Electromagnetic Induction: Faraday's Law

OBJECTIVE: To understand how changing magnetic fields can produce electric currents. To examine Lenz's Law and the derivative form of Faraday's Law.

EQUIPMENT: Circular Coils apparatus, lab Mac’s sound card, FFTScope software, bar magnet, paper clip, cables, small (magnetic) compass, paper clip, multimeter w/long cable

INTRODUCTION: Have you ever wondered how the speaker or microphone in your corded or Bluetooth headset (or speaker) works? You may recall (perhaps in middle school or high school) that sound waves from your voice are converted to electricity by the microphone and that electricity is converted back to sound waves by the speaker, but how does that actually happen? Such inventions as the telephone, electric generators, electric guitar pickups, electrical transformers, car cruise controls, induction stoves and blood flow meters all exploit the fact that a changing magnetic field can give rise to an electrical current, a phenomenon we call **electromagnetic induction**. The mathematical law that relates the changing magnetic field to the induced current (or, more accurately, the induced voltage or *emf*) is called **Faraday's Law**, named after the man (among others) who first observed it in the laboratory around 1830.

You may recall from lecture that magnetic *flux* through a surface in a magnetic field **B** is

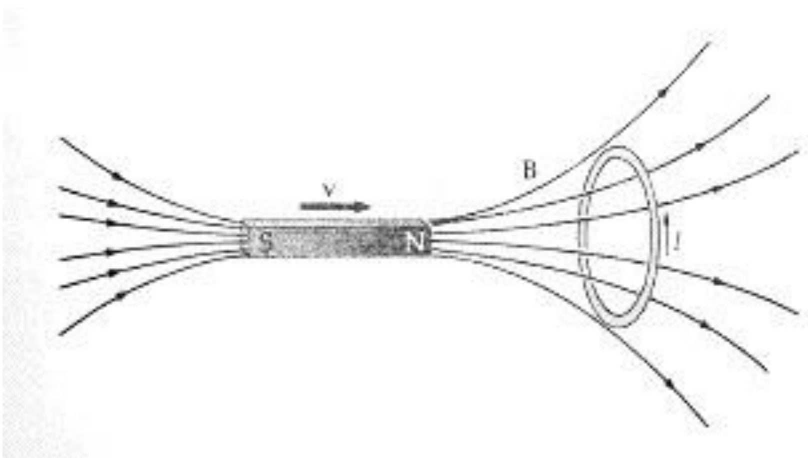
$$\Phi = \int \boldsymbol{B} \bullet \hat{n}\, dA$$

Where $\hat{n}$ is a unit vector perpendicular to area element dA

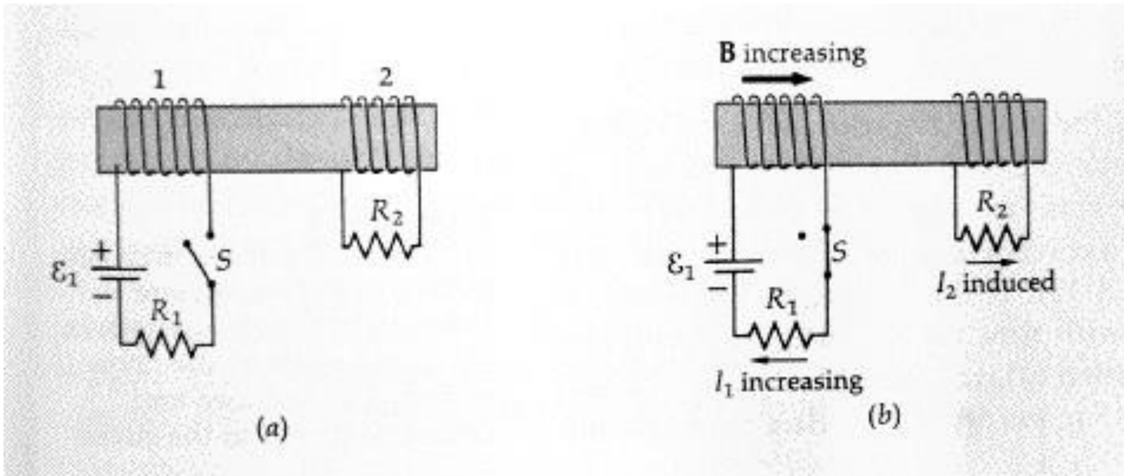
note that if $\boldsymbol{B}$ is constant anld the surface is a plane with area A, this reduces to

$$\Phi = BA\cos(\theta)$$

A conducting loop which has an ammeter attached to it will register a current if the magnetic flux through the loop changes in time. The change may arise from motion:



