Electromagnetic Induction (E6)

Objectives

• Examine how the emf induced in a coil depends on motion of permanent magnets.

• Examine how the emf induced in a secondary coil depends on frequency and amplitude of the current in a primary coil.

Theory

A. Faraday's Law

The <u>magnetic flux</u> $\Phi_B = |\vec{B}_n| A = BA\cos\theta$ is defined as the average of the normal component of the magnetic field $\overline{B}_n$ multiplied by the area A, where θ is the angle between $\overline{B}$ and the normal to the surface. You may picture it as the net number of magnetic field lines that are intercepted by a surface.

The magnitude of the induced emf may be determined from Faraday's Law, which states that: **"the magnitude of the induced emf around a loop is equal to the rate of change of the magnetic flux through the loop"**.

$$\mathcal{E}(t) = -\frac{\Delta\Phi_B}{\Delta t} \tag{1}$$

For coils containing N individual turns, the induced voltage is a sum of emfs from each individual loop and is given by the following equation.

$$\mathcal{E}(t) = -N\frac{\Delta\Phi_B}{\Delta t} = -N\frac{\Delta\left(|\vec{B}_n| A\right)}{\Delta t} \tag{2}$$

The polarity of the induced emf can be found using **Lenz's Law: "the induced current is always such as to oppose the change of flux that generated it"**. That is, the direction of the induced current tends to maintain the original flux through the conducting loop. Lenz's Law is represented by the "**-**" sign in Faraday's Law. It may not be obvious, but the Lenz's law is a consequence of the energy conservation principle.

B. Voltage Induction from Changing Magnetic Fields.

Just as moving charges create a magnetic field, a moving (or changing) magnetic field can create a current in a loop of wire. When this happens, it is said that a voltage has been <u>induced</u> which drives the current. This induced emf depends on how fast the magnetic flux is changing. An extremely slow change in magnetic flux produces virtually no emf, whereas a rapidly altering magnetic field induces a great voltage.

The changing magnetic field necessary for an induced voltage can be obtained by:

a) moving permanent magnets near a conducting loop, or

b) using a second coil and moving that coil near a conducting loop (no change to the current in that coil), or

c) using a second coil and changing the current in that coil (no movement of that coil).

The magnetic field inside a **coil** is proportional to the current in the coil (see E5 - Theory section of the lab manual).

$$B = \frac{\mu_0 n}{\sqrt{1+\left(2R/L\right)^2}} \times I = const_1 \times I \implies B \propto I$$

Since the cross-section area of the coil A does not change and the magnetic field inside the coil is perpendicular to the coil cross section (i.e., $\left|\vec{B}_n\right|=B$), Equation (2) can give as

$$\mathcal{E}(t) = -N\frac{\Delta\left(\left|\vec{B}_n\right|A\right)}{\Delta t} = -NA\frac{\Delta(B)}{\Delta t} = -NA\frac{\Delta(const_1 \times I)}{\Delta t} = const_2 \times \left(-\frac{\Delta I}{\Delta t}\right) \implies \mathcal{E}(t) \propto \left(-\frac{\Delta I}{\Delta t}\right) \quad (3)$$
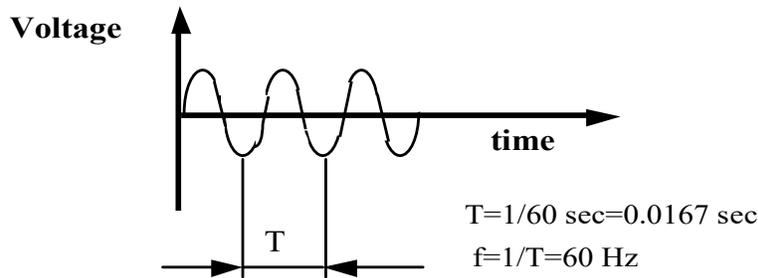
In other words, according to Faraday's Law the emf induced by a coil is proportional to the changes of the current in that coil.

$$\mathcal{E}(t) \propto \left(-\frac{\Delta I}{\Delta t}\right) \propto \text{ frequency of } I(t) \quad\quad\quad (4)$$

C. Applications of Induction

Generators

Electromagnetic generators use induction to create the electrical current in our outlets. Power plants convert mechanical power into electrical by rotating a loop of wire in a magnetic field. The changing magnetic flux, therefore, produces an electrical current in the wire. The power line voltage (AC) vs. time graph is represented by a sinusoid.

Voltage

T=1/60 sec=0.0167 sec

f=1/T=60 Hz

T

time

The emf induced in a planar coil that is rotated in magnetic field B is given by the following equation:

$$\mathcal{E}(t) = NAB\omega\sin(\omega t) = \mathcal{E}_0 \sin(\omega t), \quad\quad\quad (5)$$

where, N is the number of loops in the coil, A is the area of the coil, and ω is the angular velocity of the rotating coil.

Mutual Induction

If two coils are in proximity to each other, then a changing current in one coil (called the primary coil) induces an emf in the other coil (called the secondary coil). The emf $\mathcal{E}_2$ induced in the secondary coil by a change of current ΔI_1 in the primary coil is equal to the following.

$$\mathcal{E}_2(t) = -M_{12}\frac{\Delta I_1}{\Delta t} \, , \tag{6}$$

where Δt is the time interval during which the change occurs. The constant M_{12} is called the mutual inductance between the two coils and is measured in Henries (H). 1 H = 1 V*s/A

Transformers

The principle of induction can also be used to carry electrical energy across empty space from one device to another. If one conductor containing a time-dependent (AC) current is placed near a second conductor, then the changing magnetic field of the first can induce an emf in the second.

