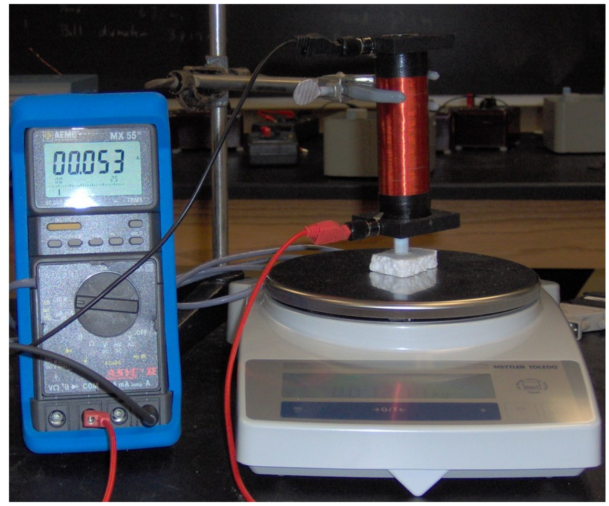
Ferromagnetic Levitation Pandemic Edition

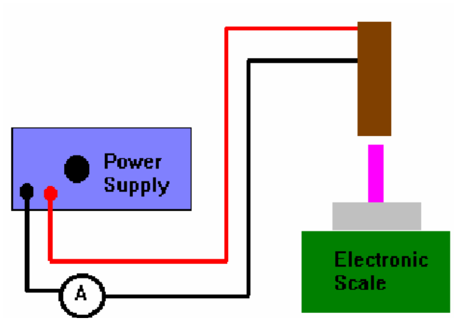
In class, we will learn that the magnetic field near the center of a long tightly-wound solenoid is given by:

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



where n is the number of turns per unit length of the solenoid and I is the current through any one winding.

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.

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.

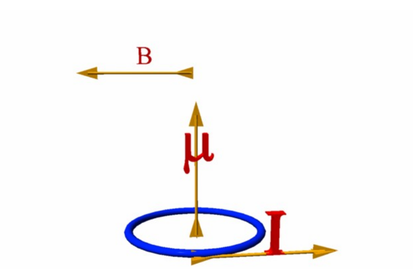
How objects respond to external magnetic fields

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 although strong enough magnetic fields can induce magnetic properties in just about anything.

We can regard the motion of the charged particles as being replaced by current loops. We define the magnetic moment of a current loop of area A which is surrounded by a current I as

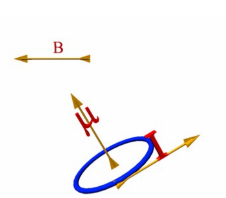
$$\vec{\mu} = I\vec{A}$$

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, the permeability of free space.



Imagine placing 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:

$$\vec{\tau} = \vec{\mu} \times \vec{B} \quad .$$



This means that the torque in the image to the right is coming out of the screen.

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. 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. The torque exerted by a uniform external magnetic field on an individual current loop is then given by: $\vec{\tau}=\vec{\mu}\times\vec{B}$. 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. The magnetic moment of this current loop is given by: $\vec{\mu}=IA\hat{z}$. Now, let us apply an external field in the +x direction. The torque on the current loop will be given by: $\vec{\tau}=IAB(\hat{z}\times\hat{x})=IAB\hat{y}$. 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. It is a statistical alignment rather than one large magnetic moment alignment.

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 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.

[I] A permanent magnet (using your magnet)

For each of the 4 investigations today, you will connect the ammeter to the μA connection and the scale will be the μA setting on the meter. The first 3 measurements are with the DC output from the power supply. The last measurement is with the AC output. You will read a small current even without the power supply on because the solenoid is acting as an antenna.

You will need to switch the meter off before moving on to the AC measurment, then hold pk+/- while switching the meter on and turn it then to the μA setting.

