

# Solenoids, Faraday's Law, Lenz's law Pandemic Edition

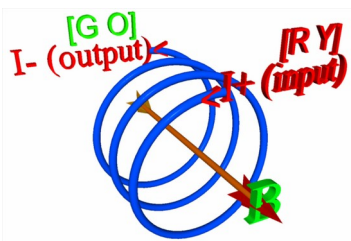
## Experiment I: Solenoids

revised 2021-1

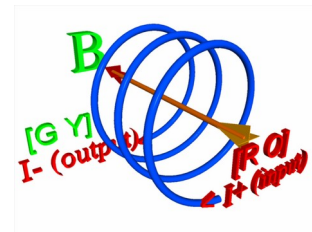
In order to understand how a transformer works, it is useful to understand some subtle details about solenoids. In class, I showed you how to calculate the magnetic field from a solenoid near its center:

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

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)

Negative : Left Handed:  $[RY] \rightarrow [GO]$       Positive : Right Handed:  $[RO] \rightarrow [GY]$

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. Note that what I call positive or negative is really quite arbitrary here.

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. Since you will be using the compass here, make sure you calibrate the compass to know which end points north.** You should use your compass to then determine the direction of the magnetic field inside the solenoid. **You'll want to confirm this and make sure you understand how to use the right-hand rule here.**

**While we're at it**, you may want 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.

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} Write these in your report.

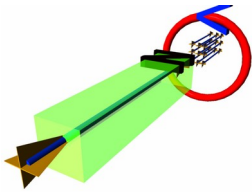
**Confirmation:** I know what the polarity of my solenoid is: \_\_\_\_\_

**Confirmation:** The threads are wound in a \_\_\_\_\_ handed direction.

## Lenz's Law

A note more to me than anyone else: The scope setting is setup 8.

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.



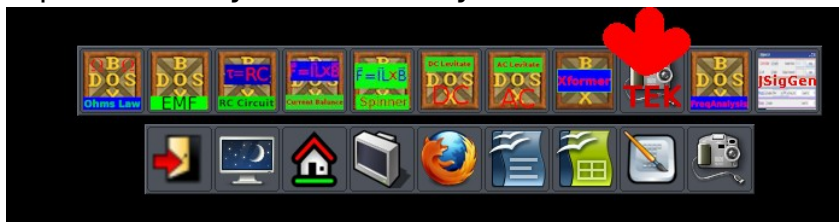
The **north pole** of a magnet is moving **towards** a **planar loop** as shown by the direction of the (big) arrow inside the magnet. In order for the circuit to oppose the magnetic flux change (which is increasing), the current needs to flow in the counter-clockwise direction as indicated. Now let's 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.

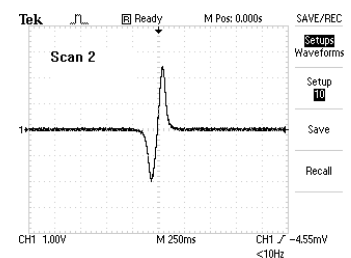
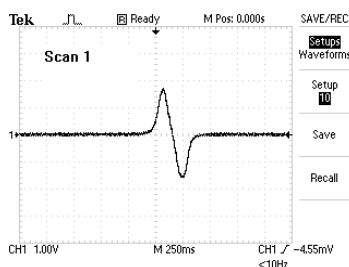
When you use an oscilloscope, there are many settings possible. In next week's lab, you will use them in a more sophisticated way to do ac impedance analysis. For today, however, you can think of the scope as providing a graph of time on the x-axis and voltage on the y-axis. So when you do a screen capture, you are essentially making a graph of this. One thing you will often hear when using oscilloscopes is the term "trigger." This means that when the detected voltage reaches a certain level, the oscilloscope will start to scan. As you might expect, there are many variations on these settings and sometimes it takes work to get all the scope settings done correctly. I'll have this set up at one location for you to use.

The program which will obtain a screen dump from the oscilloscope is shown below. Click on it once and when you are ready to make a screen dump, press the space bar. The image will be provided in your I directory after it is transferred.



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. I have oscilloscopes connected to your computer stations for this purpose. The screen dump from the TEK photo icon will be in your I directory and it will be TK#####.tif. The numbers after the TK are generated by the particular time at which the image was taken but you will probably want to write down what each file corresponds to as it is being acquired.

### Faraday's law part I:

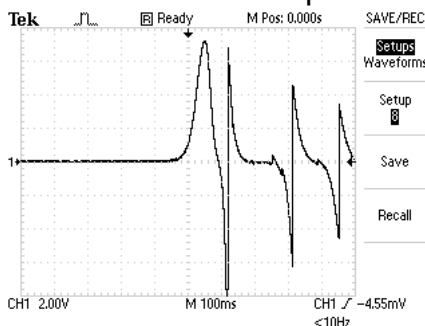
Fortunately, however, it's a bit easier to verify parts of Faraday's law than it is Lenz's law. In class we learn:

$$\text{Non-calculus: } \text{emf} \equiv \mathcal{E} = -\frac{\Delta \Phi_M}{\Delta t} \quad \text{Calculus: } \text{emf} \equiv \mathcal{E} = -\frac{d\Phi_M}{dt} .$$

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.