Transformers are usually composed of two coils called the primary (#1) and secondary (#2) coils. The primary coil is typically connected to the power source. A changing magnetic field from the primary coil induces a voltage in the secondary coil. In turn, this induced emf can establish a current in the secondary coil. It is not possible to change DC currents using transformers, because a DC current does not induce any emf voltage in the secondary coil.

The magnitude of the induced emf and thus the current depends on how far apart the two coils are located. If the coils are separated, then the #2 coil will only intercept a small portion of the #1 coil's changing magnetic flux. Therefore, the induced emf will be very small. However, if the two coils are very close, then the #2 coil will encounter most of the changing magnetic flux. The induced emf will be increased.

The induced emf in the #2 coil can be further enhanced if a magnetic steel core is placed inside the #1 and #2 coils. When a current flow through the #1 coil, the magnetic steel core essentially becomes a magnet, which strengthens the magnetic field of the #1 coil. Furthermore, the magnetic field becomes concentrated in the magnetic steel core and thus extends to the #2 coil well.

Ideally, if the #1 and #2 coils have an equal number of turns (loops of wire), then the induced voltage of the #2 coil will be equal to the voltage of the #1 coil. These voltages will not be equal, however, if the coils contain a different number of loops. If the #2 coil has a

greater number of loops than the #1 coil, then the voltage induced in the #2 coil will be greater than in the #1 coil. The voltage has been stepped-up. If the #2 coil has fewer turns than the #1 coil, the induced voltage will be less than the #1 voltage.
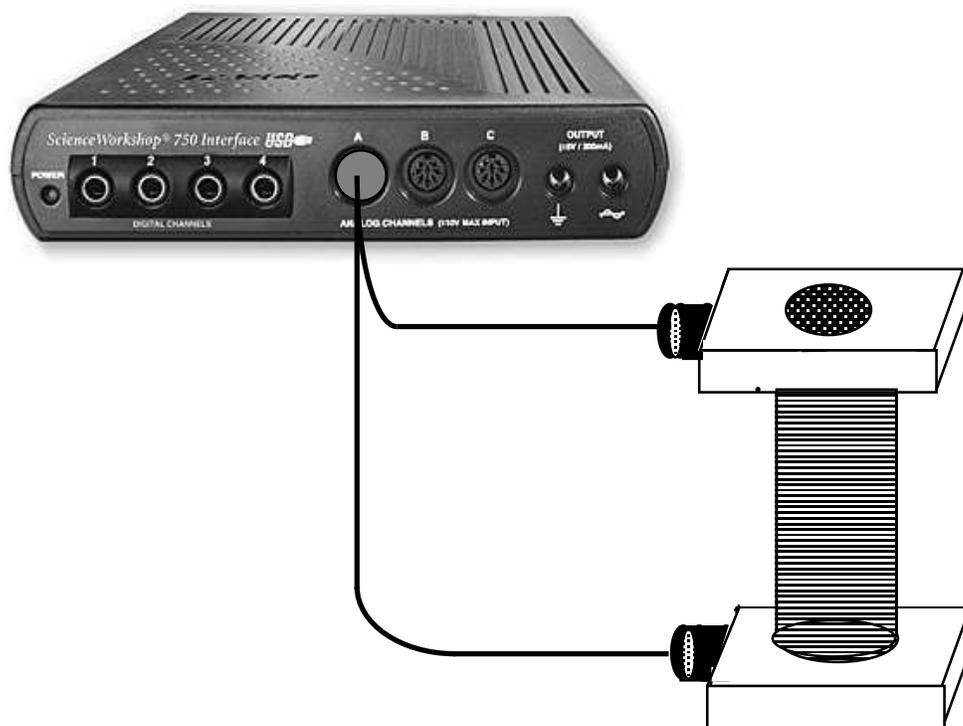
The exact relationship between number of turns and voltages is shown below for an **ideal transformer**. Keep in mind that the induced voltage may be less for a real transformer.

$$\frac{number\ of\ turns\ for\ the\ secondary\ coil}{number\ of\ turns\ for\ primary\ coil} = \frac{secondary\ coil\ (\#2)\ voltage}{primary\ coil\ (\#1)\ voltage} \quad or \quad \frac{N_S}{N_P} = \frac{V_S}{V_P} \quad (7)$$

Procedure:

