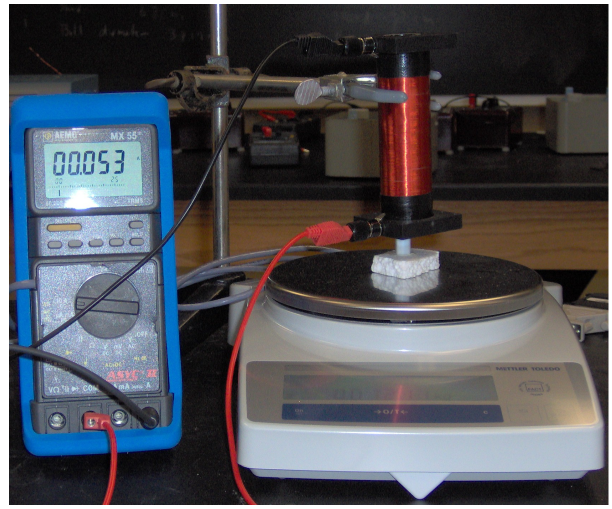
Ferromagnetic Levitation

Revised for 2015

Be sure to read the experimental note below!

In class, we will learn that the magnetic field near the center of a long tightly-wound solenoid is given by:

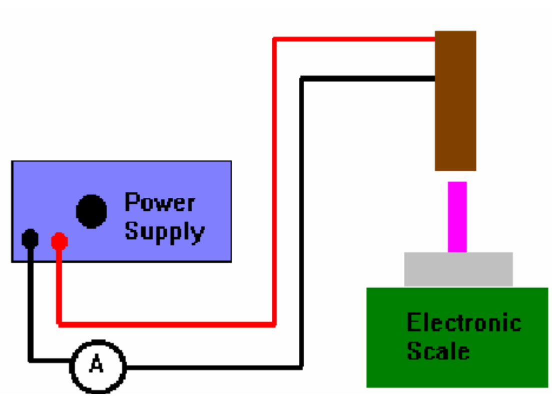
$$|\vec{B}| = \mu_0 n I$$



where n is the number of turns per unit length of the solenoid and I is the current through any one winding. We will also find out that near the ends of the solenoid, the magnetic field is about ½ of this value.

As a preliminary investigation today, I want you to determine the polarity of your solenoid coil with the compass that I have provided. You may need to remember how we determined the direction of the magnetic field in last week's lab. You should also observe what happens when you reverse the direction of the current in your coil to confirm that the polarity is reversed.

You are today going to use a solenoid coil in order to produce a magnetic field which will be used to probe different materials for magnetic properties.



You will vary the current through the coil, thus varying the magnetic field from the end of the coil. (Although you will record the fact that the magnetic field does indeed vary, this is, in fact, not the measurement that you will ultimately need).

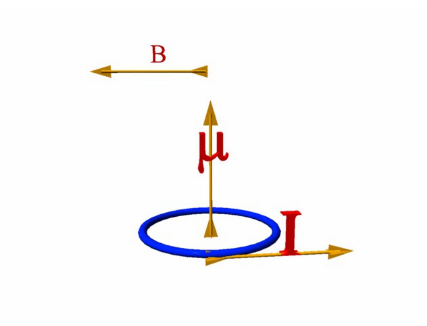
Thus, as far as getting the magnetic field that will be interacting with the object under test, you should have no problem. Be sure, however, that you are using the dc volts to supply the coil with current for this part of the lab. Your magnetic field is quite weak but it will be capable of providing enough magnetic field to show significant interaction with magnetic objects placed near the end of the coil.

Before we go further, we need to talk about how objects respond to external magnetic fields. If we are going to understand some depth to what is going to happen, we need to understand something about the origin of magnetism. Magnetism has its origin in unpaired spins on atomic orbitals. This is not the whole story … it turns out that only certain orbitals are magnetic since atoms are electrically neutral. We won't pursue this to quite this depth, however.

When we investigate the macroscopic phenomena of magnetism, we can regard the motion of the charged particles as being so small that they can be replaced by current loops. We define the magnetic moment of a current loop of area A which is surrounded by a current I as

$$\vec{\mu}=\mu_0 I\vec{A}$$

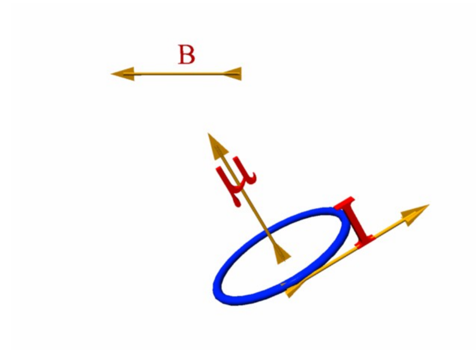
You need to make sure that you don't get confused by the symbols $\vec{\mu}$ and μ_0 : one is a magnetic moment while the other is a constant.