Or the change in flux may be due to the changing current in a circuit. In (a) below there is no induced emf in loop 2 but when the battery is connected, the increasing current in loop 1 produces a changing magnetic field and hence induces an emf in loop 2.



Faraday noted that the emf induced in a loop is proportional to the rate of change of magnetic flux though it:

$$\xi = -N\frac{d\phi}{dt}$$

where ξ is the **electromotive force** induced (measured in volts) and N is the number of turns of the coil. Provided each turn of the coil is sized and oriented like the others, its contribution is simply additive; hence the coefficient N in front of the flux derivative.

Notice the negative sign. **Lenz's Law** states that *the induced emf (and current) will be in a direction such that the induced magnetic field opposes the original magnetic flux change.* Keep in mind that the induced current will now produce an induced magnetic field. The direction of that magnetic field will be opposite to the direction the flux is changing:

APPARATUS:

Examine the apparatus. There are three sets of coils, two of which are fixed with respect to each other (wrapped in black tape) and which share the same number of turns and diameter. These two coils (total number of turns N=20) act in concert with each other, each producing a magnetic field in the same direction. These outer coils produce a fairly uniform magnetic field inside the apparatus – recall the Helmholtz Coils setup from the E&M Forces lab that generated a field that remained constant throughout the path of the electron beam.

The third inner coil (total number of turns N=11) is more rectangular than circular, smaller than the other two, and can be rotated with respect to them using the knob on the side of the apparatus. There are protractor markings around the knob to measure the angle between inner and outer coils. FFTScope software, which controls the PC's sound card, will act as a signal generator. It will be used to drive the outer coils with a periodic waveform that will produce a changing magnetic flux, inducing a current in the inner coil. You can also induce a current manually (signal generator off) by moving a small magnet close to the inner coil. In both cases, you will use FFTScope to examine the induced current in the inner coils.

PROCEDURE:

NOTE: DO NOT DISCONNECT OR CHANGE THE APPARATUS WIRING. PLEASE EXERCISE CARE WITH THE COIL APPARATUS-TURNING THE ANGLE KNOB TOO MUCH IN ONE DIRECTION MAY DAMAGE THE WIRES!

A. Induction by moving a constant magnetic field (40pts)

You will induce an emf in the small coil manually, *creating a changing flux* through the small coil by *moving* the magnet's magnetic field through it**.**

1. Examine the magnet on your table. One end of the magnet corresponds to magnetic North, the other to South. Draw a diagram of the magnet, sketching magnetic field lines. Determine North and South using the small compass provided, recalling that the compass needle is itself a magnet and that like poles repel (unlike poles attract). Remember that field lines represent lines of force; the more closely together the lines are drawn, the stronger the magnetic force is at that point. Draw your diagram in the lab report – or photograph it for inclusion into the lab report, and also indicate the direction of all the field lines with arrows. (10 pts)

2. Rotate the knob on the side of the apparatus so that the angle marker is set to 0 or 180 degrees. This should orient the plane of the inner coil horizontally - parallel to the table surface.

3. First make sure the volume level on your computer (see right side of menu bar) is set to ½ of maximum) and that your external PC speakers are on (knob turned clockwise, green light on). Open FFTScope, which is in the Lab Apps folder on the Desktop. Now it's time to turn on data collection - near the bottom of the app window, select the "Oscilloscope: Left" option to measure the induced voltage/current (input), then click on the "Data Acquisition On/Off" box to its right – this turns on data acquisition. You

should now see the horizontal graph axis, as well as upper and lower numerical limits for the vertical axis. There will also be a red trace almost superimposed over the horizontal axis – this is the response trace (curve) of the inner coils, which is the induced signal, close to zero millivolts (mV):

