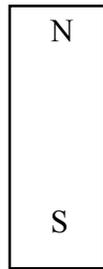


H-Faraday's Law – Warm Up

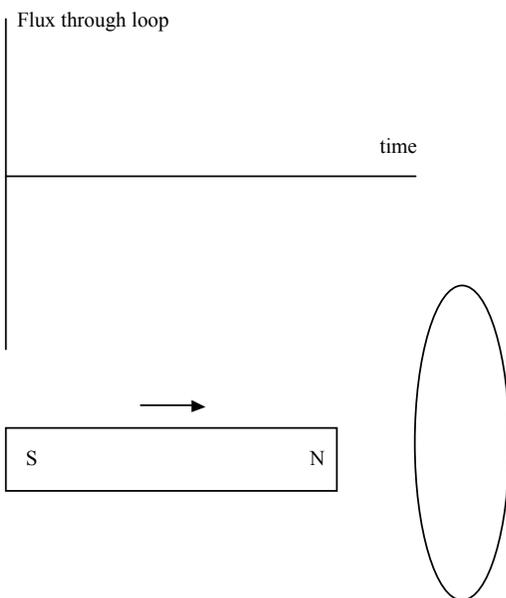
1. Field lines of a permanent magnet

For the permanent magnet in the diagram below draw several magnetic field lines (or a magnetic vector field if you prefer) corresponding to the magnetic field. Be sure to use arrows to indicate the direction of the field.



2. Changing flux

A long permanent magnet moves through a circular wire at constant velocity. If field lines going to the right through the loop correspond to positive flux, sketch the flux through the wire as a function of time. Consider times from the position shown until the magnet has passed all the way through and is well to the right of the loop.



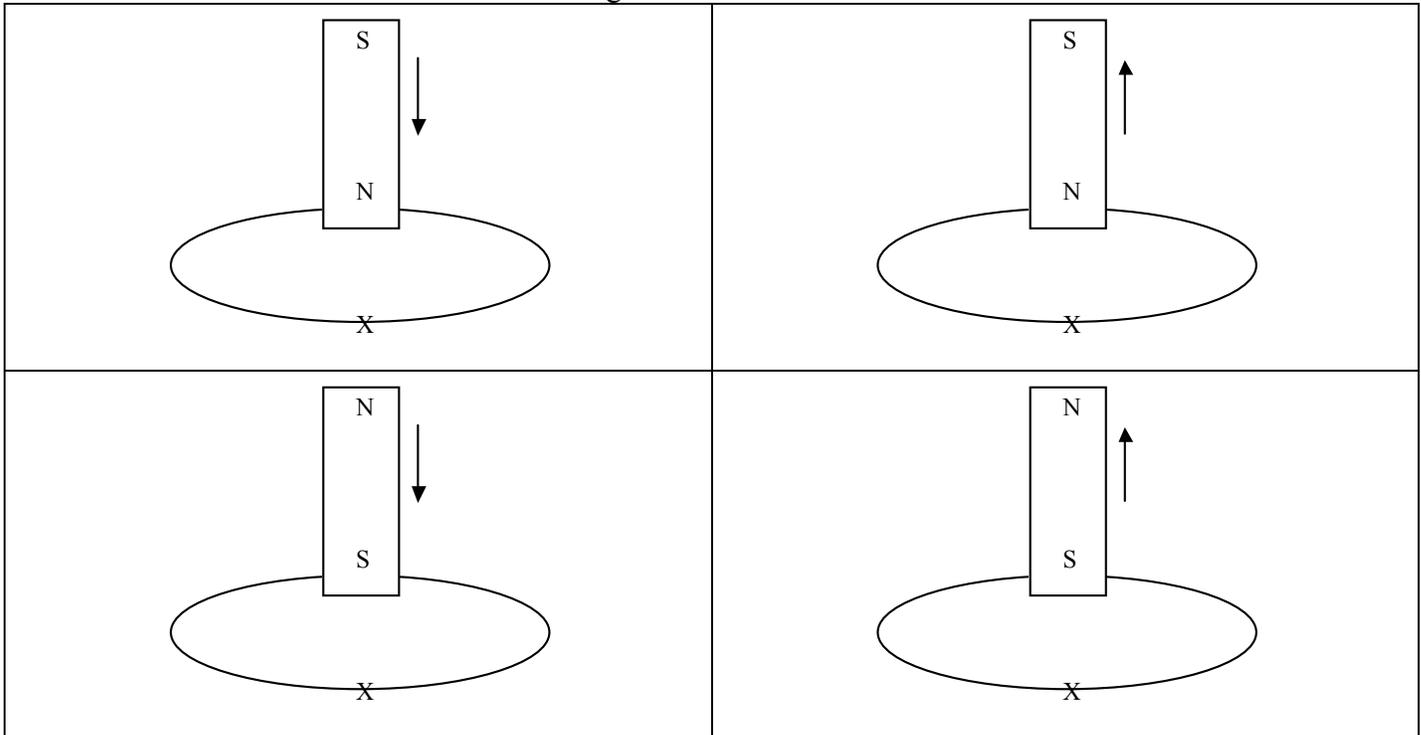
How would your graph change if the magnet were twice as strong?

