Lab 10

Electromagnetic Interactions

What You Need To Know:

The Physics Electricity and magnetism are intrinsically linked and not separate phenomena. A changing magnetic field can create an electric field and a changing electric field can also cause a magnetic field. Although you are not required to know Maxwell's equations at this point, we write the two relevant integral equations here so you can see how the electric field E can be created by a changing B-field and vice versa.

Equation (1) is responsible for the Faraday effect.

$$(1) \qquad \oint \vec{E} \cdot \vec{dl} = -\frac{\partial}{\partial t} \iint \vec{B} \cdot \hat{n} \, dA$$

In Equation (2) the 2nd term on right is responsible for the magnetic Faraday effect also known as the Ampere-Maxwell law responsible for the Faraday effect.

$$(2) \qquad \oint \vec{B} \cdot \vec{dl} = \mu_o I + \mu_o \varepsilon_o \frac{\partial}{\partial t} \iint \vec{E} \cdot \hat{n} \, dA$$

The minus sign in front of the expression for the changing B field, $-\partial B/\partial t$ is in fact Lens's law! Knowledge of electromagnetic interactions is essential in order to understand the operation of car ignitions systems, motors, generators, alternators or transformers and metal detectors to name a few devices.

Oersted discovered that currents create magnetic fields in 1820. He used a small compass needle and noticed a deflection of the N pole as he moved the compass around a wire carrying a steady current. This showed that a current carrying wire has a magnetic field circulating around it. You can calculate this field using the $\oint \vec{B} \cdot \vec{dl}$ equation with the 1st term on the right hand side.
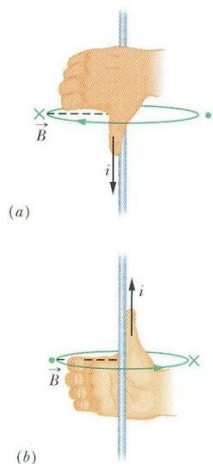
Rearranging, $B(2\pi r) = \mu_o I$, you get the B field magnitude a perpendicular distance r away from a current carrying wire. The direction of the B field circulation can be found using the **right hand rule (RHR). Put you right thumb in the direction of the + current I, then your fingers curl in the direction of the B field.** [Picture Ref: Halliday and Resnick "Fundamentals of Physics", 9th Extended Ed. , p766 Fig 29-4, (Wiley & Sons , 2003).]

Faraday tried to get currents from magnets, which he succeeded in doing in 1831.
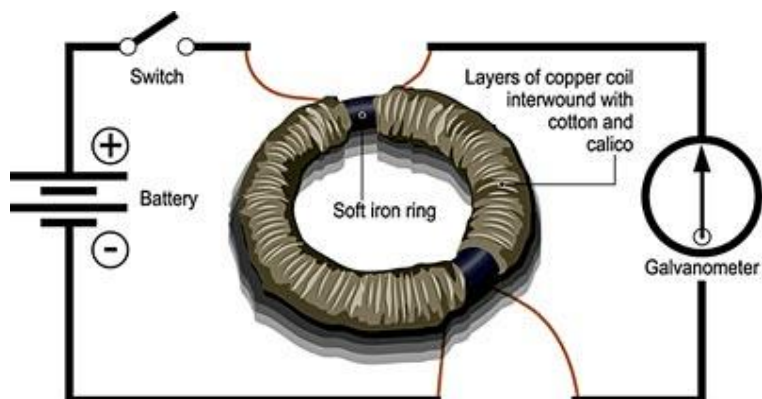
There are 2 coils here, both wrapped on the same iron core, to increase the magnetic field. As the switch is either opened or closed, Faraday noticed a deflection on the Galvanometer, which is essentially just an ammeter, a device to measure current I.


