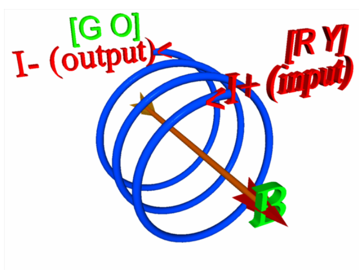
Lab 7: Spring 2007

Experiment I: Solenoids

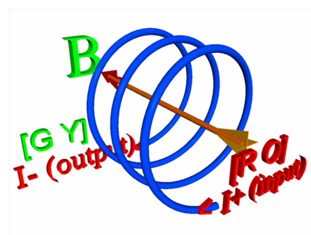
In order to understand how a transformer works, it is useful to understand some subtle details about solenoids. In class, I showed you how to calculate the magnetic field from a solenoid near its center:

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

Now the direction of a magnetic field comes from application of the right hand rule, which you all are by now familiar with. However, there is some subtleness regarding the direction of the magnetic field inside a solenoid. In particular, Nature remarkably cares about whether the wires on a solenoid are turned in a right-hand fashion (so that a normal screw could screw into to windings) as opposed to a left-hand fashion. Note: a good test for the winding direction is to ask this: will a right handed screw (the normal type encountered) advance by a clockwise twist of my right hand? If the answer to this is yes, then the threads are right-handed. This problem is intrinsically a 3-dimensional problem so we need to look at application in detail here. I've reproduced two solenoids below for you to look at and agree with for right-hand rule field direction.



A Left-handed Solenoid (negative polarity)



A Right-handed Solenoid (positive polarity)

$$\text{Positive: Right Handed : [RO]} \Leftrightarrow \text{[GY]}$$

$$\text{Negative: Left Handed : [RY]} \Leftrightarrow \text{[GO]}$$

As you can see from this simple application of the right hand rule to each of these two situations, the direction of the magnetic field depends upon the direction of winding in the solenoid. This means that, in fact, there are two types of solenoids possible. I'll refer to this as the "polarity" of the solenoid, although this term can be confusing ...if is the magnetic polarity that I am talking about, not the electrical polarity. You'll notice in each of the two pictures above, if you grab the solenoid with your right hand and let your fingers curl in the direction of the current then the magnetic field points in the direction of your thumb. We could probably develop a total new right hand rule just for solenoids but this is not really the thing we want to do: you don't want to develop a new right hand rule for every electrical element you run into.

One thing that you will notice, however, is that the direction of coil winding on the solenoid is directly determined by the polarity of the solenoid. Here is a test for the direction of coil winding: apply a current to one end of the solenoid. If the magnetic field points out of the end that the current is injected into, then I'll call this a negative polarity solenoid. On the other hand, if the magnetic field pointed into the current injected end of the solenoid, then I'll call this a negative polarity solenoid. Basically in a right-handed world, a positive polarity solenoid is wound in the right-handed direction while a negative polarity solenoid is wound the left-handed direction.

For your first experiment today, I want you to be able to identify the polarity of the two very open coils I've made up for you. You do this by injecting a current (about 2 A DC) into the end with a red dot and removing it on the end with a green dot. You can use your compass to then determine the direction of the magnetic field inside the solenoid: I've tried to put orange and yellow markers on the solenoids so that the magnetic field goes in the direction from orange to yellow. You'll want to confirm this and make sure you understand how to use the right-hand rule here.

Confirmations: negative solenoid: _____________ Positive solenoid:______________

While we're at it, you need to determine the north pole of your magnet. To do this, you need to hold the compass near one end. If the north end of the compass points towards the magnet, then this is the south end of the magnet. On the other hand if the south end of the compass points towards the magnet, then this is the north end of the magnet. I want you to take the marker and mark the north end of your magnet after you are 100% sure you know which is the north end and which is the south end.

Confirmation: I know how to identify the north end of a magnet: ____________

Now that you have confirmed the polarity of some solenoids that you can clearly see the direction of the winding in, I want you to next confirm the polarity of your solenoids that I have provided you with. I also have three solenoids wound in the opposite direction for comparison. You should be able to confirm that the same color coding which was used to represent magnetic field directions is also properly applied to the solenoids I've provided you with. From this, you can determine the polarity of your solenoid.