How would it change if the loop had half the area?

3. Direction of the induced current

A permanent bar magnet is pushed or pulled towards or away from a circular wire. Using Faraday's law and Lenz's law determine the direction of the current in the wire.

- Draw the direction of the current on the segment of the wire marked with an "X".



H-Faraday's Law

GOAL.

- To measure the induced emf for various changing flux situations.
- To understand how transformers work.

EQUIPMENT.

- Large coil (3400 turns)
- 2 smaller coils (fine wire, thick wire)
- Permanent bar magnet ("cow" magnet)
- Differential voltage probe
- LoggerPro software
- LabPro computer interface
- **FARADAY.cmb1** and **FARADAY_AC.cmb1** experiment files

INTRODUCTION. The goal of this laboratory is to better understand Faraday's Law by performing a series of activities. The details of Faraday's law and Lenz' law are covered in your text. Mathematically, Faraday's law relates the induced emf to the rate of change of the magnetic flux through a circuit,

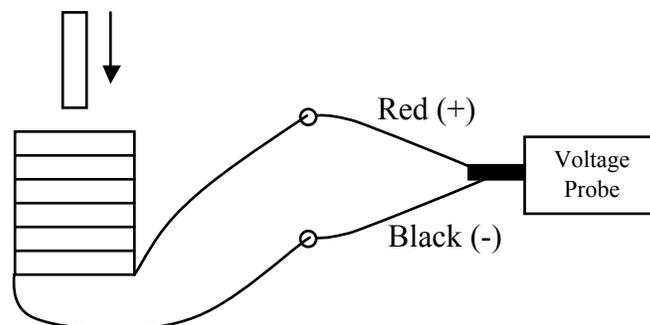
$$\varepsilon = -\frac{d\Phi_m}{dt} = -\frac{d}{dt}(\vec{B} \cdot \vec{A}) \quad \text{Eqn. 1}$$

where ε is the induced emf, Φ_m is the magnetic flux, \vec{B} is the magnetic field and \vec{A} is area of the planar loop. Basically, it says that a changing magnetic flux in a circuit induces an emf (voltage). Lenz's Law gives the direction or polarity of that voltage and corresponds to the minus sign in Eqn. 1.

WARNING: Do not bring the magnet near the computer screen.

ACTIVITY 1. Moving magnet in a coil.

In a direct and simple way you will change the magnetic flux inside a coil of wire and observe the induced voltage. Your apparatus consists of a large coil, a bar magnet, and a computer with appropriate probes and software. The latter will be used to detect induced voltages in the coil as the magnet is moved near the coil.



Estimate. Before making measurements, let's *estimate* a typical induced voltage. (We want to know whether to expect 20 mV or 20 kV or something in between.)

What is the flux through the loop when the magnet is "far" from the coil? $\Phi_{\text{far}} =$ _____

When the magnet is "in" the coil, the flux through a typical loop is the product of the average magnetic field strength, B_{ave} , times the loop area A .

Measure the area of a typical loop of the coil. $A =$ _____

Measure the maximum magnetic field at the end of your magnet B using the "gauss meter" on the front desk of the lab room, $B_{\text{max}} =$ _____. Note: 10^4 gauss = 1 Tesla

Of course, what is needed is the field strength averaged over the volume of the large coil. An appropriate average value for a typical magnet is one tenth of the maximum value. $B_{ave} = B_{max}/10 =$ _____.