**Picture Ref.**: http://www.engineering-timelines.com/how/electricity/transformer.asp
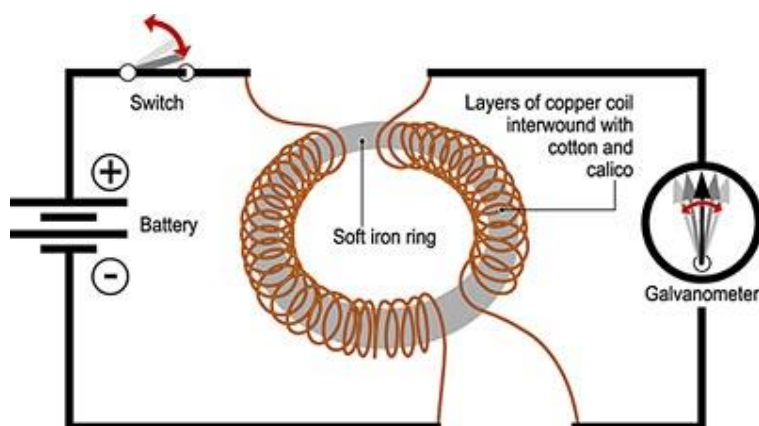
The needle on the Galvanometer would show a momentary deflection one way if the switch was opened and the opposite way if the switch was closed. **Faraday's observation that the meter jumps *ONLY* when the switch is opened or closed suggested that a current was generated only by a *CHANGING* B-field. Not a static magnetic field. If the critical point was <u>changing</u> the magnetic field through the coil then the iron ring is not necessary. This is electro-magnetic induction.**

We can show a similar result by using wire loops or small coils (instead of longer solenoids) and see a deflection on an ammeter (current meter) when a bar magnet is moved into and out of the loop. OR, you could use a static magnet and move a coil or loop into and out of the magnetic field, only the relative motion is needed.

In the diagram below, as the bar magnet moves down, the needle deflects left. The top of the loop acts like a N-pole opposing the changing magnetic field. Current flows anti-clockwise.
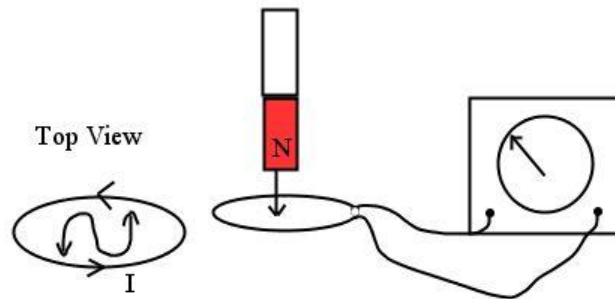
In the diagram below, as the bar magnet is pulled up, the needle deflects right. The top of the loop acts like a S-pole trying to pull the bar magnet back, opposing its upward motion. The current flows clockwise.
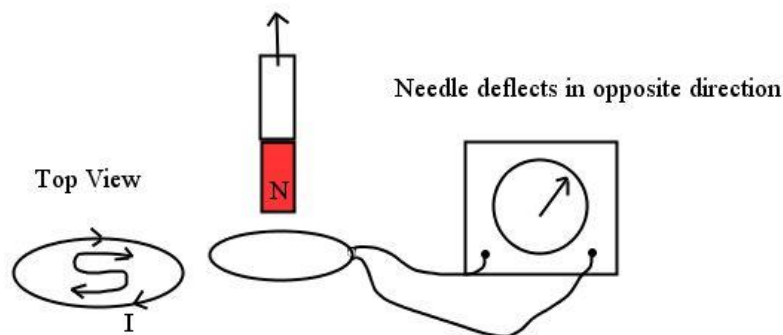

The current will always flow in a direction such as to oppose the changing magnetic field causing it. This is Lens's law! And the reason for the negative sign in the first Eq. for curl E. Note that the units for E, the electric field, are volts/meter. If you have a voltage applied to a wire loop is it as if you had a battery attached to it, and a current will flow. The integral form of the first Eq. is

$$\oint \vec{E} \cdot \vec{dl} = -\frac{\partial}{\partial t} \iint \vec{B} \cdot \hat{n} \, dA$$

The E-field is integrated around a closed loop (the wire loop). Note that E. d ℓ is a voltage, like you would get from a battery. This causes a current to flow around the wire loop and it is caused by the changing magnetic field through the loop. This comes from the moving bar magnet. You can use the right hand rule (RHR) to determine the direction of the current in the wire loop… although drawing N and S and putting arrows on the end works just as well and maybe faster!

[Alternate use of RHR: Do you need the top of the coil to act as a N pole or a S pole? Use your right thumb to point in the direction of the magnetic north, then your fingers will curl in the direction of the current flow.]