When you change the current, in each case, permit the scale to settle down before making a measurement. Also make sure you turn the current up enough between measurements so that the scale has a different reading each time.

Both acquisition programs run in very similar ways to other acquisition programs you have used in the lab, so an explanation here is not needed.

You will use a maximum current of about 0.5 A for the 3 DC measurements.

Take the permanent magnet provided and place it on the scale with a position close to the hole in the solenoid. The cap and the magnet must not touch the solenoid. Below you can see my position for this. You can look down through the solenoid to make sure the magnet is properly centered.

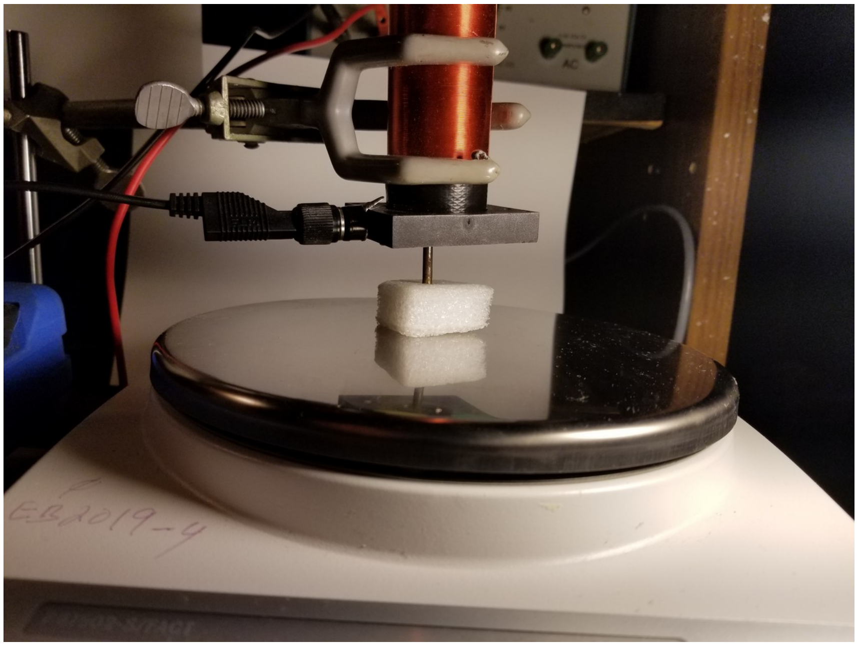
Now you need (before making measurements) to apply current and insure that a **positive current results in a negative scale reading.** It is best to tare the system at zero current before this. If you get a positive current with a positive scale reading, you will need to reverse the directions of the magnet in the cap.

The acquisition program for this part of the lab is DCLevi.

Be sure to tare your scale at zero current (with your power supply switched off). Increase your current to about 0.5 A collecting **10 data points**. You may then (slowly) decrease your current (you won't need to take data on the way down). **Put your data into the helper {DC Magnet Mag Lev} and fit first the linear plot and then fit the polynomial plot using the control bars. Provided your data was sucessfully taken, you may move on to the second part of today's lab.**

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

Take the nail provided insert it into the demagnitizer and demagnetize it by pressing the button. You should hold the nail while doing this (you will feel a tug on the nail). Then place it on your scale as I have indicated in the image below. The nail will partially insert into the solenoid. You should not need to raise or lower the coil since I have tried to position everything correctly for every part of the lab today.



With the power supply switched off, tare your scale.