{These questions are referring to the new solenoids, not the older ones}

Confirmation: I know what the polarity of my solenoid is: ___________________

Confirmation: The threads are wound in a ___________ handed direction.

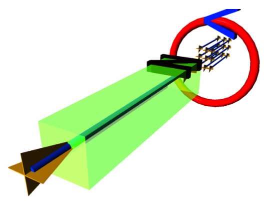
Lenz's Law

Important!!!

You need to be very careful to correctly record your scan file names here and knowing exactly the case and subcase you are observing.

Consider application of Lenz's law to a specific planar current loop: for right now I want to remove the complications from the winding direction. We are going to do a thought experiment. Imagine bringing the north end of the magnet towards the center of the current loop. My paraphrase of Lenz's law says that the circuit will do what ever it can to keep the magnetic flux in its interior from changing.

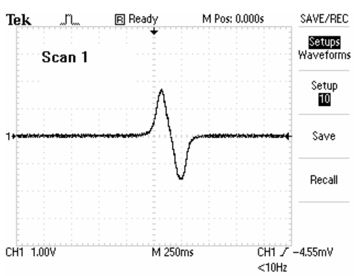
We'll only experiment with the newer solenoids here in the interests of time and clarity. The older solenoids are, in fact, left handed solenoids.



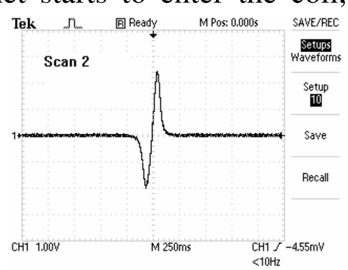
The **north pole** of a magnet is moving **towards** a **planar loop** as shown by the direction of the (big) arrow inside the magnet. In order for the circuit to oppose the magnetic flux change (which is increasing), the current needs to flow in the counter-clockwise direction as indicated. Now let's suppose that the circuit is not a planar loop: instead it is a solenoid. Let's look at each of the two situations to determine the direction of current flow. Our primary guide here is the magnetic field that comes from the current needs to point in the opposite direction of the magnetic field from the north pole of the magnet.

You will find it helpful to hold the "wax encased" solenoid while you study the following.

Let the north end of a magnet come towards the yellow end of the right handed coil. Current must flow from red to green in order to produce a magnetic field in the direction from orange to yellow inside the solenoid. This is the direction that is required to produce a magnetic field that will oppose the change in magnetic flux. Were it not for the negative sign in Faraday's law, this can be verified by connecting the probe of the oscilloscope to red while connecting the ground clip to green. However, the negative sign forces us to connect probe to green while ground goes to red in order to achieve correct polarity.



When the north pole of a magnet starts to enter the coil, green would initially go positive. A scan of the situation described is shown in scan 1. The situation will be exactly reversed if you bring the south end of the magnet towards the yellow end of the coil. A scan of this situation will look like that shown in scan 2.



Now if you reverse the situation: bringing the north pole of the magnet towards the orange end of the solenoid, with the probe connected to red while the ground clip is connected to green, the situation will again look like scan 1. Reversing the direction of the magnet will make the situation look more like scan 2.
You should verify each of these 4 situations

(1) North comes towards Yellow: Scan 1: [Probe at Green]:________
(2) South comes towards Yellow: Scan 2: [Probe at Green]:________
(3) North comes towards Orange: Scan 1: [Probe at Red]:__________
(4) South comes towards Orange: Scan 2: [Probe at Red]:__________

For practice, you'll probably want to try making a screen capture of the oscilloscope.