It is important to note that current is only present during the MOTION. If the coil, or the bar magnet in the first instance, does not move, then there is no changing B-field and no current.
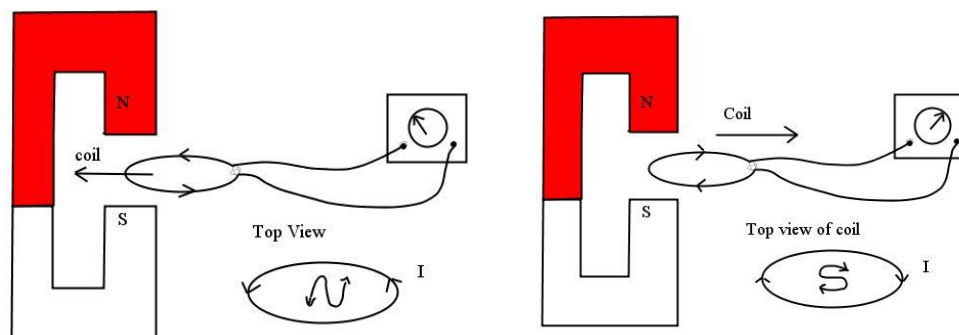
We will define the magnetic flux through the loop (coil) to be $\Phi = \dfrac{\partial}{\partial t} \iint \vec{B} \cdot \hat{n}\, dA$.

Faraday's law states that a changing magnetic flux, $d\Phi/dt$, through a coil will produce an electric field cable of driving currents around the loop. The electro motive force EMF (or voltage) is defined by the integral of the electric field around the loop,

$$\text{EMF} = \oint \vec{E} \cdot \vec{dl} = -\frac{\partial \Phi_B}{\partial t}$$

For a one turn loop this would be the end of it, but since a coil has N turns we must add in the current for each turn of the coil. Then the EMF becomes,

$$\text{EMF} = \oint \vec{E} \cdot \vec{dl} = -N\frac{\partial \Phi_B}{\partial t}$$

Basically magnetic flux refers to the number of field lines passing through the loop/coil.

In the left picture you see the magnetic field produced by the loop or coil. A coil with a current running through it acts just like a bar magnet. You have probably come across electromagnets before. Turn on the current and the coil becomes strongly magnetic, like a magnetic crane in a scrap yard used to pick up old cars.

In the right hand picture you can see how the field lines will change as you move the bar magnet towards the loop. More and more magnetic field lines will pass through the loop, so clearly the magnetic field is changing. We say the magnetic flux linkage increases, as more field lines pass through the loop. Note that if the coil/loop was horizontal no magnetic field lines would pass through it! So there would be no induced EMF and hence no current in the loop. If you turned the loop 30 degrees upward only the fraction cos(30) of the field lines would pass through the loop. The unit vector $\hat{n}$ always points perpendicularly out of the loop, the area refers to the area enclosed by the loop. So $\vec{B} \cdot \hat{n} da = BA \cos \theta$ where θ is the tilt angle of the loop.
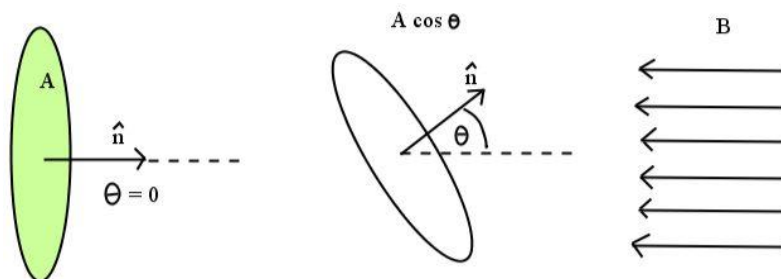
Self Induction (one coil)

The emf self-induced in a coil is, $V_1 = -N_1 \dfrac{d\phi_1}{dt} = -L \dfrac{dI_1}{dt}$, where the self inductance,

$L = \dfrac{\phi}{I}$. If the B field inside a solenoid (coil) is $B = \mu_o N \dfrac{I}{\lambda}$ the magnetic flux through

each coil is $\phi_B = AB = \pi r^2 \mu_o N \dfrac{I}{\lambda}$ then the self inductance is $L = \dfrac{\phi}{I} = \pi r^2 \mu_o N \dfrac{I}{\lambda}$.

Here, λ is the length of the coil/solenoid.