4. Press the Y-Autoscale button near the top. You have shrunk the vertical scale, magnifying the signal. The trace now comes to life; what you are seeing is noise. Press the “3X Zoom out” button to expand the vertical scale, which gives your graph room to display a real signal that you are about to induce using the small magnet. Note the time Sampling Window on the lower right is set to 10ms – a very small time interval. First, stop collecting data (unclick the aforementioned box) and increase this value to around 300ms (it may change slightly from that upon entering the value), so that you can have enough horizontal room in the plot to see the width of the signal you are about to induce. Resume taking data by selecting “Oscilloscope: Left” and zoom/rescale as needed.

5. Pick up the small magnet by the sides and hold it such that it's oriented vertically (standing up). Now position it right above the inner coil of the apparatus, without touching. Pull the magnet quickly upwards, while watching the trace on the FFTScope screen. If the pulse appears to be too large for the graph window, try Autoscaling *while*

moving the magnet to include the pulse. You can also freeze the trace of the pulse by pressing the Spacebar on the keyboard – this will enable you to examine it in detail.

Why doesn't the response waveform look "perfect"? There may be a significant distortion of the waveform due to the **capacitance** of the sound card in the Mac you are using; you may have learned from lecture, or the previous lab, that capacitance is a restorative force analogous to a spring in Mechanics. This accounts for the "reflection" pulse/peak (opposite in sign to the true, initial pulse – the left side of the waveform) that you will see. **Always note the orientation of the true pulse - which is the *leading* (leftmost) pulse/peak**.

Does the emf pulse trace go up or down? (5 pts)

6. Flip the magnet over such that the side you previously had up is now down. If you repeated Step 5, which way would expect the pulse to move - up or down? Discuss this with your lab partner before proceeding.

Repeat Step 5. Which way did the pulse actually go, up or down ? (5 pts)

7. Keeping the same magnet orientation in the previous step, try rotating the inner coil 180 degrees and again pulling the magnet upwards from it. Which way does the pulse move now, up or down? (5 pts)

8. Try to get a rough estimate of emf pulse height by freezing the trace (with the Spacebar), clicking on the plot (you may have to click twice) and position your cursor on the peak of the pulse, noting the Left Input reading (in mV; along the Y-axis); do the same with the baseline directly under the pulse (which may be slightly lower than the

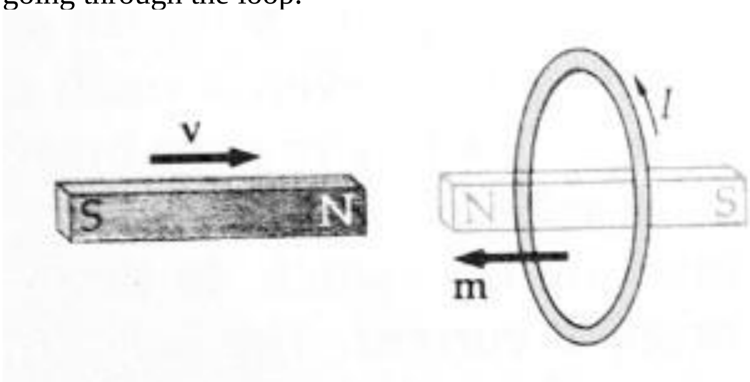
X-axis) and note that Left Input reading (in mV). The difference between the two reading will be the pulse height. What was the maximum pulse height that you could momentarily generate on the inner coil? (5 pts)

9. Now orient the inner coil such that its plane is vertical, i.e. 90 degrees with respect to the table surface, and also with respect to the plane of the outer coils. Pull the magnet away from the coil again.