With the magnet in the coil calculate the flux through a single coil, $\Phi_m^1 = B_{ave} A =$ _____.

Estimate the magnetic flux through all N coils, $\Phi_m^{tot} = N\Phi_m^1 =$ _____.

Find the total change in flux, $\Delta\Phi_m^{tot} = \Phi_m^{tot} - \Phi_{far} =$ _____.

Estimate how long it will take to push or pull the magnet into or out of the coil, $\Delta t =$ _____.

If the magnet is pushed in or pulled out of the coil in time Δt , then the average induced emf will be the change in the flux divided by the time. Calculate the expected induced voltage (emf): $\varepsilon = \frac{\Delta\Phi_m^{tot}}{\Delta t} =$ _____.

Measure. Now make measurements by connecting the voltage probe to the coil and opening FARADAY.cmbl. Start collecting, then move the North pole of the magnet straight down into the middle of your coil, observe the induced voltage, and compare its average value to the estimate you made above. Save this data using "Experiment/Store latest run" and repeat the experiment with the South pole of the magnet going in first. Was the induced voltage the same or different?

Make a chart that indicates the sign and magnitude of the induced voltage for the following situations:
(Note: These correspond to the pictures in the warm-up exercises.)

- North pole put into the middle of the coil at medium speed.
- North pole removed from the middle of the coil at medium speed.
- South pole put into the middle of the coil at medium speed.
- South pole removed from the middle of the coil at medium speed.

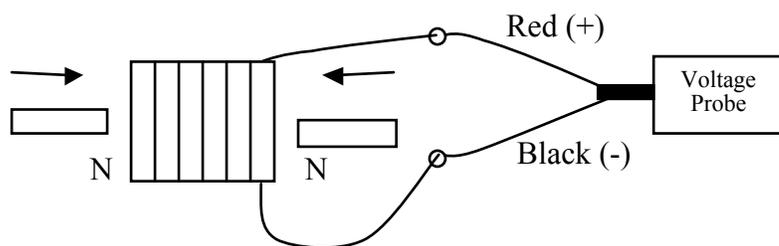
Faraday's Law contains the word "changing." You observed induced voltages when the magnet was moved into or out of the coil. Let's see what happens if there is no change.

Hold the magnet at rest near the center of the coil. Now start collecting data, wait about one second and then rapidly pull the magnet out.

Print this out and label the regions of the plot corresponding to "no motion" and "motion."

ACTIVITY 2. Moving magnet from opposite side.

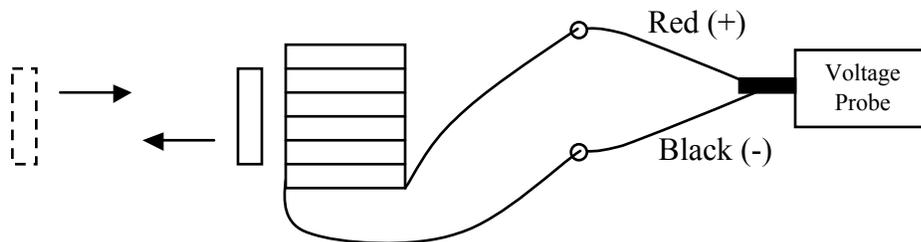
Now lay the coil on its side and move the north pole of your magnet into the coil from the left side. Then do the same thing from the right side. Observe whether the induced voltage is the same or not in the two cases.



ACTIVITY 3. Moving a magnet near a coil.

You don't need to actually insert the magnet into the coil to change the magnetic flux in the circuit. You just need to change the magnetic field inside the loops.

Lay the coil flat again, its axis vertical. Hold the magnet with its axis vertical a meter or so to the left or



right of the coil and at the same height as the coil. Bring the magnet from far away to just next to the coil, parallel to the coil axis, just against the outside of the coil. Do it quickly and look for an induced voltage. (You may need to zoom in on the voltage axis.) Now quickly move it away, back to where it started. Describe the induced voltages. Are the results similar to any of the previous experiments?