A self induced emf appears whenever the current in the coil is changing with time, ie. When you turn it on or off. The voltage (emf) induced in the coil is such as to oppose the changing field causing it, so the emf will oppose the battery polarity. It is sometimes called the "back-emf" because it is in the opposite direction to the battery voltage. If ε is the voltage from the battery, then with a resistor and an inductor (coil) present the voltage equation would read,

$$\varepsilon - L\frac{dI}{dt} - IR = 0 .$$

See diagram of a simple series RL circuit below (from onlinephys.com)

Note the battery voltage is positive, there is a voltage drop across the resistor and inductor (coil). You can solve this equation for $I(0) = 0$ at time $t = 0$, by dividing by L and using a particular integral to solve:
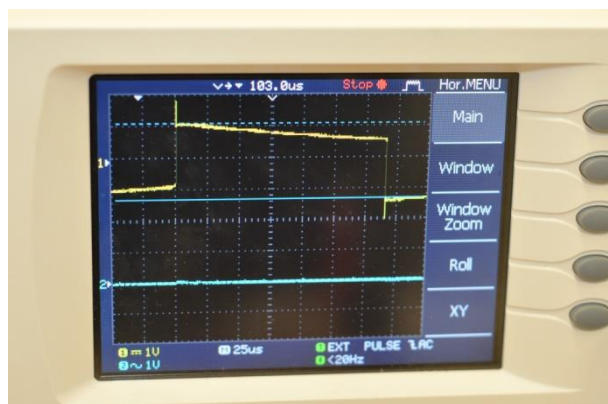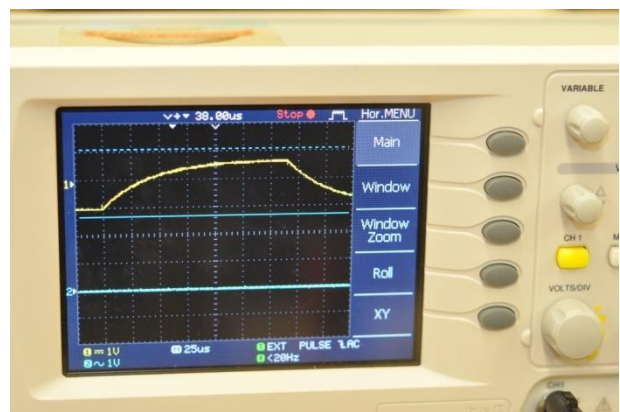
The result is,

$$I(t) = \frac{\varepsilon}{R}\left(1 - e^{-t/\tau_L}\right)$$

Where the time constant, $\tau_L = \frac{L}{R}$. $V_B = \varepsilon$ battery voltage in figure below sum of V_R and V_L.
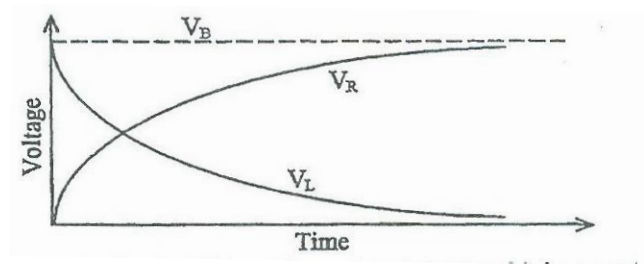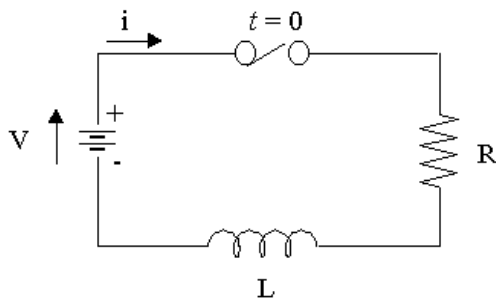
To the right is what the voltage looked like across the inductor (coil). Same input to CH1 as above. It is OK to change the volts/div scale if you want to.

To the left is what the voltage across the resistor looks like. 1V per div and 25 μs time/div. I was using a square wave generator input of 3 KHz at 1V. Measure $t_{1/2} \sim 40\mu s$.

Inductance of a solenoid is: $L = \dfrac{\mu_o N^2 \pi r^2}{\lambda}$ where λ is the length of the solenoid, r is the radius and N is the number of turns.

