}$$

In theory you should be able to plot  $B$  vs  $z$  for the permanent magnet using the mag field sensor. If possible, use small increments (perhaps 1 cm...perhaps 2 mm...no clue here). In this special case, do an exponential trendline. This trendline is an approximate function for  $B(z)$ . Note: to use an exponential curve fit in Excel, only use non-zero values of  $B$ . In my fake data below I assumed the sensor stopped giving non-zero values for  $z > 6$  cm.

$z$ (m)	$B$ (T)
0.01	0.0074
0.02	0.0041
0.03	0.0025
0.04	0.0006
0.05	0.0001
0.06	0.0001



$\frac{dB}{dz}$  is the derivative of your trendline.

my fake data case I find  $\frac{dB}{dz} = -2.92e^{-97.4z}$ .

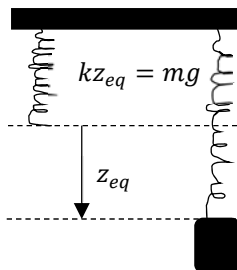
In



You should be able to estimate the size of  $v$  by either making a video and using Tracker or by using the equations discussed in the “oscillations crash course” discussed next.

To get  $v(z)$  the speed of the magnet at any distance  $z$  from the coil:

First get the spring constant of each spring. Simply hang a mass on it and let it come to equilibrium. See figure near right. We see  $k = \frac{mg}{z_{eq}}$ . A lot of our springs have  $k \approx 3 \frac{\text{N}}{\text{m}}$ .



When you place springs in parallel (by adding springs to *either* end of the glider) the effective spring constant is simply the sum of all springs.

$$k_{eff} = k_1 + k_2 + \dots$$

See figure far right showing springs in parallel. Expect  $k_{eff} \approx 6 \frac{\text{N}}{\text{m}}$

Oscillations terms:

$A$  = Amplitude = maximum distance from equilibrium in meters

$T$  = Period = time to complete one cycle in seconds

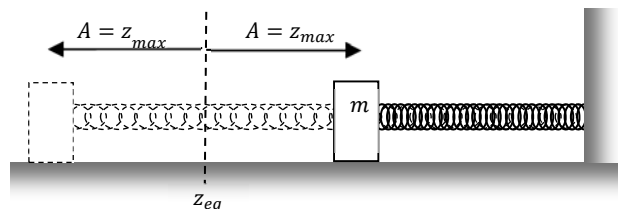
$f$  = Frequency = the # of cycles per second in Hertz

$\omega$  = Angular frequency =  $2\pi f$  in rad/sec

$$\omega = 2\pi f = \frac{2\pi}{T}$$

For a horizontal mass-spring system where the mass is released from rest on the right side of the figure the following equations are valid:

$z = A \cos(\omega t)$	$v = -\omega A \sin(\omega t)$	$\omega = \sqrt{\frac{k_{eff}}{m_{system}}}$
$z_i = A$	$v_{max} = -\omega A$	$v_i = 0$



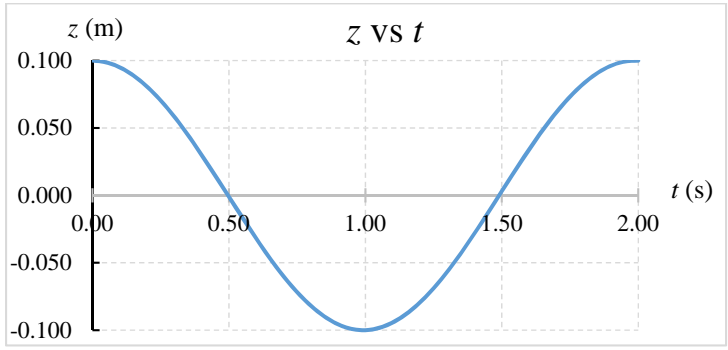
Strictly speaking,  $m_{system} = \frac{1}{3}m_{springs} + m_{glider}$ .

Fortunately for us, with our super light springs  $m_{springs} \ll m_{glider}$ . Therefore  $m_{system} \approx m_{glider}$ .