Activity 1: Voltage Induction Using a Magnet

In this activity, you will see how a magnet can be used to induce a voltage in a closed conducting loop. To start this activity, you should locate the long red copper coil and make sure that it is attached to the signal interface as shown below.
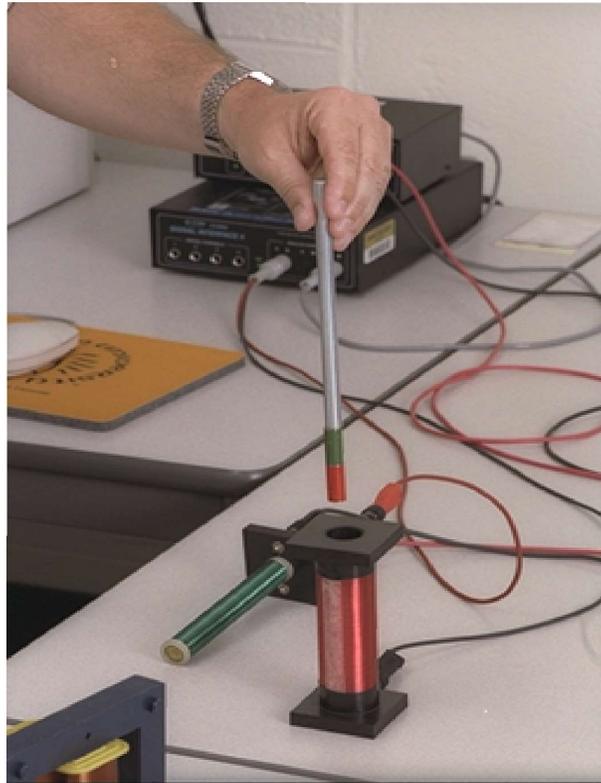

Download files for experiment E6. Locate the "E6, Activity 1" file and double click to start the program. You will then see a graph for voltage vs. time data. To begin collecting data for the induced voltage of the copper coil follow the steps below.

1.1.   Make sure that the smaller, inner coil has been removed from the larger, outer coil. Locate the long silver metal rod and the red/green <u>magnet</u>. The rod as shown below will attract the magnet:
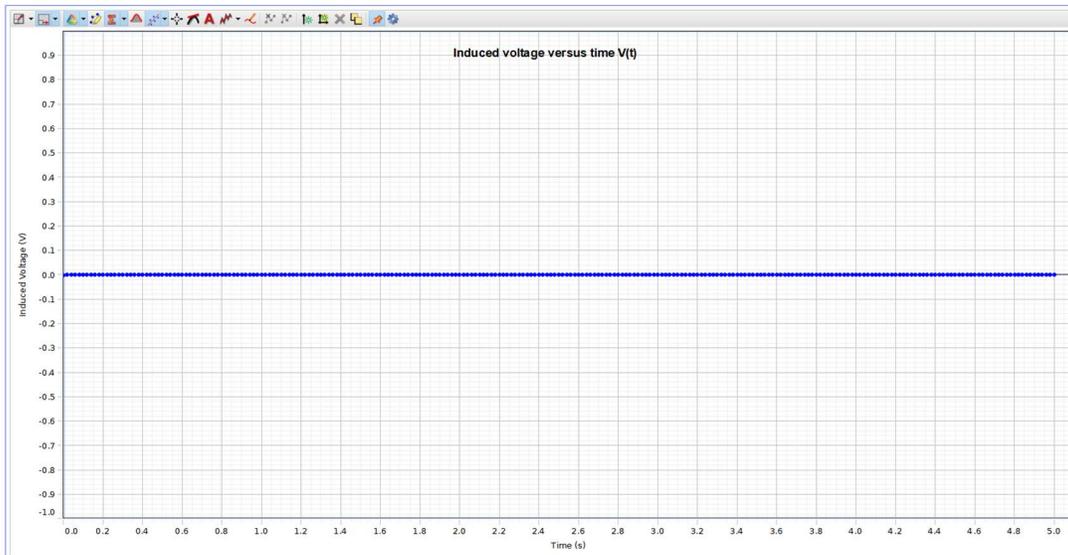

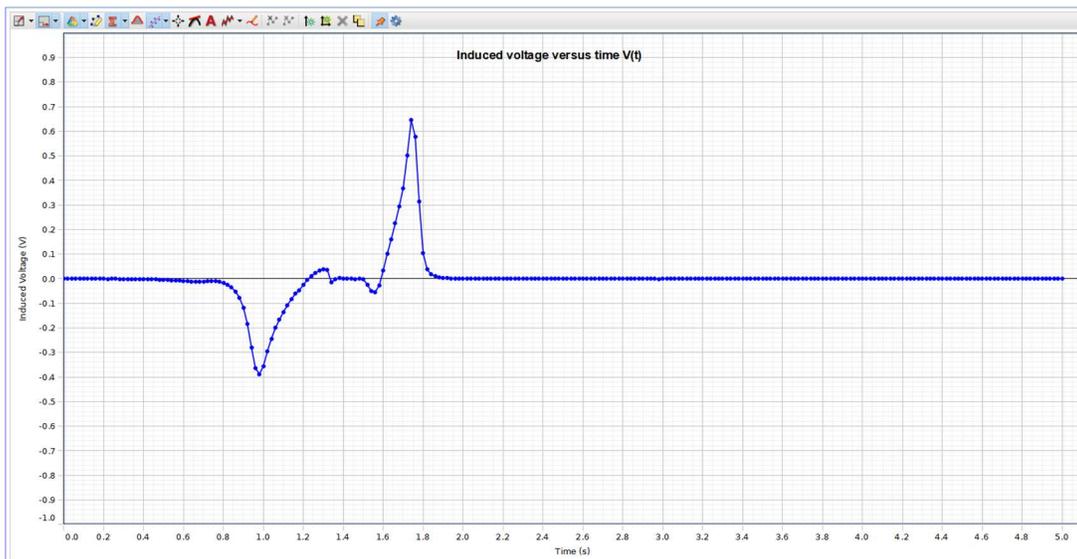Use the metal rod as a convenient "handle" for the magnet.