What was the maximum pulse height that you could momentarily generate on the inner coil? (5 pts)

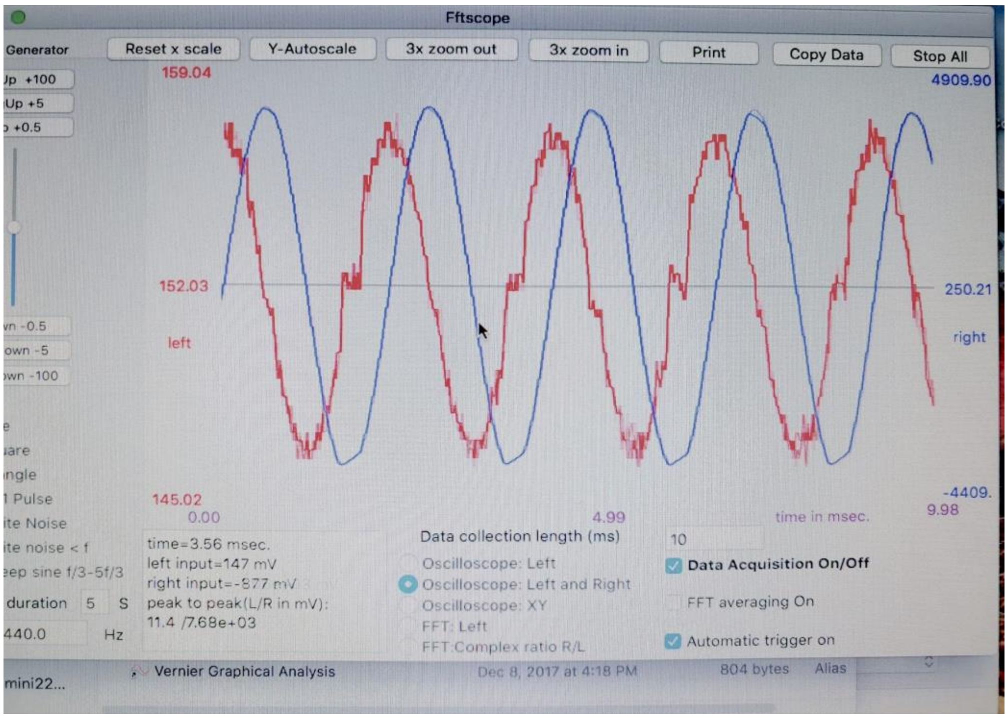
If you moved the magnet the same way you did before, why is this pulse height different? (5 pts)

In this section we have physically moved a magnet around a coil, inducing a current in it. In order to do this we have performed **work** on the magnet because we had to oppose a force to keep the magnet moving, even at constant velocity. What is the source of this force? According to Lenz's Law, the induced current produces an induced magnetic field, which is represented by a **magnetic moment** (denoted by **m** on the diagram below, which **opposes** the motion of the magnet. This magnetic moment can be thought of as "virtual magnet" whose poles either oppose or attract the real magnet, depending on the direction of motion. In either case, the direction of induced current can be identified using your right hand: point your extended thumb in the North direction of the magnetic moment; your fingers will curl in the direction the current is going through the loop.



Doing work on a magnet to create a current is the basis behind an **electrical generator.** In hydroelectric dams, falling water turns large paddles connected to electrical generators that convert mechanical energy to electrical energy. Conversely, we can use changing flux to **do** work. This is the principle behind an electric motor.

B. Induction by varying a magnetic field (35pts)



You will now induce an emf in the smaller coil using a changing magnetic field supplied by the outer coils. There will be no motion of the coils involved. The signal generator will provide the outer coils with a fluctuating current to vary the magnetic field, and hence the magnetic flux, through the inner coils. The fluctuating current will be sinusoidal, triangular or square in waveform shape.

0. Look at the back of the Mac Mini on your lab desk; it's the computer that resembles a somewhat flat, square box in Aluminum or white – see if there is small silver/black box connected to it (via USB port), which would in turn be connected to your speakers (with green & orange connectors). If there is no small box, you can proceed to Step 1 below.

If there is a small box (an external sound card), unplug the silver USB cable that connects it to the Mac Mini and plug it back in. This will ensure that audio connection that is sometimes interrupted by the computer's sleep is restore.