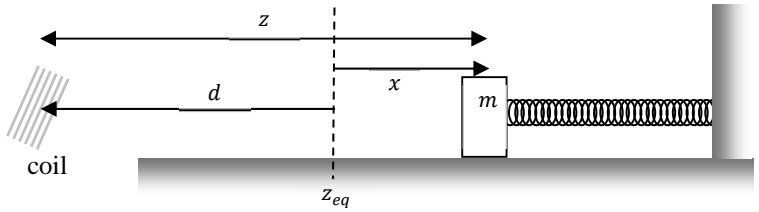
I made some plots on the next page showing what we might expect for an oscillation. Look at those now.

$k_{eff}$ (N/m)	$m_{system}$ (kg)	$\omega$ (rad/sec)	$A$ (m)	Period (s)
6	0.600	3.16	0.100	1.99

$t$ (s)	$z$ (m)	$v$ (m/s)
0.00	0.100	0.000
0.05	0.099	-0.050
...	...	...
2.00	0.100	-0.013



In our magnet and coil experiment, we want to know the velocity of the magnet when it is distance  $z$  from the coil...not distance  $x$  from the equilibrium position. If  $d$  is the distance from the equilibrium position to the center of the coil we want to use  $z = d + x$ . Notice: when  $x$  is negative (left of equilibrium), the calculation for  $z$  gives a number smaller than  $d$ .



We can now put this together with  $\frac{dB}{dz}$  and try to predict the shape of the electrical signal!

$$\mathcal{E} = -(N\pi r^2 \cos \theta) \frac{dB}{dz} v$$

$$\mathcal{E} = -(N\pi r^2 \cos \theta)(-2.92e^{-97.4z}) (-\omega A \sin(\omega t))$$

Note: at each value of  $z$  in the  $\frac{dB}{dz}$  equation, we can sub in

$$z = d + x = d + A \cos(\omega t)$$

This gives

$$\mathcal{E} = -(N\pi r^2 \cos \theta)(-2.92e^{-97.4(d+A \cos(\omega t))}) (-\omega A \sin(\omega t))$$

I will assume the following constants for my fake oscillation data.

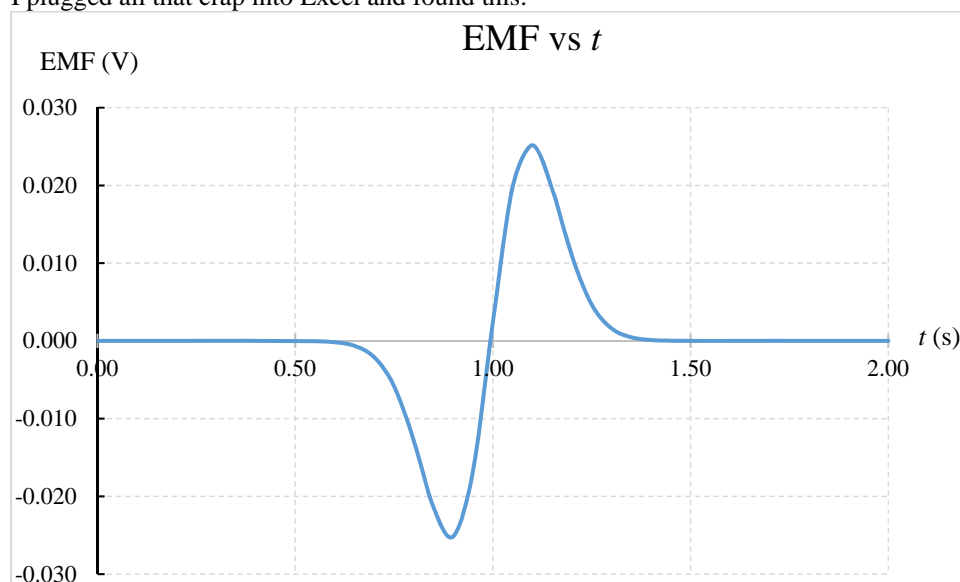
$k_{eff}$ (N/m)	$m_{system}$ (kg)	$\omega$ (rad/sec)	$A$ (m)	Period (s)
6	0.600	3.16	0.100	1.99

If we have an oscillation with amplitude  $A = 10 \text{ cm} = 0.10 \text{ m}$ , the distance  $d$  between the coil and the equilibrium position must be slightly *larger*. Let us assume  $d = 12 \text{ cm} = 0.12 \text{ m}$ .