## Transformers

Now you are ready to understand how transformers work which is the last part of this lab. Your meters will need to be on the 10MΩ input impedance setting. You will also need to be able to switch from DC to AC :the best way is each time you take data with a particular acquisition program is to take 1 data point and discard it. Also you will need to initialize the RS232 interface on the voltmeters.

### 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 1/2 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  $L = \frac{\Phi_m}{I}$ . 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: $L \equiv \frac{\Phi_M}{I}$	Not needed today
current	I	$I = I_{\max} \sin(\omega t)$	cal: $\frac{dI}{dt} = \omega I_{\max} \cos(\omega t)$ non-cal: $\frac{\Delta I}{\Delta t} = \omega I_{\max} \cos(\omega t)$
Magnetic flux	$\Phi_M$	$\Phi_M = \mu_0 n^2 I [\text{volume}]$	cal: $\frac{d\Phi_M}{dt} = L \omega I_{\max} \cos(\omega t)$ non-cal: $\frac{\Delta \Phi_M}{\Delta t} = L \omega I_{\max} \cos(\omega t)$
Emf developed	emf	$\mathcal{E}_L = -\omega L I_{\max} \cos(\omega t)$	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  $\Phi_M$  is the flux through only 1 of the total of N turns):

Input or primary side:	$\text{cal: } \mathcal{E}_p = -N_p \frac{d\Phi_M}{dt}$ $\text{non-cal: } \mathcal{E}_p = -N_p \frac{\Delta\Phi_M}{\Delta t}$
Output or secondary side:	$\text{cal: } \mathcal{E}_s = -N_s \frac{d\Phi_M}{dt}$ $\text{non-cal: } \mathcal{E}_s = -N_s \frac{\Delta\Phi_M}{\Delta t}$

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.

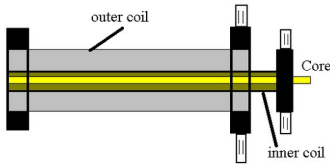
The particular coils used with today’s lab have the following electrical properties:

**Outer coil:** 2920 turns, #29 wire,  
 inductance  $63 \pm 2 \mu\text{H}$ , resistance:  $76 \pm 2 \Omega$ , capacitance:  $124 \pm 2 \text{ pF}$   
 Dimensions: 11 cm coil length x 3.5 cm coil outside diameter

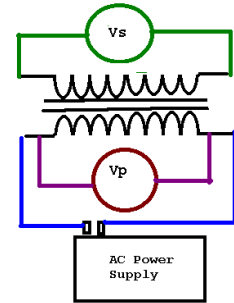
**Inner coil:** 235 turns #18 wire  
 inductance  $78 \pm 22 \mu\text{H}$ , resistance:  $0.4 \pm 0.1 \Omega$ , capacitance:  $142 \pm 2 \text{ pF}$   
 Dimensions: 12 cm coil length x 1.7 cm coil outside diameter

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)	

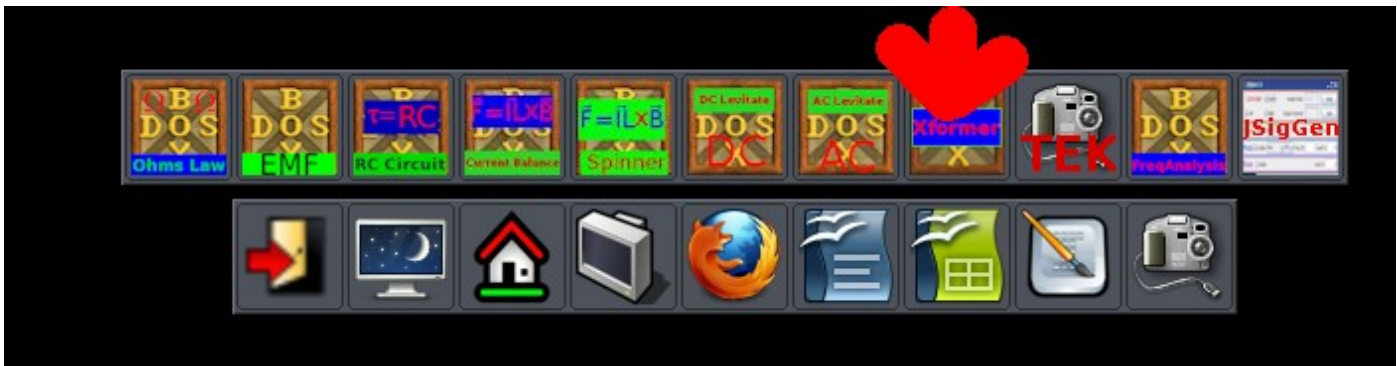


Sometimes (usually) you will see a center connection (called the center tap) which is used to establish ground or neutral. So here is how to get 220V and 110V into your house: the input to your house comes in on two wires, so that in time,



the maximum potential between the two leads is 220V. This is run through a transformer with a center tap. The output is then this: the center tap is called “neutral” which is not quite the same as ground. Between one end of the transformer and neutral, 110V exists although the phase is different between this and the other end of the transformer and neutral. Between the two ends of the transformer, 220 volts results. The neutral is usually tied to ground: a separate and usually green wire to the same connection as neutral is called the ground. The neutral wire, however, might be at a different potential than what you would measure if you stuck an electrode into the earth. A lot of this has to do with difficulty in making good electrical contact with the earth. It is simply not correct to assume that the earth is always a perfect conductor.