1.2.   Put the magnet inside the coil and let it stay there. <u>Do not move the magnet</u>. Click on the

 button found below the graph. The computer will then begin to collect data for the voltage that exists in the coil. Click on the statistics tool and select the mean value. What is the average (mean) value of the induced emf?

1.3.   Put the magnet in motion. Click on the button to begin data recording. Quickly, move the magnet into and out (**once**) of the hole at the top of the coil. The computer will collect data for the induced voltage. The program will automatically stop recording data after 5 seconds.
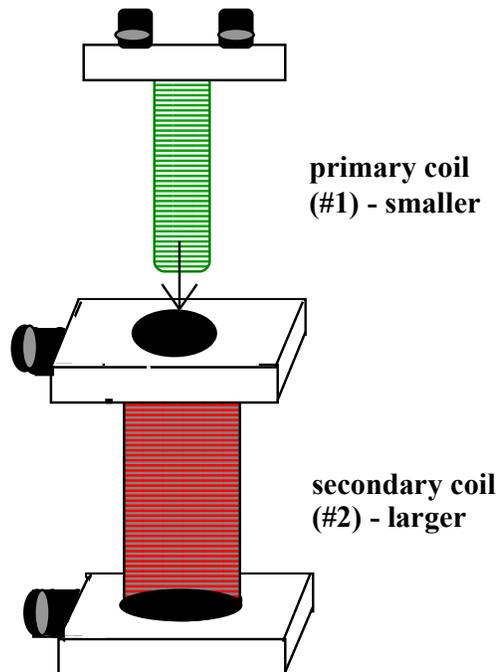

Click on the statistics tool ⨊ and select the maximum value. **Print** a copy of this graph.

1.4.   Move the magnet into and out of the coil (just once), but this time, do it slowly. What is the induced emf compared to the result for *Activity 1.3*? Explain the difference using the Faraday's Law.
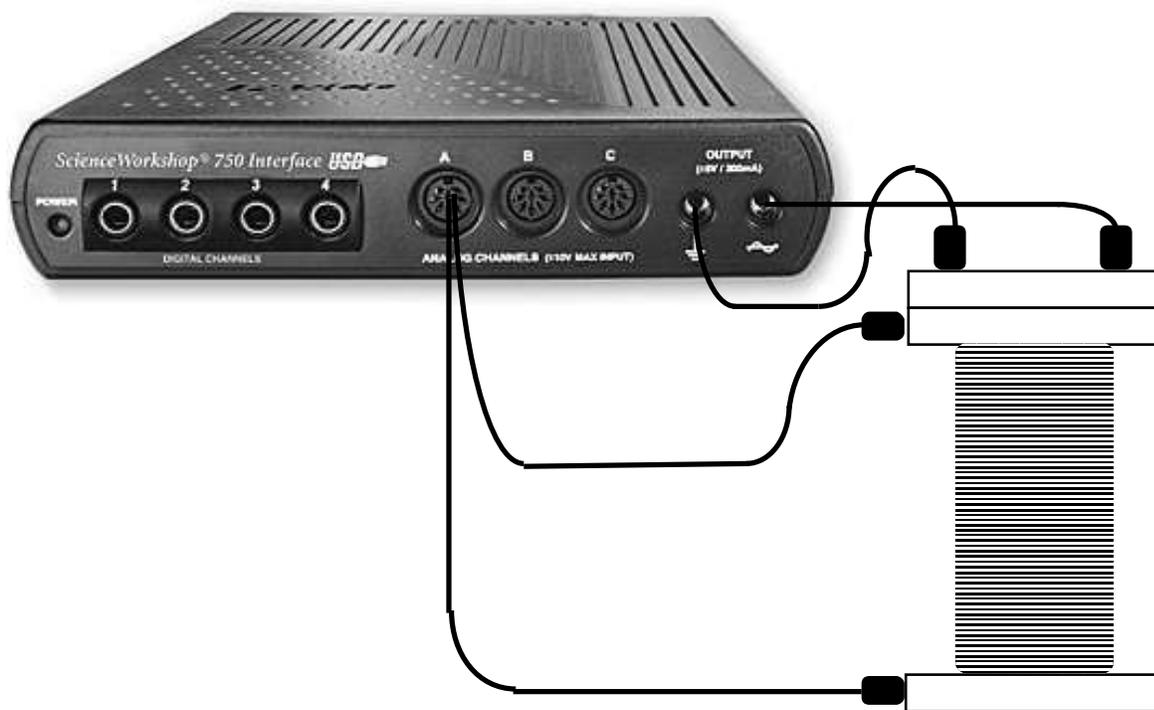
1.5.   <u>Reverse</u> the orientation of the magnet and record data again. Did you notice any change? Record your observation on the <u>data sheet</u>.