Now place this in an external magnetic field at right angles to the magnetic moment as shown. The torque on this current loop is at right angles to both the magnetic moment and the magnetic field:

$$\vec{\tau}=\vec{\mu}\,X\vec{B}.$$

This means that the torque in the image to the right is coming out of the screen. Now you will remember from last semester that the change in angular momentum is in the direction of the applied torque. You need to use the right hand rule for angular momentum to then see that the coil begins to flip in the direction shown to the right. All in all, this is a fairly complicated application of right hand rules. In fact, the motion gets just a bit more complicated because for a system of random magnetic moments, a "conical" orientation which is statistically in the direction of the magnetic field will occur and a precession about the direction of the magnetic field will be observed with correct techniques.



Here is another explanation of the same thing from a previous version of this lab. The torque exerted by a uniform external magnetic field on an individual current loop is then given by: $\vec{\tau}=\vec{\mu}\,X\vec{B}.$ The torque on the current loop is such that the current loop will tend to align with the external magnetic field. This can be seen as follows: consider the current loop in the x-y plane, carrying current from the +x axis towards the +y axis, and then on around the loop. Then, the magnetic moment of this current loop is given by: $\vec{\mu}=\mu I A\hat{z}$. Now, let us apply an external field in the +x direction. The torque on the current loop will be given by: $\vec{\tau}=\mu_0 I AB(\hat{z}\,X\,\hat{x})=\mu_0 IAB\,\hat{y}$. The effect of this torque will be to cause a change in the angular momentum of the current loop in the direction of the applied torque. In this case, this means that the coil will begin to rotate so that the change of angular momentum is in the +y direction. You need a right hand rule from last semester to see what this means. Curl your fingers around an axis so that your thumb points in the direction of the change of angular momentum. Your fingertips will be pointing in the direction that the velocity would need to change in order to produce this angular momentum. The coil then flips about the y-axis and the magnetic moment of the coil would want to align with the external magnetic field. I've made an animation that shows this rotation of the magnetic moment that you may want to look at.

Ultimately it is the alignment of many of these current loops into macroscopic domains and the eventual alignment of these domains that results in the large scale magnetic effects that you are familiar with.

Now in magnetic materials, you are really not going to be doing very much with an external magnetic field on the microscopic scale. The magnetic moments in ferromagnetic materials such as iron are pretty much already aligned and the internal fields are quite large that bind these spins into the same direction. Instead, a very interesting phenomena occurs in a material such as iron. Groups or regions within the iron "break off" from the direction that the rest of the spins have and form domains. The act of magnetizing a piece of iron basically comes from reorientation of these domains into one preferred direction. That is, in fact, then why you are able to magnetize a piece of iron even with a relatively weak magnetic field.

A permanent magnet will have its domains largely ordered and additional magnetic field application will not have a significant effect upon the material until the magnetic fields become quite enormous. Thus, you would expect not to see a magnetically induced magnetization from the application of a magnetic field to a permanent magnet. A demagnetized piece of iron, on the other hand, will be susceptible to domain reorientation which will show an increase in magnetization.

Now, since we know that opposite poles of a magnetic material attract each other, we can test these statements based upon measurements of the force that an electromagnet exerts on a material.

Experimental note: *Make sure your MX55 reads DC or AC for the proper experiment. You can switch by running the appropriate acquisition program and taking 1 data point. Throw away the results for this initialization. Also: make sure you permit the balance to settle before taking each data point!*

[I] A ferromagnetic material which is not magnetized. (using your nail)

Take the nail provided and place it on your scale. Insert the end of the nail into the end of the coil. You will want to lower the coil so that only about 1 cm of the nail is sticking out of the coil. The flat end of the nail should be resting on the electronic scales. Start your data acquisition program entitled "**DCLevi**". This will take the force and current reading when you press the space bar. You will want to tare your scale at zero applied solenoid current before your first data point is taken. Your MX55 should be monitoring DC Amps with plugs in {com} and {10 A}. You should also choose the 10 MΩ input impedance: review notes on how to do this on the lab site.
Now increase the current applied to your coil in very small increments (about 0.01 A) and record your data of current (in amps) vs. weight/g (in kg). Increase your current up to the point at which your nail is lifted up. If you observe a negative force, that means the nail is being lifted up. If the nail is being lifted up, the magnetization induced in the nail is in the same direction as the magnetic field inducing the magnetization. (We can have all types of things happening here … for ferromagnetic materials, it is the same direction). I guess you need to think about this statement a bit to convince yourself that it is correct. If your nail is lifted, write down the current at which it was lifted for future reference.