Mutual Inductance

Sometimes you need to change the voltage of the supply, either you need a higher or a lower voltage. You can do this by using a transformer, which consists of two coils, usually wrapped around each other to maximize the magnetic flux through the secondary coil. For example you need a transformer for a fluorescent light bulb which needs 3000V to operate, and spark plugs in your car which need 15,000V to force the spark to jump the gap.   In the picture below there is a starter motor coil, for a car, showing the two coils one wrapped around the other. The magnetic field from the first coil or primary coil causes a changing flux which passes through the secondary coil. The changing magnetic flux causes an EMF in the secondary thereby creating a current in the secondary coil. The induced EMF = voltage = V_2 in secondary depends on the relative number of turns in the secondary N_2 and number of turns and voltage in the primary and the current in the primary and of course how much magnetic flux is passing through coil 2 from coil 1.

$$V_2 = -N_2 \frac{d\phi_2}{dt} = -\frac{d}{dt}(N_2 \phi_2)$$

If we assume that the magnetic flux is the same for the two coils, then $\phi_1 = \phi_2 = \phi$ and

$\frac{V_1}{V_2} = \frac{N_1}{N_2}$.   This is approximately true for similar sized coils and when all the field lines from one coil pass through the second. If you move the coils further apart, the flux through the second coil is reduced. If you tilt one coil relative to the axis of the other the flux through the second coil is reduced and each will affect the voltage in the secondary.

When coil 1 produces a current in coil 2 we use mutual inductance, $M = \frac{N_2 \phi}{I_1}$.   We just use M instead of L. The starter motor in a car is an example of a <u>step up transformer</u>… going from primary 12V to secondary 15,000V. The S.I. unit of inductance, either L or M, is Henry symbol H.
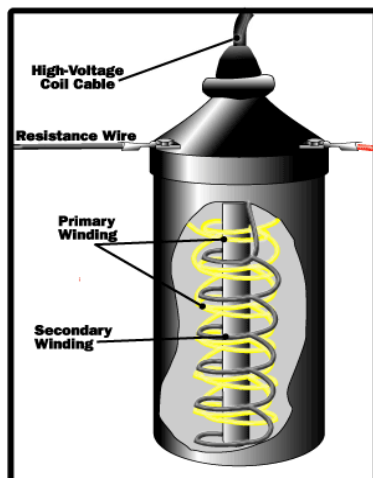
To find the voltage in the secondary coil, $V_2 = \frac{N_2 V_1}{N_1}$.

A step-up transformer has more turns on the secondary than the primary. The secondary voltage is greater than the primary voltage.

A step-down transformer has more turns on the primary. The voltage on the secondary is smaller than the primary voltage.
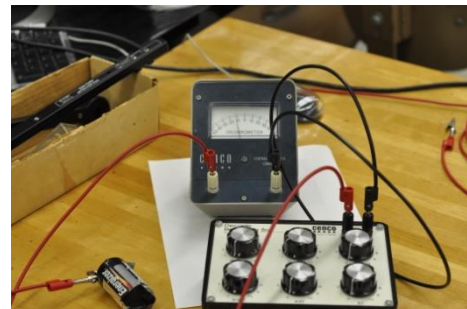
http://www.engineering-timelines.com/how/electricity/transformer.asp
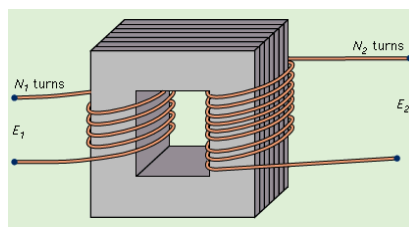
from http://onlinephys.com.

What You Need To Do:

Part 1 – Defining Deflection You will need the galvanometer, resistance box, a battery (1.5 V D cell) and some cables and some tape to attach to the D-cell battery. The photo to the right shows a 10 kΩ resistance in series with the battery and galvanometer.

A) Hook the positive terminal of the galvanometer to the positive terminal of the battery.

B) Hook the negative terminal of the galvanometer to one side of the resistance box.

C) Hook the other side of the resistance box to the negative terminal of the battery.

D) With at resistance box at 10 kΩ, you should see a deflection to the left. If you hook the battery in the wrong way, you will get a deflection to the right of about 10-12 points on the galvanometer scale. Now you know which way the galvanometer will deflect for a + or – current.