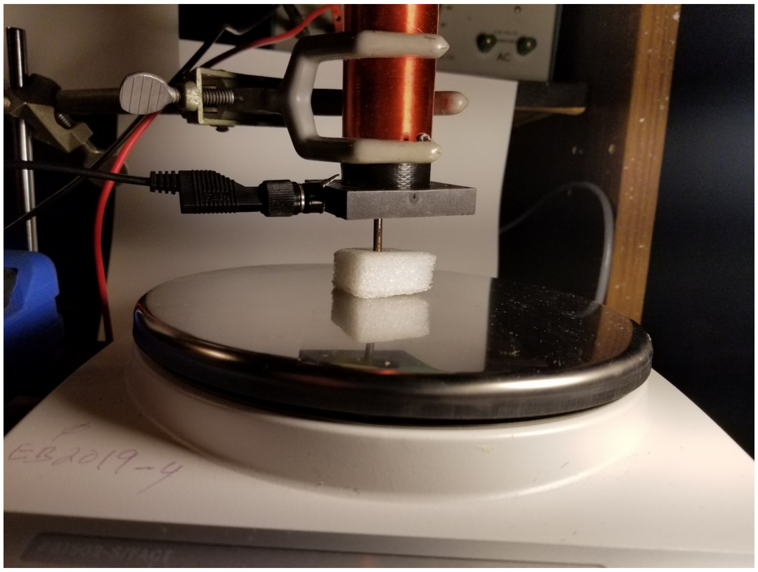
Start your data acquisition program entitled “**DCLevi**”.

Now increase the current applied to your coil in increments up to about 0.5 A collecting 10 data points. **Do not apply enough current to lift your nail.** If you do, you will have to redo this portion of the lab. Record your data of current (in amps) vs. weight/g (in kg). **Make sure the scale changes for each reading.**

After you collect your data, paste the data into the spreadsheet helper {DC Nail Mag Lev} and fit your data to both the linear fit and the polnomial fit using the control bars as in previous labs. If your data is not high quality, you will want to repeat this experiment.

[III] Ferromagnetic Hysteresis. (using your nail)

Take the nail provided insert it into the demagnitizer and demagnetize it by pressing the button. You should hold the nail while doing this (you will feel a tug on the nail). Then place it on your scale as I have indicated in the image below. The nail will partially insert into the solenoid. You should not need to raise or lower the coil since I have tried to position everything correctly for every part of the lab today.



With the power supply switched off, tare your scale.

Start your data acquisition program entitled "**DCLevi**".

Now increase the current applied to your coil in increments up to about 0.5 A collecting 10 data points. **Do not apply enough current to lift your nail.** If you do, you will have to redo this portion of the lab. Record your data of current (in amps) vs. weight/g (in kg). **Make sure the scale changes for each reading.**

For this portion of the lab, you will collect **more data concentrating on lower currents**. The steps are these:

Collect about 15 data points (20 is nicer) with more at your current to about 0.5A maximum.
Collect about 15 data points (20 is nicer) lowering your current back to 0A.
Switch the black and red leads on the power supply.
You will now have negative current readings on the ammeter.
Collect about 15 data points (20 is nicer) with more at your current to about 0.5A maximum.
Collect about 15 data points (20 is nicer) lowering your current back to 0A.
terminate the program and paste the data into the Nail

Paste your data into the helper {DC Nail Hysteresis}. There is no fit required here. What you are to notice, however from your plot is that the nail has a magnetic memory so that the raising and lowering curves to not fit over each other. Also you should observe the remnant magnetization. This is seen in the lowering current curves. The point at which zero force is observed is shifted. It is not easy to measure remnant magnetization at zero current so we measure at small currents.