Activity 2: Voltage Induction Using a Coil with Current

In this activity, you will see how an emf can be induced using a coil with a current. You will first need to locate the smaller coil and insert it into the larger copper coil as shown below.

primary coil (#1) - smaller

secondary coil (#2) - larger

Now, you will need to hook up the smaller, primary coil to the "OUTPUT" terminals of the data interface as shown below.
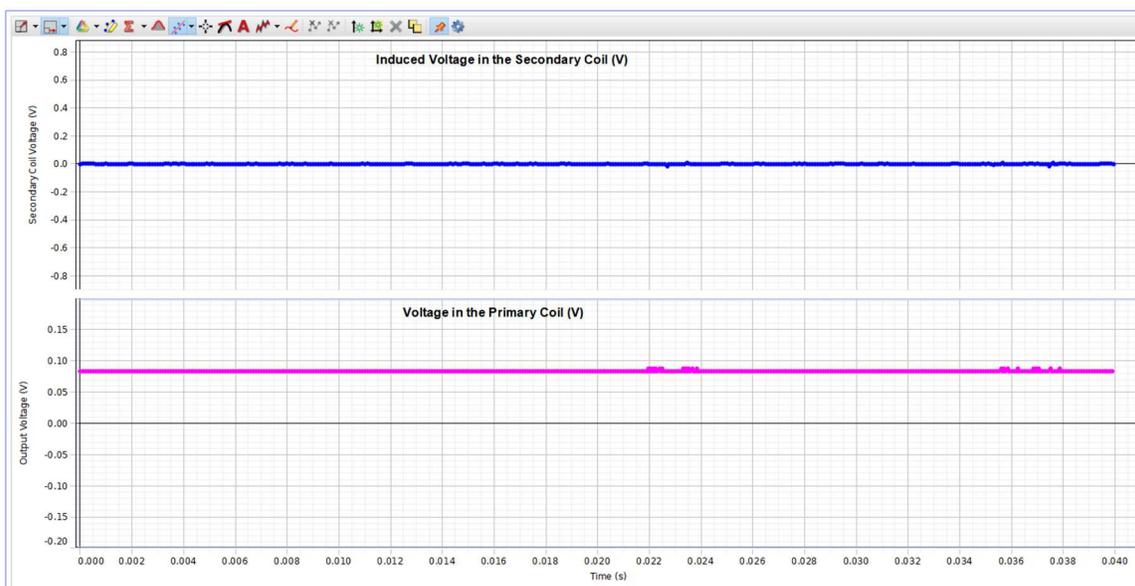
The current from "OUTPUT" runs through the smaller, primary coil and generates a magnetic field. That field would remain constant if you used a constant DC current or would change if you applied an AC current. The induced emf in the larger, secondary coil is measured by the signal interface.

A. Once the coils have been properly arranged, you will measure the emf induced in the secondary coil due to a <u>direct current</u> in the primary coil.
This is a similar situation as in step 1.2 of the previous activity done with a permanent magnet that does not move.
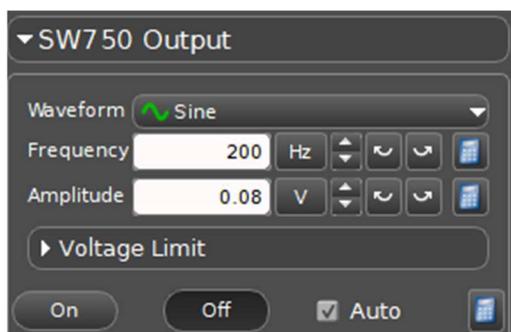
2.1.   You need to open the next activity configuration. Select: "E6, Activity 2" and open it.

2.2.   Press the **Record** button. A <u>direct current</u> generated by the 0.080 V from the data interface box will be supplied to the smaller, primary coil. After 0.04 s (= 40 ms) the data interface will automatically stop recording data.

2.3.   On your data sheet, write the amplitude of the induced emf.

B. **In the second part of this activity, you will examine the induced emf produced by an alternating current (AC).**
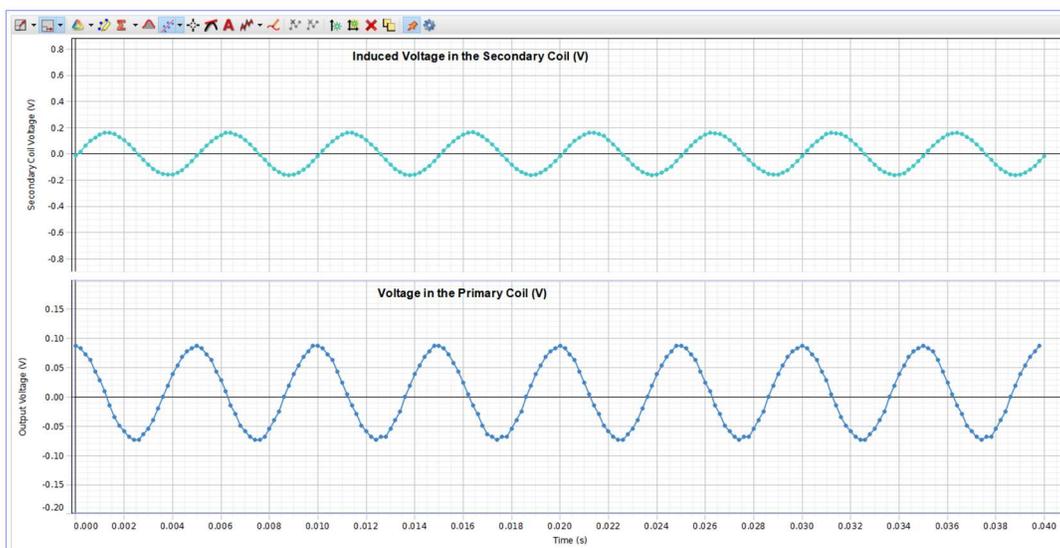
This is a similar situation as in steps 1.3 and 1.4 of the previous activity done with a moving permanent magnet. However, instead of moving the primary coil, we change the magnetic flux by applying AC voltage to the primary coil.