Part 2 – Inducing A Current Now you need the galvanometer, compass, small cylinder magnet, and the coil inside the plastic box with wires sticking out. You will use the compass to determine which end of the magnet is north. *The green end of the compass will point toward the N end of the compass.*

A) Disconnect the circuit from **Part 1**. Now hook the coil up to the galvanometer. See photo to the right.
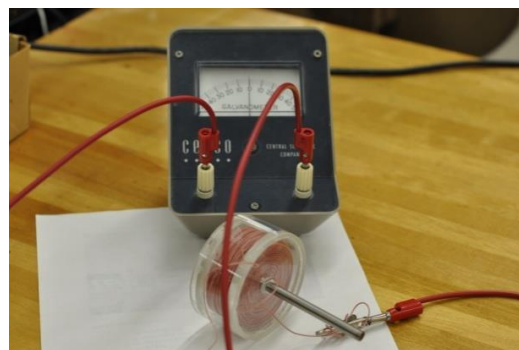
B) Push the North end of the magnet into the coil… note deflection on the galv.

**C)** Now withdraw (pull) the magnet, again note the deflection on the galv.

C) Push the South end of the magnet into the coil, note deflection on galv.

D) Pull the South end of the magnet out of the coil, noting the deflection on the galv.

E) For each case above note, which way does the current flow? CW or CCW? Does the front face of the coil act as a N pole or S pole?

F) Notice here that the magnet is stationary, and so the galvanometer reading is exactly zero. You only get current when the magnet is MOVING! There should be opposite deflections when the magnet moves into or out of the coil.

Part 3 – Mutual Inductance Now you will be using 2 coils on sticks, and the short piece of iron which fits nicely into the coils to hold them parallel and at a fixed distance apart. I'm not too fussy about how you measure the separation so here we will simply measure from the front of one coil to the back of the other… we only need to see what happens to the voltage in the second coil as we change the magnetic flux through it… by using different distances between the coils. The closer the coils are together the more magnetic field lines will pass from the 1st coil to the 2nd (the bigger the flux).
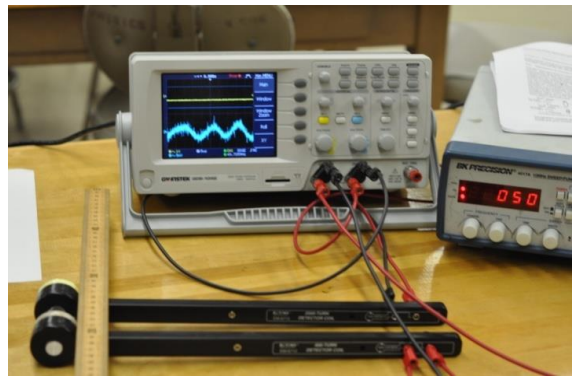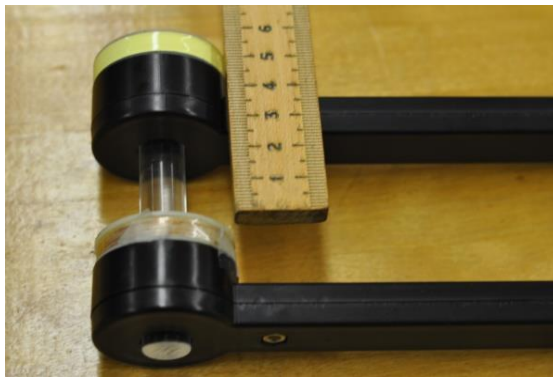
You will be using the 2 coils with handles, signal generator, oscilloscope, ruler and several cables.

A) Set the signal generator to sin output and 50 Hz. Use the 1 kHz range and use the coarse and fine adjustment knobs.

B) Turn on the oscilloscope and set the voltage/div to 1 V and CH 1 to 5-10 ms time/div . This will allow you to see the sin wave nicely for CH 1. CH2 should be set to the same.

C) Hook up the signal generator to the primary coil with 400 turns. Hook this up to CH 1. Turn on the signal generator if you haven't already. You should see a nice sin wave for the yellow CH 1 input, if you have the time/div set to about 10 ms.

D) Hook the secondary coil with 2000 turns to the CH 2 inputs. Thread the coils onto the iron rod and make them touch. You should see a blue sin wave for CH 2 now. Hit the run/stop button to take a measurement of the voltage for CH 2.