Lifting Current [A]:_______________

[II] Response to AC Magnetic Fields (using your nail)

Hopefully you will have lifted up your nail in the first part. This is always a thrilling part of this lab! Now reduce your current to zero and change your current leads from the DC leads to the AC ports. You will need to run the acquisition program "**ACLevi**" now. Take your first data point and discard that file. The program needs to set the MX55 into the AC mode for measurement. Now I want you to increase your AC current in **Very small increments** up to the point that audible vibrations start to occur (but less than 5 A) while recording data with your acquisition program. In fact, the nail may or may not lift in this part of the lab but for sure what will probably happen is that it will be demagnetized. You will observe that the weight becomes less. This may be interpreted as owing to the domains within the nail responding (although, perhaps not fully) to the rapidly changing magnetic field. There are additional reasons that the nail will respond to the changing magnetic field.

Reduce your current slowly down to zero (you won't need to take data now). This should insure that your nail is pretty much demagnetized with the additional benefit that you have taken some AC data. One note here: the ac current measured is RMS current, not quite the same as the peak to peak measured by DC operation. Your meter connections are {μA mA} with the knob set on the μA mA setting.

[III] Ferromagnetic Hysteresis (using your nail)

Note: be sure you understand how to do this properly so that a nice hysteresis plot will result. If in doubt, ask.

Return your leads to the DC outputs from the power supply and set the mx55 on the 10A scale. Also change the input to the mx55 to the A scale.. Start the program "**DCLevi**" and take 1 data point to throw away. This initializes the meter properly.

Your procedure now is to increase the current in small increments, taking data (the smaller, the better) but stop short of the point at which your nail levitated before ... perhaps 0.4 A below this point will be ok (call this I_{max}). Now decrease your current also in small increments (taking data). When you reach zero, reverse the red and black leads and continue downward till you reach the negative of your previous I_{max} (continuing to take data). Now increase your current back to zero (still taking data). You will make a plot of this data and observe the fact that the induced magnetization does not instantly remove once it is induced. From your data plot you should be able to explain in words the evidence that it shows for hysteresis. There are other ways to show this but our set up works pretty well with the one warning ... your data may not look like traditional ferromagnetic hysteresis curves ... the scale does not actually measure magnetization in zero field (hmm ... why? because our system requires a magnetic field to obtain a weight reduction or increase).

Your lab write-up should explain why hysteresis is evident in your data. You may want to magnify portions of the plot to show the detailed behavior and you may want to add plots of another color to clearly show important directions.

[IV] A permanent magnet (using your magnet)

Take the permanent magnet provided and repeat the same experiment as in part I. You should use the program "**DCLevi**" to acquire data. Be sure to tare your scale at zero current before your first data point is taken. Increase your current until the magnet is lifted or about 5 A DC is obtained. You may then (slowly) decrease your current (you won't need to take data on the way down). I also want you to confirm that reversing the current direction reverses the direction of the force in this case although you don't need to acquire data for this observation.

Check: reversing current reverses force direction: ____________

Analysis

On the spreadsheet helpers for this lab, I have provided you with the possibility to do two types of fits: linear and polynomial fits. In order to completely understand what is going on, you will want to run both solvers. Also make sure you delete my data. If you take more than 400 data pairs, you will need to modify the spreadsheet helper except for the hysteresis experiment (I had about 440 data pairs there and should have taken more. You'll also notice that my nail lifted up. You should avoid this in your work.)

Here is the idea: the magnetic field inside the solenoid is proportional to the current through the coil. If this magnetic field does not induce a magnetization in the body being lifted, the reduction in force on the scale will be proportional current to the first power only:

$$F \propto I^1 \Rightarrow F = L_0 + L_1 I^1 .$$

A fit to your data that shows this behavior will indicate that the object was only attracted to the external magnetic field but insignificant domain reorientation occurred. This is what you would expect for a hard magnet.

If the body being lifted experiences an induced magnetization which is roughly proportional to the impressed magnetic field then the reduction (and it will always be a reduction in the ferromagnetic materials case) in weight will be proportional to current squared:

$$F \propto I^2 \Rightarrow F = P_0 + P_1 I^2 .$$

In each case, if you did correctly tare your scales, the intercept should be almost zero.

What you will want to do is to run the solver for the two cases to see which provides a better description to the data. Not only will the graphical analysis make the correct interpretation clear, but you can also look for the fit with the smaller SQR(sdev(SD)).

In your write up to this experiment, include your graphs and an interpretation of the results. You'll want to phrase this explanation in your own words. And, I believe you will now be able to answer this question: suppose you had a material which had a proportionality between the force and current that behaved like:

$$F = C_0 + C_1 I^1 + C_2 I^{2.}$$

What would be a possible interpretation of the presence of C_1 and C_2?

Troubleshooting the solver

In this analysis, you will need to select your target cell and also your minimization cells. Make sure that you choose correctly. I've written the defined names beside them on the spreadsheet helper. Also, make sure you choose minimize since the solver, by default, maximizes things.