Faraday's law part I:

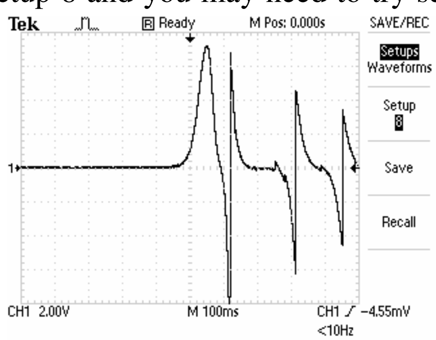
Fortunately, however, it's a bit easier to verify parts of Faraday's law than it is Lenz's law. In class we learn:

$$\text{Non-Calculus: } emf = -\frac{\Delta\Phi_M}{\Delta t} \qquad \text{Calculus: } emf = -\frac{d\Phi_M}{dt}$$

Now we can pretty easily verify that, regardless of polarity, the quicker you insert the magnet into the coil (regardless of polarity), the larger the induced emf will be. I would suggest that you only observe this for two separate scans: for scan (1), move your magnet in slowly and for scan (2), move your magnet in more quickly. You will want to not go in so quickly that scan 2 is not fully displayed and you do not want to go so slowly that the oscilloscope does not trigger.

Faraday's law part II:

Orient the solenoid so that the "red" end is on the table (and connected to the positive oscilloscope probe). The "green" end is upward and connected to the oscilloscope ground. Hold your magnet over the hole in the coil and drop it. You may need to select setup 8 and you may need to try several times to get a nice scan. When you obtain your own nice scan, what I want you to do is to explain it in words. You may find it useful to color in portions of your image using paintbrush to enhance your discussion. I hope you get an appreciation for some of the possible measurements you can make with solenoids, magnets and oscilloscopes. Be sure to note which magnetic pole which enters the solenoid first.



Faraday's law part III:

We are actually going to do now a firm calculation involving Faraday's law, drawn from measurements of a bouncing magnet in a solenoid.

You may recall last semester that the angular frequency of a spring-mass system was given by:

$$\omega = \sqrt{\frac{k}{m}} \Rightarrow f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}; \omega = 2\pi f$$

where k is the spring constant and m is the mass attached to the spring. The actual measurement of f is accomplished by the oscilloscope and has units of Hz. We investigated the spring-mass system in lab 08: Simple Harmonic Oscillation.

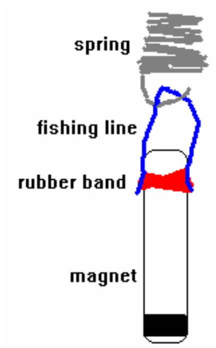
Today, however, we are not going to investigate this as much as we are going to use the frequency generated by a spring-mass system to bounce a magnet over a solenoid coil. However, I need to remind you of the equation of motion for the spring –mass system is:

$$\text{position: } y(t) = A\sin(\omega t + \varphi)$$

$$\text{velocity: } v(t) = \omega A\cos(\omega t + \varphi) = v_{max}\cos(\omega t + \varphi)$$

In fact, in our case, the emf produced by an oscillating magnet over the solenoid coil is given by:

$$|emf| = \begin{matrix}\text{non-calculus} \\ \text{calculus}\end{matrix} = \begin{matrix}\left|\frac{\Delta\Phi_M}{\Delta t}\right| \\ \left|\frac{d\Phi_M}{dt}\right|\end{matrix} = (\text{area}_{\text{solenoid}}) N_{\text{eff}} B_{\text{eff}} \begin{matrix}\left|\frac{\Delta y}{\Delta t}\right| \\ \left|\frac{dy}{dt}\right|\end{matrix} = [\text{constant}]\cos(\omega t + \varphi)$$



The constant is not something that is going to be easily measured for our purposes, but the time dependence will be. At the end, we will can investigate the loss of energy from this system due to resistance in the solenoid if you like.

Here is the procedure: with a rubber band and a short piece of fishing line, fashion a hanger holding onto the south pole of your magnet. Place the "red" end of your negative polarity solenoid on the table. Adjust the hanger so that the spring is only slightly stretched when the magnet is in the "green" end of the solenoid. release it and if you were careful, the oscilloscope ought to be able to record the oscillations of the system. I have tried to use setup 9 for the acquisition of this data. In this case, you'll probably want to make a screen capture of the resultant oscillations but you will most certainly want to run the program "TeK for Faraday's Law" choosing drive I as the destination for the data file. I think good advice is to run the screen capture first and then run the TeK wave form program. This program will take the digitized waveform output (all 2500 points) and put it into a .csv file on your I drive for later analysis. I have not had too many problems with getting the program to operate properly however do be aware that it will take a bit of time to transfer all this data. After you acquire your data, use the solver to modify the frequency, phase and amplitude. You will want to guess the frequency measured by your TeK here so you ought to note the TeK frequency.