E) Copy the small table on the next page into your notebooks, distance of separation between coils and Voltage CH2. Explain why the voltage changes?   Think about flux through coil 2 and how that would change.

Distance (cm)	V_{Ch2}
0	
1	
2	
3	
4	
5	

F) Now using V_1 = 1 V for the primary coil, you will determine the voltage $V_2 = V_{Ch2}$ for the secondary coil by using the number of turns on each coil. Fill in the table below. (Don't forget the Equation on page 6, $V_2 = \dfrac{N_2 V_1}{N_1}$.)

Primary	**Secondary**	V_{Ch2}
400	2000	
400	400	
2000	300	

Part 4 – LR Circuit (See notes on page 5.)
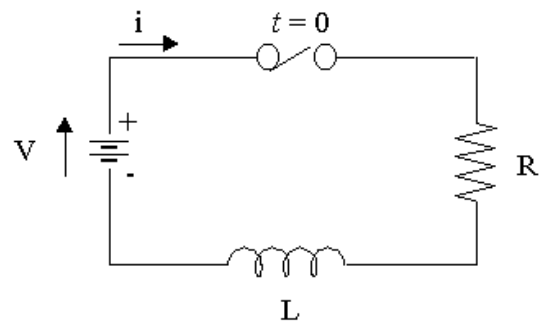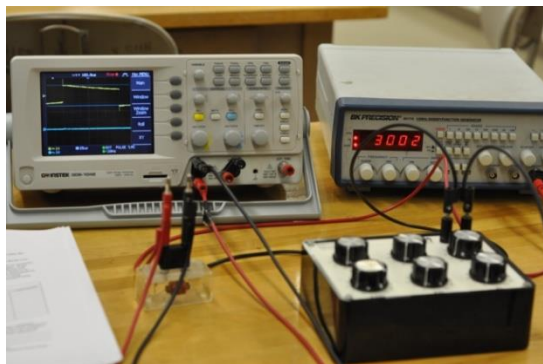
The photo shows the voltage drop across the coil (inductor L).

You are using the small coil with the two banana plugs attached to it. Set the resistance box to 1KΩ. Set the signal generator to 3 KHz and square wave. Turn on the scope and the generator. For the scope use white menu button under trigger, set CH 1 as the source, slope coupling, DC coupling. Set time/div to 25 μs. Use the 500mV setting for volts/div.

A) Set up the circuit in series. The negative output of signal generator goes to the resistor, which goes to the coil (inductor). The other end of the coil goes back to the signal generator. You have not hooked up the oscilloscope yet.

B) To measure voltage across the resistor connect cables ONLY across the resistor to the +/− terminals on the scope.

C) To measure voltage across the coil (inductor L) connect cables ONLY across the coil to the +/− terminals of the scope. You will only have the resistor OR the coil attached to the scope at any one time, use the same cables for both. Make sure the positive end of the resistor/coil is connected to the + terminal on the scope.

ε is the battery voltage which is the sum of V_R and V_L. The coil (inductor) also has resistance. Here $R = R_0 + R_L$. Find the resistance of the coil (inductor) R_L from V_L and I_0 . ($R_L \sim 250\Omega$) The current is the same through the resistor R_0 and coil, hence $I_0 = V_R /R_0$ …

$$I(t) = \frac{\varepsilon}{R}\left(1 - e^{-t/\tau_L}\right)$$

The $\dfrac{\varepsilon}{R}$ is the max current I_0. **Measure $t_{1/2}$** . Solve for $t_{1/2}$ by setting $I(t) = I_0 /2$ and solve the above Eq. Note that $\tau_L = L/R$ and $t_{1/2} = \tau_L \ln(2) \sim 40\mu s$. Use battery voltage $\varepsilon = 1V$ from the signal generator.. Find the time constant τ_L . Fill in the table below and find L *experimentally* using τ_L.

Use … L = 50 mH, $\varepsilon = 1$ V, $R_L = V_L/I_L \approx 250 \ \Omega$, $\varepsilon = V_L + V_R$						
R_0 (kΩ)	$R = R_0 + R_1$ (Ω)	V_R	$T_{1/2}$	$I_0 = V_R/R_0$	$T = t_{1/2}/\ln 2$	$L = R\tau$
1	1250 Ω	0.8 V	27 µs	0.8 mA	39 µs	49 mH
2						
3						
4						
5						
6						
7						
8						
9						
10						