1. Predict what the response waveforms will look like for two of the following three (your instructor will demo one of them before you do your experiment): sine, triangle and square driving waves. Think of the mathematical relationship between magnetic flux (driving signal) and induced emf (response signal). Draw predicted waveforms – or photograph your drawings with your smartphone - for inclusion in your lab report. (5 pts – **you will only be graded for attempting to draw the predicted waveforms, not their correctness**)

2. Look at the left side (Signal Generator) of the FFTScope window; it should be set to Off. **Change it to Sine and select 1000Hz as the Frequency**. Select the Automatic Trigger On option at the bottom; this will track the waveform and keep it from "travelling". Click on "Oscilloscope: Left and Right" at the bottom of the window to simultaneously view both driving waveform (blue) and induced waveform (red). Autoscale if necessary to see the entire wave height. Click and drag a rectangle across a portion of the graph – this will "zoom in" on the waveforms, making them appear less compressed in the horizontal direction. You may have to Autoscale again after this. If you zoomed in too much, you can press the Reset X Scale button in the toolbar. **Remember that you can always "freeze" the scope waveforms for closer inspection by pressing the Spacebar.**

3. Switch to the other waveforms – triangle, square. Quickly check that the frequency and amplitude (driving signal only) remain the same as you toggle between them; only the shape changes. **If you are seeing a noisy signal when you Autoscale, turn up the volume knob on the PC speakers; however, if you are getting flat-topped driving waveforms, you are overloading the sound card input - turn down the volume knob.**

4. Sketch the observed induced response for the sine, square and triangular waveforms on your lab report – or sketch them on papers, photograph and include in your report. (3 x 5pts = 15pts total)

5. Examine the graphs you just drew. What is the general relationship between the driving and induced waveforms? Think of the mathematical relationship between magnetic flux and the emf and note that spikes in the graph represent a very rapid rate of change. Remember that the derivative of a function is very similar to the slope. (5 pts)

6. Let us now check how magnetic flux through the smaller coil changes as we rotate it within the fairly uniform field of the outer coils. Make sure Sine is selected in the Signal Generator on the left. Increase the frequency to between 1000-2000 Hz by entering this value in the lower-left corner of the FFTScope window; this will provide more sensitivity in the measurement of the response amplitude. Don't worry about the stability of the scope trace; we are only interested in examining the amplitude as a function of angle.

Start off with an inner coil angle of 0 degrees (coil plane parallel to table). Select Oscilloscope: Left, since we are only examining the response trace. Vary the relative angle between inner and outer coils from 0^0 to 180^0 in 15^0 steps, each time recording the peak-to-peak amplitude (the Peak-to-Peak (mv) Left value) a few seconds after changing the angle to give it time to settle down. *There is no need to pause the data collection as you will just be turning the knob and noting the Peak-toPeak value.* Record all your your data in your lab report, and also your plot it, with title and labels (using Google Sheets or Microsoft Excel or Logger Pro). **There is no need to curve-fit the data**. (10 pts)

C. Check of Lenz's Law (25 pts)

In part A it was not possible to predict the direction of the induced voltage (induced pulse on FFTScope) even if the direction and motion of the magnet's field was known, simply because they way the coil was wound and how it connected to the positive and negative voltmeter (the sound card in the computer) was not visible. You will now wind a cable, connect it to a ammeter (multimeter), and predict the direction of the induced current in your homemade coil when a bar magnet is pulled. You should then perform the experiment and check the result against your prediction.

1. If it's not already connected, connect the long banana-to-banana cable to the multimeter; one end plugged into the COM (ground) terminal, the other into the mA terminal. Set the selector dial to µA (micro amps).

2. Practice winding the cable around two or three of your fingers (as shown below); you should be able to get several turns (N in the Faraday's Law equation.) out of its length.

3. Make the prediction: if you partially inserted the bar magnet into the coil (knowing which end was N and which was S), and pulled it out quickly, what would be the direction of the induced current in the coil? **Note this convention – if the current enters the ammeter through the left (μA) terminal, the display reads positive (no negative symbol); if the current enters the current through the right (COM) terminal, the display reads negative.** If you need help in getting started, refer to the diagrams and explanations at the bottom of Page 2 and also at the bottom of Page 7 of this write-up (both showing the direction of the induced current when a magnet moves through a coile), but remember that what is taking place in the diagram may not the exact same situation as what you are about to do (check to see if your movement is increasing or decreasing your magnetic flux through the coil).