You will notice that although the fit is quite good, it definitely misses at the peaks. I believe I can give several reasons for the departure from a pure sin behavior. First, the magnet wiggles from side to side just a little. This induces an emf also (although it is small) and it supplies and removes energy from the y-motion direction. However, another reason that the departure occurs is probably even closer to reality: it has to do with resistance of the coil. According to the literature associated with the coil, the resistance of the coil is given by: $R = 76 \pm 2\Omega$. This means that at any instant in time, the power removed from the spring – mass system is given by: $P = \frac{V^2}{R}$. This means, for our purposes, at any instant in time, we have: $P = \frac{[\text{constant}]^2}{R}\cos^2(\omega t + \varphi)$. The average power loss over one complete cycle is then:

$$\langle P \rangle = \frac{1}{2}\frac{[\text{constant}]^2}{R}$$

We'll talk more about average power losses in AC circuits soon in class. I do have a demonstration of this effect that is quite impressive. Remind me to show this to you in lab. For now, however, although this is a significant loss, I don't believe it is the most significant element leading to a departure from a pure sinusoidal behavior. I think the most significant factor is that as the magnet goes deeper into the solenoid, more and more coils become effective in the flux calculation. It would be possible to estimate this by knowing how deeply the magnet is penetrating into the solenoid however we won't pursue this effect here. One final effect, of course, is that the spring itself is heating up and radiating energy through mechanical means.

Motor demonstration

You now know very much about Faraday's law, solenoids and Lenz's law. You will see one additional interaction: when a current is directed through a coil, the coil acquires a magnetic moment (you know this from the first part of the lab). This magnetic moment will interact with an external magnetic field almost exactly like a magnet interacts. The current loop will experience a torque and respond accordingly. I have made a very primitive DC motor which I'll show you as a demonstration. These motors are very easy to make. However, since a magnetic flux is also changing through the motor coil, the motor will send a reverse emf though the circuit by Faraday's law.

Transformers

Now you are ready to understand how transformers work which is the last part of this lab. I will need to switch the RS232 connections before you can do this portion of the lab. When you are ready, get me to do this for you.

Magnetic Field inside a Solenoid

The magnetic field inside a solenoid is a quantity that we calculate in class, and it is as important to magnetostatics as the parallel plate capacitor was to electrostatics. For an ideal solenoid of length L, consisting of N turns and thus having a turn density given by $n = \frac{N}{L}$, the magnitude of the magnetic field near the center of the solenoid is given by:

$$B = \mu_0 n I$$

while at the ends of the solenoid the magnetic field reduces to ½ of this value

Let's assume an ideal and very long solenoid with N turns and ignore the end effects. We also shall now let the cross sectional area of the interior of the solenoid be A. The magnetic flux through the solenoid when the solenoid carries a current I will be given, in magnitude, by:

$$\Phi_M = N[BA] = N[\mu_0 n I A] = \mu_0 n^2 I[LA] = \mu_0 n^2 I[\text{Volume}]$$

where the volume is that of the interior of the solenoid. The inductance provides us with a measure of how much magnetic flux a circuit element can contain for a given amount of current. It is defined as $L = \frac{\Phi_B}{I}$. It is not a steady magnetic flux that will produce an induced emf in a circuit: rather it is a changing magnetic flux that results in an induced emf. Let us assume that the current applied to the solenoid has a time dependence given by: $I = I_{max}\sin(\omega t)$. The various needed quantities that we need and their time rates of change are given by:

quantity	symbol	Time dependence	Rate of change
Inductance	L	Defined: $L \equiv \frac{\Phi_B}{I}$	Not needed today
current	I	$I = I_{max}\sin(\omega t)$	$\left\{\begin{matrix} \text{Cal}: \frac{dI}{dt} \\ \text{Non}-\text{Cal}: \frac{\Delta I}{\Delta t} \end{matrix}\right\} = \omega I_{max}\cos(\omega t)$
Magnetic flux	Φ_M	$\Phi_B = \mu_0 n^2 [\text{Volume}] \equiv LI$	$\left\{\begin{matrix} \text{Cal}: \frac{d\Phi_B}{dt} \\ \text{Non}-\text{Cal}: \frac{\Delta\Phi_B}{\Delta t} \end{matrix}\right\} = L\omega I_{max}\cos(\omega t)$
Emf developed	$\mathcal{E}$	$\mathcal{E}_L = -\omega L I_{max}\cos(\omega t)$	Not needed today

An emf develops across an inductor when the current input to an inductor **changes**. The relation between the emf and the current are shown above. If we assume now that two solenoids are perfectly coupled so that all the magnetic flux from the first solenoid penetrates also the second solenoid , then we have that the emf developed will be given by Faraday's law (note below Φ_M is the flux through only 1 of the total of N turns):

Input or primary side:	$\mathcal{E}_P = -N_P\left\{\begin{matrix} \text{Cal}: \frac{d\Phi_M}{dt} \\ \text{Non}-\text{Cal}: \frac{\Delta\Phi_M}{\Delta t} \end{matrix}\right\}$
Output or secondary side:	$\mathcal{E}_S = -N_S\left\{\begin{matrix} \text{Cal}: \frac{d\Phi_M}{dt} \\ \text{Non}-\text{Cal}: \frac{\Delta\Phi_M}{\Delta t} \end{matrix}\right\}$

Let us now take the ratio of the two to obtain the transformer equation:

$$\frac{\mathcal{E}_P}{\mathcal{E}_S} = \frac{N_P}{N_S}.$$

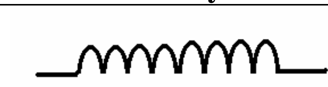
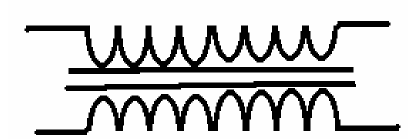
The appearance of such a very simple result is completely deceptive! Among the other things that you need to remember here is that **if the magnetic flux is not changing, then you will not get an induced emf.** This fact allows transformers to also be used to remove a dc offset from an ac signal. Also notice that in terms of power, if the transformer is ideal so that power input is equal to power output, then we can use this to determine how transformers convert current: $\frac{I_s}{I_P} = \frac{N_P}{N_S}$. We won't use this second result today, however.

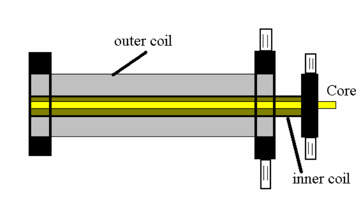
The particular coils used with today's lab have the following electrical properties:

Outer coil: 2920 turns, #29 wire,
inductance 63 ± 2 μH, resistance: 76 ± 2 Ω, capacitance:124 ± 2 pF
Dimensions: 11 cm coil length x 3.5 cm coil outside diameter

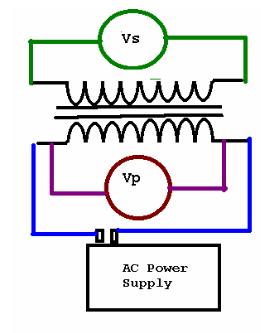
Inner coil: 235 turns #18 wire
inductance 78 ± 22 μH, resistance: 0.4 ± 0.1 Ω, capacitance:142 ± 2 pF
Dimensions: 12 cm coil length x 1.7 cm coil outside diameter

We will call the "primary" side of our transformer (solenoid) the side which is connected to the power supply. The "secondary" side will then be the other solenoid. In each of the four experiments below, the circuit diagram will be the same.

Element	Electrical Symbol
Inductor	
Transformer (no center tap)	



Sometimes you will see a center connection (called the center tap). Our circuit for today's lab is thus quite simple. Also note that the black switch on the power supply should be set to "off".