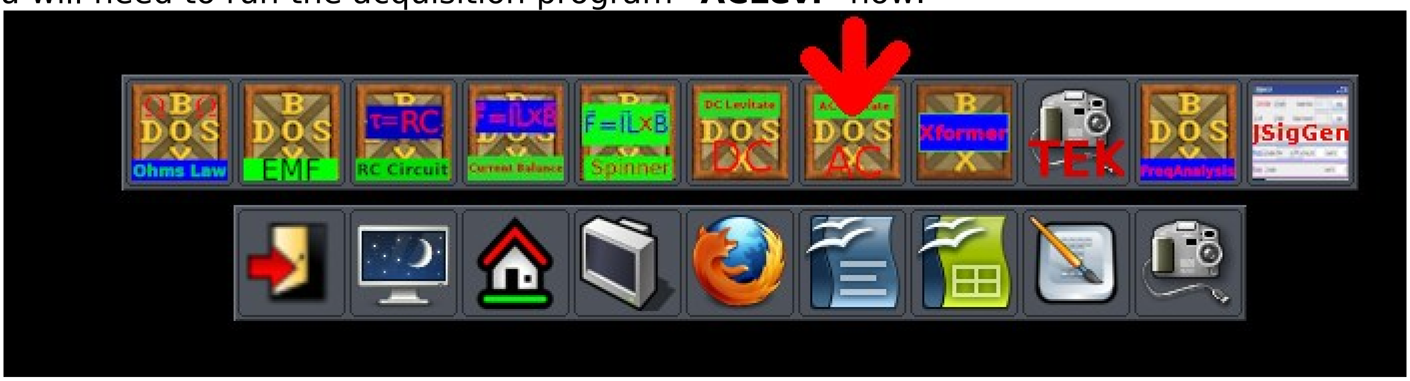
Before you move on to the ac portion of this lab, you should now confirm that you can lift the nail by turning on the DC current until the nail is lifted. This is always a thrilling part of this lab!

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

Reduce your current to zero and switch off the power supply. Switch the leads to the AC output from the power supply. It will not matter which lead is connected to which output, so long as it is the ac output. Switch the meter off. Hold PK+- which switching the meter back on and turn it to the μA setting.

Take the nail provided insert it into the demagnitizer and demagnetize it by pressing the button. You should hold the nail while doing this (you will feel a tug on the nail).

You will need to run the acquisition program "**ACLevi**" now.



Now I want you to increase your AC current up to about 0.175 A maximum collecting 10 data points. When you watched the movie, you noticed the resonance that happened and also the buzzing from the power supply. 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.

After you collect your data, paste the data into the spreadsheet helper {AC Nail Mag Lev} and fit your data to both the linear fit and the polnomial fit using the control bars as in previous labs. If your data is not high quality, you will want to repeat this experiment.

After you have completed the 4 sections, return your equipment to the original conditions.

Analysis

On three spreadsheet helpers for this lab, I have provided you with the possibility to do two types of fits: linear and polynomial fits.

Here is the partial explanation: 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:

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

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 (in weight will be proportional to current squared:

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

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)).

For the AC measurements, you would have a magnetic field proportional to the RMS current, however it is changing direction. The nail encounters this changing magentic field and by Lenz's law and Faraday's law, there will be currents induced in the nail so as to oppose the change in magnetic flux in the nail. This will produce then a magnetic moment in the nail that will be attracted into the solenoid. In this case, you should see that the polynomial fit provides a better fit because of the fact that the magnetic moment is being induced by the solenoid.

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:

$$F = C_0 + C_1 I^1 + C_2 I^2 \quad .$$

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

Summary of the lab

[I] A permanent magnet (using your magnet)
[II] A ferromagnetic material which is not magnetized. (using your nail)
[III] Ferromagnetic Hysteresis. (using your nail)
[IV] Response to AC Magnetic Fields (using your nail)

Fit your data for [1],[2] and [4]. Observe in each of these three cases which provides the best description for your data. Do note that the same number of parameters are used for each fit and the same error criteria is used for each fit so the errors can be directly compared here. Also note that the linear fit used here is not a linear least squares fit.

Observe that the nail can be lifted. It is probably best to do this when you start using the nail to observe the maximum current that should be applied. Demagnetize the nail after doing this.

Possible hypothesis for your writeup

A weak external magnetic field does not induce a magnetic moment in a hard magnet.

A weak external magnetic field does induce a magnetic moment in a ferromagnetic material.

Hysteresis and remnant magnetization can be observed by inspecting force vs current measurements.

Faraday’s law and Lentz’s law provide the mechanism to observe induced currents in a conductor.