2.4.   First, you will need to switch the current flowing to the smaller, primary coil from DC to AC by selecting the "Sine Wave" waveform from the Signal Generator menu as shown below.

Set the Signal Generator to the "Sine Wave" AC mode with **the same amplitude (0.080 V) as we had for DC** - *Activity 2.2*). The frequency should be set to $f = 200$ Hz.

2.5.   Press the **Record** button.

Click on the "Induced Voltage in the Secondary Coil" graph and use the statistics tool

Σ▾ to find the maximum (=amplitude) induced voltage value $\mathcal{E}_{max}$. Click on the

"Coordinates" tool ✛ and select "Multi-Coordinates" option to <u>find period and frequency</u> of the induced voltage. What is this frequency relative to the frequency in the primary coil? Record results on the data sheet. **Print** a copy of this graph.

The "Multi-Coordinates" ✛ tool displays the voltage data for both primary and secondary coil as well as time coordinate for the selected data point.

C. In the final part of this activity, you will see what happens to the induced emf if the frequency of the alternating current is changed.

2.6.   First, you will need to change the frequency from 200 Hz to 100 Hz. Use arrows or type the value directly in the "Frequency" window and hit "Enter".

2.7.   Using the "Coordinates/delta" ✛ tool, <u>find the amplitude</u> of the induced emf and its <u>frequency</u>. What is this frequency of the induced voltage relative to the frequency in the primary coil?

2.8.   How does the change in frequency change the amplitude of the induced emf? *Hint*: how does the reduction of the frequency affect the Δt in the formula $\mathcal{E}(t) = -\dfrac{\Delta \Phi_B}{\Delta t}$?

2.9.   Change the frequency to $f = 400$ Hz in the primary coil. Record data. What is the maximum value of the induced emf in the secondary coil?