Experiment T1: Transformers don't transform dc voltage.

Connect your **dc** power supply to the terminals of the outer coil. Place one of your voltmeters (the mx55) on the DC V scale and connect across the outer coil (here, the primary) leads. Place the other of your voltmeters on the DC V scale and connect across the inner coil leads. Insert the core into the system. Vary your dc voltage from 0 to 5 volts, taking readings of the two voltmeters every ½ volt or so. You will use the acquisition program DC xformer to acquire data for this part of the experiment. My spreadsheet will work better here if Vs is on port 2 and Vp is on port 1, otherwise you'll need to copy and paste individual columns. You can check which is on which by running a few data points with one of the voltmeters disconnected and then restarting the acquisition program.

The results of this can be placed into the spreadsheet page "DC-Xformer" in your helper. Plot a graph of the results with V_{outer} on the x-axis and V_{inner} on the y-axis. Run the solver to determine the slope and intercept of the curve. A slope which is close to zero indicates that there is no variation in V_{inner} you can conclude from this that there is no induced emf in the secondary coil. **Explain why this is the case in your write up.** Do not leave your voltage at 5 volts: after the readings are complete, reduce the applied voltage to zero (**But reduce it SLOWLY**!!! ... look at Faraday's law to know why... lots of voltmeters get destroyed this way.)

Experiment 2: A step-down transformer.

{You should not have your solid iron core inside the innermost coil here}

Connect your ac power supply to the terminals of the outer coil. Place one of your voltmeters V ACscale and read applied voltage across the outer coil [Vp]. Place the other of your voltmeters on the V AC scale and read output voltage across the inner coil [Vs]. Place your core entirely inside the two coils. Now, vary your applied ac voltage from 0 – 5 volts, taking readings every 0.5 volts [Vp]. Again, it is best if you keep Vp on port 1 for my spreadsheet to work easier.

Plot a graph of the results with V_p on the x-axis and V_s on the y-axis. Fit your data with a linear fit in order to find the slope. You will notice that the slope is not exactly in agreement with what would come from the transformer equation. Probably the largest reason this is the case is because about ½ of the flux from the primary coil is lost. Assuming that flux loss is the largest source of the discrepancy, you are able to calculate this flux loss on your spread sheet.

Experiment 3: The effect of the core.

Connect your system as in experiment 2. Now, however, remove the iron core. Next, vary your ac voltage from 0 – 5 volts taking reading every 0.5 volts. You may need a smaller scale on the output (secondary) voltage in order to make inner core readings. I recommend something like the 200 mV AC scale, but not lower here. Plot a graph of the results with V_{outer} on the x-axis and V_{inner} on the y-axis. Compare the slope of this graph to your previous result. What can you conclude about the importance of the iron core? As you know, iron tends to concentrate magnetic flux inside the iron. With out the iron, the flux coupling is very small. Note: you may feel a tugging on the iron core if it is inserted while ac voltage is applied. This is due to Lenz's law (which is ultimately the negative sign in Faraday's law) which says an induced emf produces a flux which opposes the flux that produced that emf. Lots of mechanical devices use this fact in their design.

Experiment 4: A step up transformer.

Replace your iron core inside your system. Connect your ac power supply to the terminals of the inner coil. Place one of your voltmeters (the Unit) on the 200 V AC scale to read applied voltage. Place the other voltmeter across the terminals of your outer coil. Now, vary your applied voltage from 0 to 5 volts. Do not leave your voltage at 5 volts very long since this will trip the circuit breaker in your power supply. Take readings every 0.5 volts. Plot a graph of the results with V_{outer} on the x-axis and V_{inner} on the y-axis. Fit your data with a linear fit in order to find the slope. Compare the slope to the ideal value which is the ratio of turns in the two transformers (but, you must be careful about which ratio form to use!). You will notice that in this case very little flux is lost. By looking at the geometry of your system, you should be able to explain this.

Write-up

Your write-up should include all circuit diagrams, and discussion of each of the experiments together with the graphs from each part in addition to the normal parts of any other lab write-up. I encourage you to complete this write-up at the end of lab today