For now I will assume  $N\pi r^2 \cos \theta = 1 \text{ m}^2$  for simplicity. In theory you could determine this number using measurements. I find

$$\mathcal{E} = -(2.92e^{-97.4(0.12+0.10 \cos(3.16t))}) (0.316 \sin(3.16t))$$

I plugged all that crap into Excel and found this:



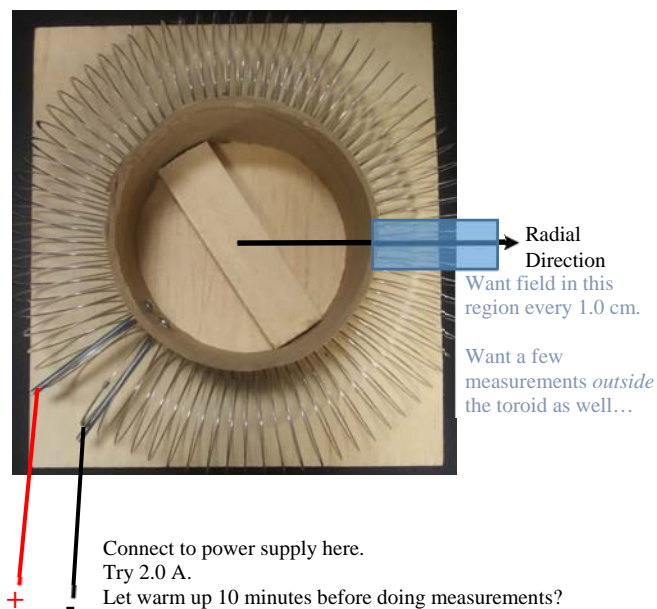
Ok...what is the point of all this? I thought, if you were really crazy, you could follow the same procedure I did and predict the size and shape of your electrical signal. Then you could export the data from the scope (or use a data studio voltage sensor) to get experimental voltage versus time data.

Ultimately, put the experimental curve from the scope on the same plot as your theoretical plot and see how close the dots are to the curve. I think this is a lot of work but might be a fun capstone project to your three semester physics sequence. I personally did it just because I thought it was possible and if we could actually predict the shape of this insane looking electrical signal!

### Option 8: Field inside a toroid

The goal of this talk is to measure and compare the magnetic field strength inside various toroids. You will want to compare the experimental data to theoretical predictions. I expect you to measure the field strength versus radial position for each of the following configurations of the slinky:

- Slinky around big cardboard tube (about 6" diameter)
- Slinky around paint buck (about 12" diameter)
- Slinky around big trash can bottom (about 18" diameter)
- Slinky around drum hoop (about 24" diameter)
- Slinky in straight line about 100" long ( $R = \infty$ )



The main data sets you want to obtain are simply measurements along a line running radially outwards from the center of the toroid. Before taking any measurements, get some current running and let the slinky reach a stable temperature (so the current doesn't drift on you during data collection). While letting the slinky warm up, read the derivation in a textbook. Think about the derivation and the direction of the mag field inside the toroid. You will need to use this knowledge (of the field direction) to ensure you have the field sensor in a reasonable orientation & setting to accurately record field strength versus radius data.

**For one toroid only** (say the smallest one), also obtain in-plane data for all points in a 1 cm grid within the toroid. Use this data in MATLAB to create a contour plot of the field strength. AGAIN, do NOT do this for every toroid...just one of them.

According to theory, toroidal field strength ( $B_{th}$ ) is given by

$$B_{th} = \frac{\mu_0 N I}{2\pi r}$$

where  $r$  is distance from the center of the circle,  $N$  is the number of turns in the slinky,  $I$  is current, and  $\mu_0$  is the standard constant. In your talk you'll probably want to show how this is derived using Ampere's law.