**** NOTE: For Activities 4-9 below use a cow magnet. ****

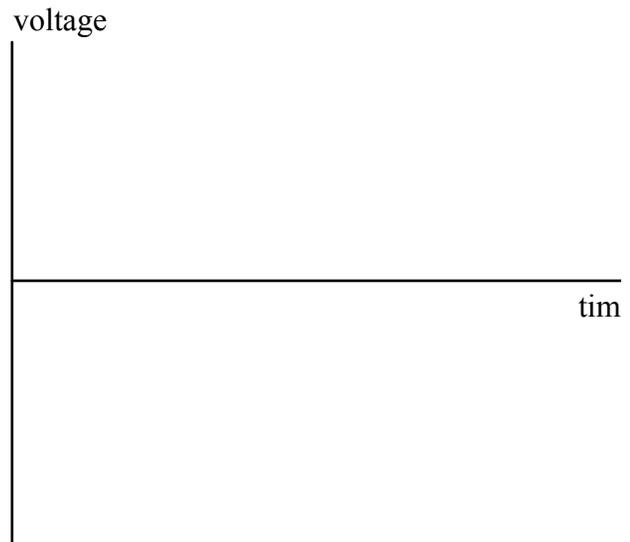
ACTIVITY 4. Moving the coil.

Up until now we have been moving the magnet and leaving the large coil stationary. It is the relative motion of the magnet and coil that produces the induced voltages. Hold the magnet still and move the coil toward the magnet. (Be careful the coil is heavy.) The effect should be qualitatively the same as seen earlier; is it?

ACTIVITY 5. Magnet falling all the way through the coil.

Consider what the display might show if a bar magnet, say with N pole downward, were dropped all the way down through the coil. From the observations performed earlier you know the voltage pattern as the magnet enters or leaves the coil. Now think about the voltage pattern as the magnet passes completely through the coil. Predict the shape of the emf vs. t on the axes.

Try the actual drop. (Please do it carefully, using the foam-lined “catcher”.) Observe what the voltage looks like and explain why.



ACTIVITY 6. Faster moving magnet.

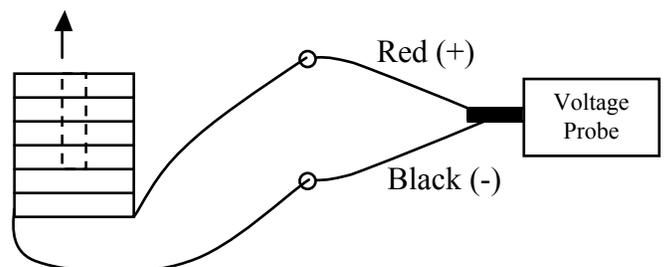
Now hold the bottom of the magnet about 1 cm above the top of the coil with magnet and coil axes aligned. Start collecting data and drop the magnet all the way through. Get a trace and *store this data*. Predict what will happen to the size and shape of the display if the magnet were moving with greater speed. Now drop it from about 5 cm above the top of the coil and see whether your prediction was correct.

ACTIVITY 7. Details of a single pulse.

Now extend this discussion of speed to the two “halves” of a single pulse. The “first half” of the pulse that you see is due to the field entering the coil, and the “second half” is caused by the field leaving it. Consider a drop from above the coil. The magnet is moving slower when it enters the coil than when it leaves. So the pulse shape of the first half of the pulse should be a bit different from the shape of the second half. Do the actual drop. Look for that effect. Sketch the shape and describe the difference between its “two sides.” You may have to do this several times, perhaps from different heights, to refine your experimental technique and your observing skills before you see the clear effect.

ACTIVITY 8. Total change in flux.

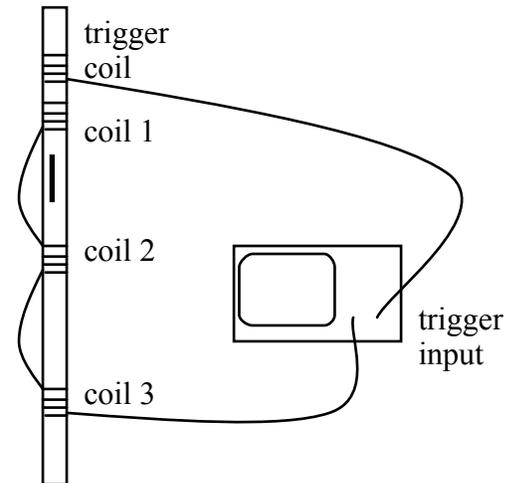
The field is a property of a magnet. Let’s integrate the emf. $\int (emf) dt = \int_{t_1}^{t_2} \frac{d\Phi}{dt} dt = \Delta\Phi$. Note that the change in flux for a given motion is independent of how fast the flux changes, it is a property of the magnet and the difference in the two positions. This