Activity 3: Transformers and Coils

In this activity, you will observe how *induction* can be used to transfer and modify AC voltages using electrical transformers. You will first need to put away the copper coils used in the previous activities and locate the two small, yellow (400 turn) coils (like those that were used in the magnetic field experiment - E5).
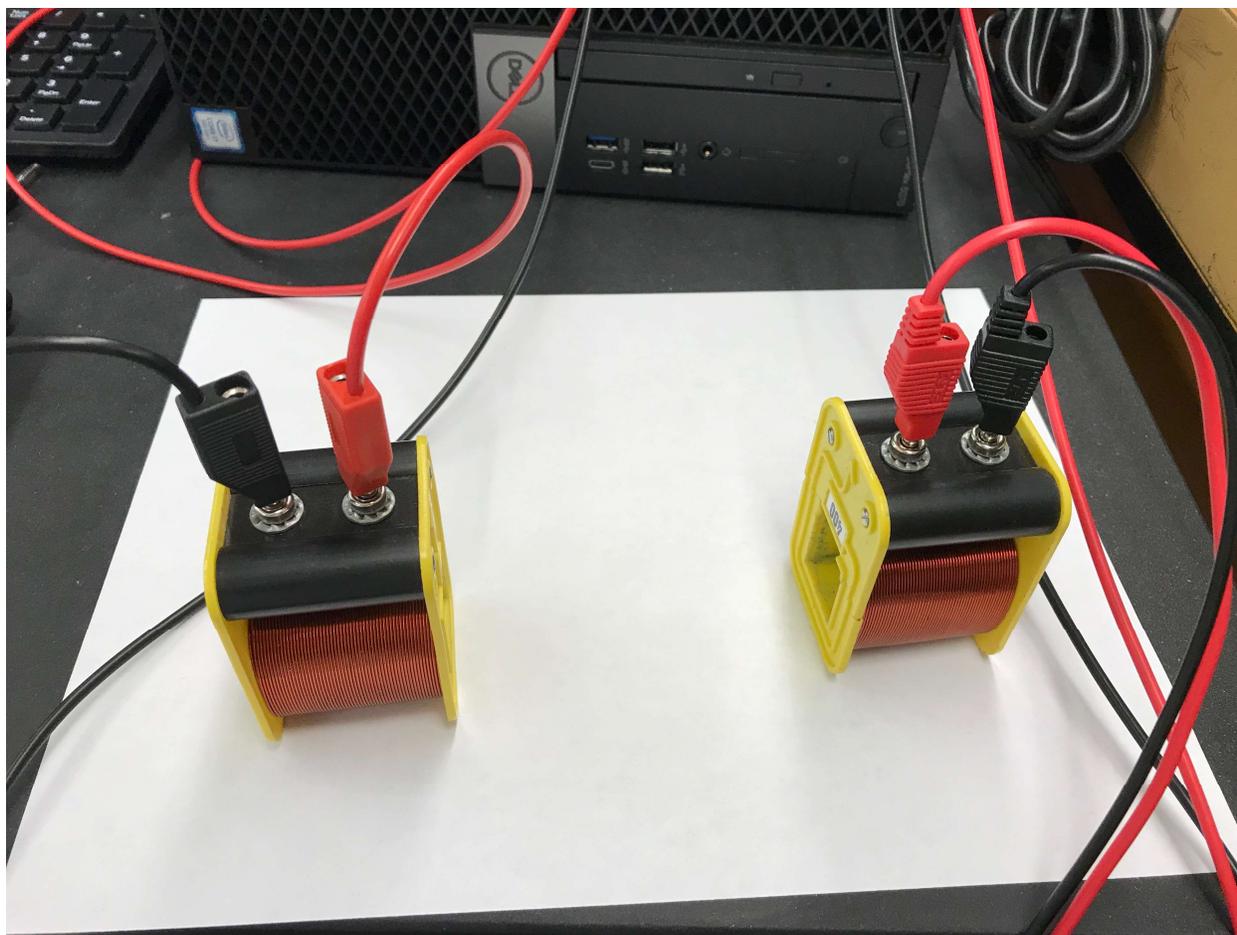
One coil (the primary coil or the #1 coil) should be attached to the current source "OUTPUT". The other coil (the secondary coil or the #2 coil) should be attached to the data interface Analog Channel A.
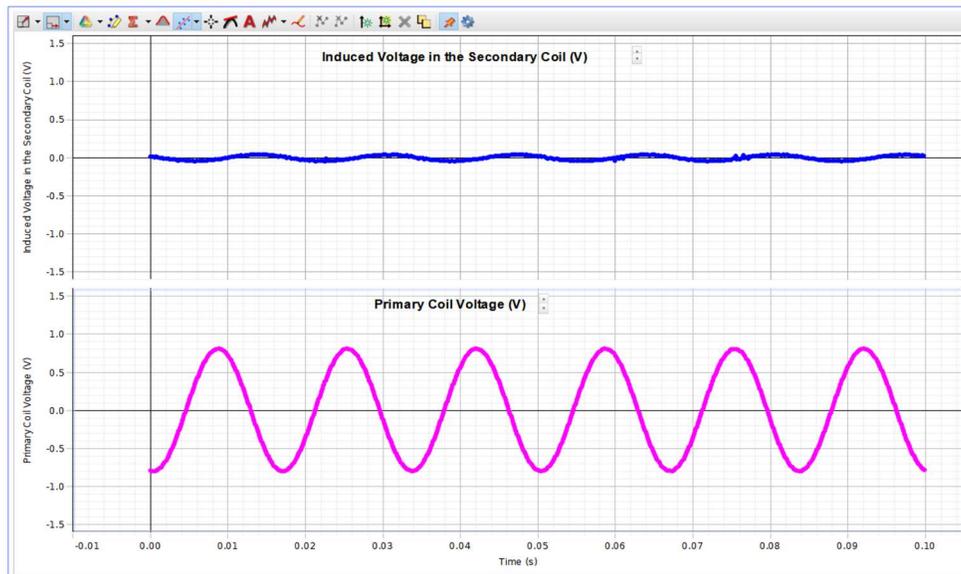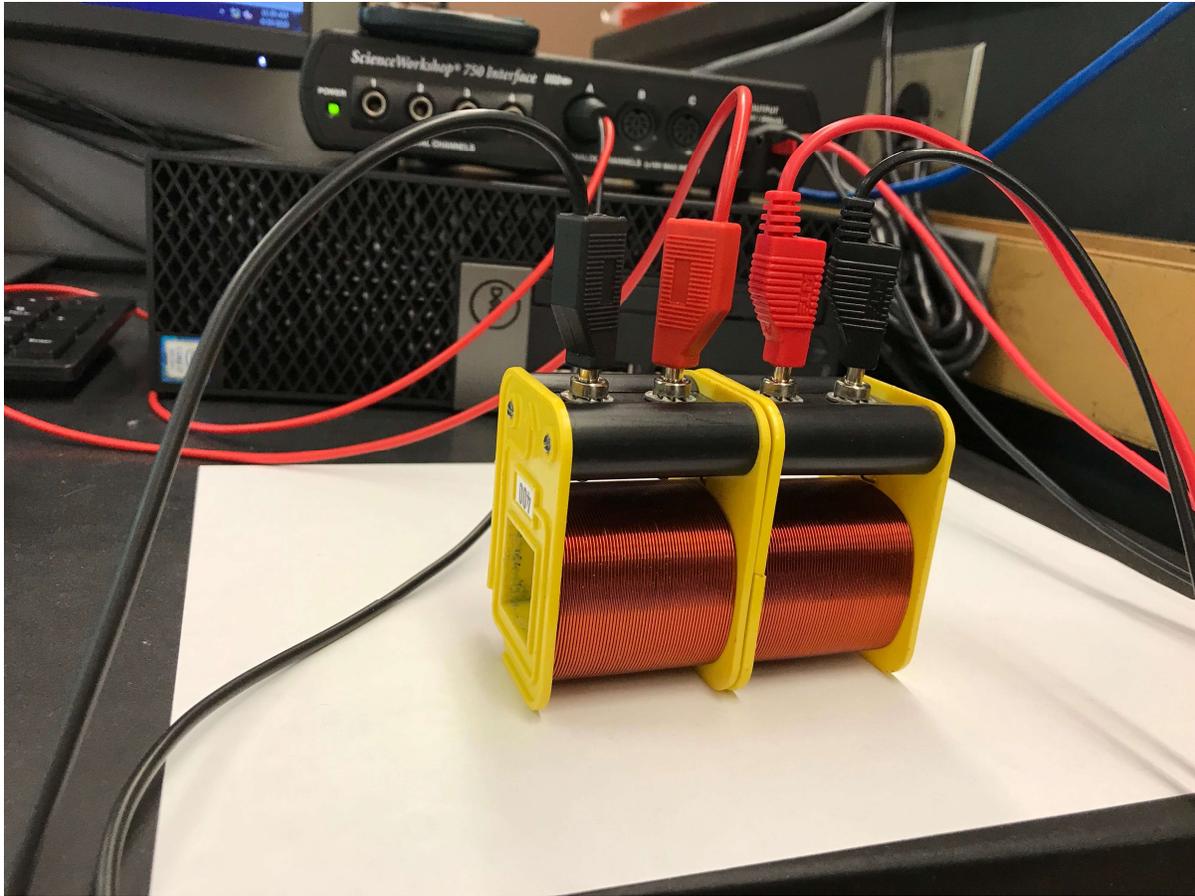