Final note, notice we expect the final case ( $R = \infty$ ) should actually use the solenoid formula ( $B_{th} = \mu_0 n I$ ).

WATCH OUT! Here  $n = \frac{N}{L}$  = # of turns *per unit length*. Notice the field strength should be constant at all points within the slinky! I threw this one in hoping we see the field strength of the other toroids gradually approaching this value. I guessed at a length I felt might make a pretty result...the actual constant value approached will obviously depending on how far you stretch the slinky.

**OPTIONS 9, 10, & 11: Python modelling****9 = Model  $\vec{B}$  created by triangle, square, circle, Helmholtz Coils, and straight wire in 3D****10 = Animate motion of charged particle in magnetic bottle****11 = Model mass spectrometer with mag field created by Helmholtz coils (not a hard coded, constant)**

For all groups, start by modelling the mag field at one point in space due to a long straight wire. Get the contribution from each segment of wire using

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \cdot \frac{d\vec{s} \times \hat{r}}{r^2} = \frac{\mu_0 I}{4\pi} \cdot \frac{d\vec{s} \times \vec{r}}{r^3}$$

Here  $d\vec{s}$  should be a small vector along the length of the wire directed in the same direction as current flow while  $\vec{r}$  is a vector from the source (from the line segment) to the point of interest (where you want to determine the field).

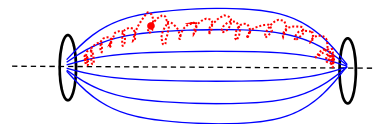
You can compare your result to a paper & pencil calculation using the Biot-Savart Law. Also, you can double check if the code matches the infinite straight wire calculation by using a very long segment and selecting a point of interest very close to the wire.

Once you can compute the field at one point in space, generalize the code to compute the field at all points on a 5 by 5 by 5 lattice near the wire. You'll probably need to think about a saturation level and scaling factor when drawing arrows representing the field at each point on the lattice. Also, you'll need some kind of if statement which prevents the code from computing  $\vec{B}$  whenever a lattice site falls on the wire itself.

All groups should then modify the code to create a circular loop of wire and determine the field on a 5 by 5 by 5 lattice near the loop. THINK: start a new code to avoid losing your previous work.

Once you have the straight wire and loop done, each group should move forwards in a different direction.

- Group 9 should get the specific parameters used by groups in the classroom and model the various fields. Once you are correctly modelling the field in 3D space, try to determine the minimum number of line segments you can use while still modelling the experimental data accurately (say within 1%). I expect you to export some of your code data to Excel and actually show a couple plots comparing your code to at least the triangle and square data (on axis data for sure, in-plane data contour plotted in MATLAB is nice as time permits). Talk with me once the codes are working and we can assess what you should do then.
- Group 10 will want to use two small coils spaced far apart with a tremendous current. Place a point charge between the coils. Tinker with the values until you notice the charge is trapped by the field for some significant non-zero amount of time. Animate the motion using the following steps:
  - Get current value of  $\vec{B}$  from both coils at the charge's position
  - Compute force using  $\vec{F} = q\vec{v} \times \vec{B}$
  - Use Euler-Cromer method from there (notice you will need to give the charge a mass)



Talk to me once you can animate the motion of a point charge near a single coil of wire. I have several ideas of how to check if your code is working from there.

- Group 11 will want to review the mass-spec problem in the workbook (28.6 I believe). You will need to animate the motion of a point charge through all three stages (initial accelerator, velocity selector, and the analyzer). For the electric fields, use parallel plates and  $E = \frac{\Delta V}{d}$ . For the magnetic fields, you are expected to model them as created by current in Helmholtz coils (not by hard coding in a constant value of  $\vec{B}$ ). In your talk, I am most interested in you verifying to the class how the velocity selector & analyzer stages work. In particular, emphasize how the motion of the particles is in the correct directions as predicted by the various right hand rules.