You may find these links useful:
https://www.pasco.com/products/guides/right-hand-rule (an explanation of the right-hand rule pertaining to a solenoid – which you essential are building – if you've not yet encountered it in lecture)

https://phet.colorado.edu/sims/html/faradays-law/latest/faradays-law_en.html (a PhET simulation of magnet through solenoid connected to both bulb and galvanometer, indicating direction of current; tic both the Voltmeter and the Field Lines boxes to help you see the direction of current flow, as well as the E-field lines).

	
Partially insert magnet into coil	Pull magnet out of the coil quickly

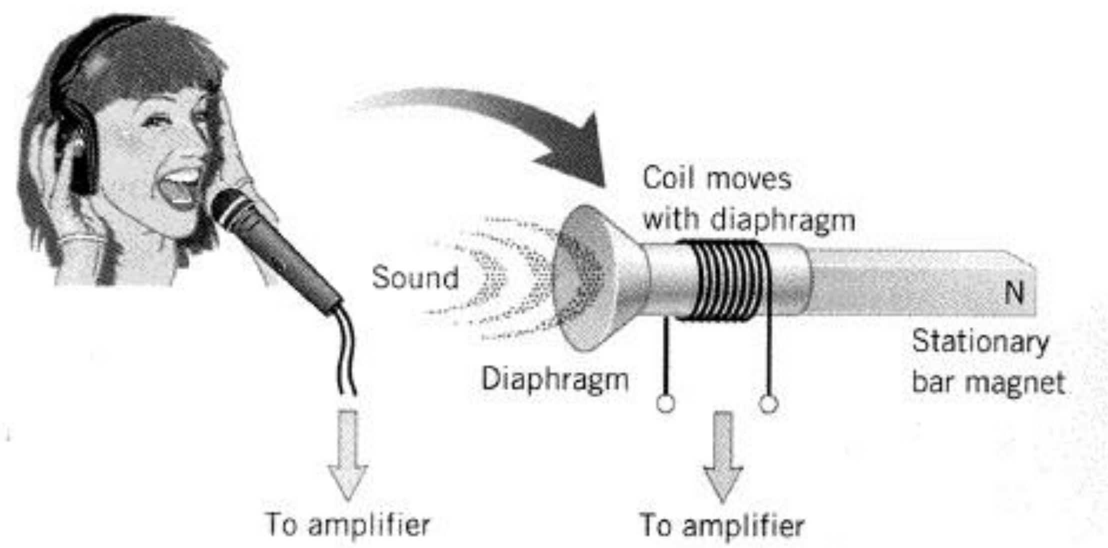
4. Do the experiment: holding your coil steady, take the bar magnet and partially insert it into the coil. Pull it out of the coil quickly, as you did in Part A, and note the reading – particularly the sign on the left side of the multimeter display. This will tell you the direction of the current in the coil. It will be tricky inducing a non-zero reading on the multimeter – too slow of a pull yields zero current; too fast also yields zero current (because it is not sampled continuously). Several tries will give you a direction of I.

5. Compare your prediction to your result, explaining everything in detail in the hand-in sheet - this means you will have to draw and include an illustration of the your

wound coil and magnet, indicating the direction of the magnet's B-field and the also the direction of the induced current. (25 pts)

Real-life Applications

Faraday's Law is the basic principle behind the simple telephone. In a microphone there is a diaphragm, around which a coil is wrapped, which can move back and forth in response to sound waves. A stationary bar magnet, placed near the coil, induces current in the coil which can then be transmitted (with amplification) to the speaker of another telephone. Conversely, when the current reaches the speaker, which consists of another coil/diaphragm/magnet combination, the varying coil current causes the diaphragm to move and displace sound waves:



Another direct application of Faraday's Law is a transformer. If the two sets of coils 1 and 2 similar to what you just used were of the same size, we can either increase or decrease voltage by varying the number of turns according to this equation:

$$V_2 = -\frac{N_2}{N_1} V_1$$

High-voltage transformers are used in conveying electricity from your electrical company to your home. Since power loss on the lines is equal to I^2R, it makes sense to use a high voltage and low current when transporting power over great distances.. Conversely, for safety reasons, low voltage and higher current is used in the home.