The program for acquisition for today’s lab is xformer. The icon for this is shown below.



I am providing in abbreviated format the instructions for each of the following 4 experiments. The **step-up configuration** has the primary side (input) on the smaller solenoid and the secondary side (output) on the larger solenoid. The **step-down configuration** has the primary side (input) on the larger solenoid and the secondary side (output) on the smaller solenoid.

### **DC xformer**

start xformer program (press d to do DC measurements)  
dc step up with core  
start at about 1/2 volt and increase by about 1/2 volts each time  
wait until secondary meter settles down to make measurement  
make 5 measurements total  
Paste data and observe RSQ value

### **ac no core step down**

turn voltage to zero  
cut power off  
Switch leads between the two solenoids : outer (larger) solenoid is input here.  
switch leads to ac (green plugs) on power supply  
Switch mx55 meters off. Reinitialize the rs232 interface and set on Vac.  
switch power on  
increase voltage until secondary meter has a reading (at about 2 VAC on primary meter)  
start xformer program  
press anything but d to do AC measurements  
increase in about 2 V steps up to about 10 V maximum  
make 5 measurements total  
turn the voltage back down

### **step down with core**

turn voltage to zero  
cut power off  
Keep input on the outer (larger) solenoid.  
Keep leads on ac (green plugs) on power supply  
insert core  
switch power on  
increase voltage until secondary meter has a reading (at about 2 VAC on primary meter)  
start xformer program  
press anything but d to do AC measurements  
increase in about 2 V steps up to about 10 V maximum  
make 5 measurements total  
turn the voltage back down

### **Step up with core**

cut power off  
Switch leads between the two solenoids: Input is on inner (smaller) solenoid.  
Keep leads on ac (green plugs) on power supply  
switch power on  
increase voltage until secondary meter has a reading (at about 0.25 VAC on primary meter)  
start xformer program  
press anything but d to do AC measurements  
increase in about 0.5 V steps up to about 4 V maximum  
make 5 measurements total  
turn the voltage back down  
Switch meters off. Reinitialize the RS232 interface and set on VDC. Move leads to DC.

## **Experiment T1: Transformers don't transform dc voltage. (no core)**

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  $\frac{1}{2}$  volt or so. You will use the acquisition program Xformer to acquire data for this part of the experiment. My spreadsheet will work better here if  $V_s$  (or  $V_{\text{secondary}}$ ) is on port 2 and  $V_p$  (or  $V_{\text{primary}}$ ) is on port 1. 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. For the DC experiment let the outer coil be the "primary" and the inner coil be the "secondary".

The results of this can be placed into the spreadsheet page "DC-Xformer" in your helper. Plot a graph of the results with  $V_{\text{primary}}$  on the x-axis and  $V_{\text{secondary}}$  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  $V_{\text{secondary}}$  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. Step-down, no core.**

**{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 on the V AC scale and read applied voltage across the outer coil [ $V_{\text{primary}}$ ]. Place the other of your voltmeters on the V AC scale and read output voltage across the inner coil [ $V_{\text{secondary}}$ ]. Place your core entirely inside the two coils. Now, vary your applied ac voltage from 0 - 5 volts, taking readings every 0.5 volts [ $V_{\text{primary}}$ ].

Plot a graph of the results with  $V_{\text{primary}}$  on the x-axis and  $V_{\text{secondary}}$  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 most of the magnetic flux from the primary coil does not enter the interior of the secondary core.

## **Experiment 3: The effect of the core. Step-down, with core.**

Connect your system as in experiment 2. Now, however, insert 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. Plot a graph of the results with  $V_{\text{primary}}$  on the x-axis and  $V_{\text{secondary}}$  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. You will notice that with the core, there is significantly more flux drawn into the interior of the secondary coil.

#### **Experiment 4: A step up transformer. Step-up with core**

Replace your iron core inside your system. Connect your ac power supply to the terminals of the inner coil. Place one of your voltmeters 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  $V_{\text{primary}}$  on the x-axis and  $V_{\text{secondary}}$  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 less 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 a 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. Make sure for the screen captures that you explain completely your understanding (which should be correct) of what is shown.

#### **Possible hypotheses for this lab**

You must use your own words here.

Magnetic field directions depend upon winding direction in solenoids.

Right hand rule correctly predicts direction of magnetic fields.

Lenz's Law is observed by differences in the polarity of magnetic flux changes.

Faraday's law and the importance of changing magnetic flux.

The transformer equation requires a changing magnetic flux even though it does not appear in the transformer equation.