Secondary Coil - #2

Primary Coil - #1

You need to open the next activity configuration. Select: "E6, Activity 3" and open it.

A. Induced voltage vs. the distance between coils.

3.1.   Begin with the two coils aligned but separated from each other (about 10 cm).

3.2.   Press the **Record** button at the top left-hand side of the screen. This will automatically send a current flowing through the #1 coil and measure the induced emf in the #2 coil. The computer will acquire data only for about 0.10 sec.
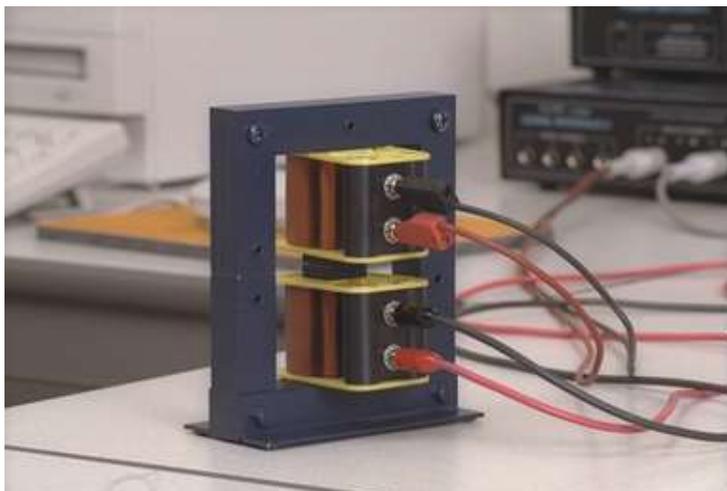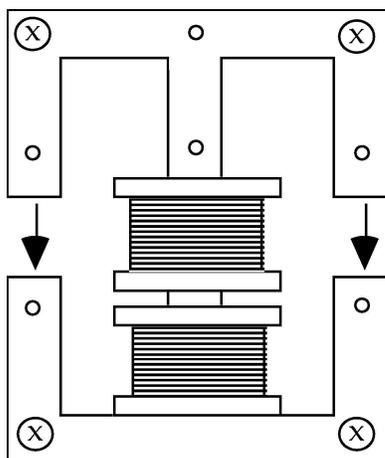
3.3.   Move the coils closer together and measure the emf again. What happened to the induced emf? Finally, get the coils as close as possible. How has the mutual inductance *M* of these two coils changed compared to 3.2? Check the *Theory* section of this file. Record your observations on the data sheet.

B. In the next part of this activity, you will see how the induced emf is enhanced using a ferromagnetic frame.

Leaving the two yellow coils attached to the computer interface, **gently** place them on the middle prong of the blue W-shaped magnetic steel frame. Then place the other blue bar on top to make a closed magnetic loop as shown below.

3.4.   Once the coils have been properly arranged press the **Record** button. Has the induced emf increased or decreased? (Record your observations and thoughts on the data sheet.)

C. In this activity, you will examine what happens to the induced emf if the numbers of turns are not the same in the #1 and #2 coils.

3.5.   First, exchange the #1 (the one connected to the OUTPUT terminals) 400-turn coil with the gray 800-turn coil. Keep the magnetic steel frame!

3.6.   Then press the **Record** button and collect your new data.
   • Is your new induced emf higher or lower than the previous (400/400) arrangement?
   • Is this a step-up or step-down transformer? Record your answers on the data sheet.

3.7.   Connect the coil #2 (400-turn coil) to the OUTPUT terminals and the coil #1 (800-turn coil) to the Analog Channel A (i.e., swap the cables). Again, keep the coils on the frame.

3.8.   Collect data for this new setup and record the new emf on the data sheet.
   • Is your new induced emf higher or lower than the 400/400 arrangement?
   • Is this a step-up or step-down transformer?

Complete the lab report and return it to the lab TA.

Make sure to complete the following tasks:

You must submit the answers to the prelaboratory questions online.   (3.5 points)

1. Two graphs from *Activities* 1 and 2.   (2 * 0.5 = 1 point)

   (Title and <u>write your name</u> and those of your partners on each graph.)

2. Your completed Data Sheets.   (5.5 points)

3. Return the completed lab report to your lab TA.