means you should have the same change in flux no matter how fast it happens. Let's test this. Hold the magnet at rest near the center of your coil then quickly pull it out. *Store this data.* Now return the magnet to the *same starting position* and then remove it slowly. Use the mouse to select a region that includes all of both pulses, then click the integrate button to find the "area" under the curves. What are your two "areas"? Are they essentially in agreement? Explain why this is so.

ACTIVITY 9. Magnet through multiple coils.

Near the front of the lab room is a "storage scope" which can save a single voltage vs. time trace on the screen. The setup consists of a "tower" of four coils stacked vertically, all connected to the scope. The top coil is used as a "trigger" to start the sweep. You will drop a magnet down a hollow tube which forms the axis of the coils. It will then pass through each of the three coils. Sketch your predicted voltage versus time curve. There will be more than one pulse. Why? What do you expect the relative amplitudes of the pulses and their spacing in time to be? Once you have your prediction, have your instructor (or someone who has worked the storage scope already) help you with the button pushing. (Once you are comfortable with the workings of this scope, you might help someone else.) Did the experiment verify your prediction?



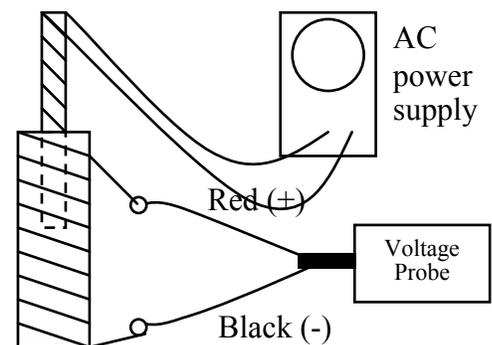
ACTIVITY 10. Electromagnet.

You know from the book and/or lecture that current in a solenoid (long coil of wire) produces a magnetic field similar to that of a bar magnet. Connect the thin solenoid to the DC power supply and keep the current less than 2 Amps. Physically move the solenoid into and out of the medium coil and observe. You should see behavior that is qualitatively similar to your observations in the activity using the bar magnet. You may need to use a very sensitive scale on the display. Did you see this effect?

It is possible to produce a significantly larger magnetic field within a solenoid if there is an iron core or rod inserted into the solenoid along its axis. Now repeat this with the iron rod inserted. You are looking for qualitatively similar behavior to what you observed before, but this time the effect should be much stronger. Did you see this effect? By about what factor did the induced voltage increase?

ACTIVITY 11. Transformer.

Now do the thin solenoid experiment without any mechanical motion. We will make a primitive transformer. Attach the thin solenoid to an AC power supply (ACV < 1 V) and place it inside the medium coil. The changing flux is now due to the changing direction of the current through the solenoid, which changes the direction of the magnetic field. The AC power supply should be set to a frequency of 60 Hz; so you will need to use **FARADAY_AC.cmb1** for this part. Set up the transformer, collect data and look for an induced alternating voltage in your coil. Did your transformer work? Once you see an induced voltage, lift your solenoid partly out of the coil, what happens? Can you increase the induced voltage by inserting the iron core?



ACTIVITY 12. Demonstration transformer.

On a side table there is an analog oscilloscope attached to a demonstration transformer. You should look at the apparatus and verify that it gives the same effect that you saw in Activity 11. In addition, both the input and output voltages are displayed and you should observe how the output voltage can be controlled by the ratio of the numbers of turns in the two coils of the transformer. Using the following equation,

$$V_{out} = \frac{N_{out}}{N_{in}} V_{in}$$

complete the following steps using a separate sheet of paper to show *all* of your measurements and calculations:

- Use the scope to measure V_{in}
- Calculate what V_{out} should be
- Use the scope to measure V_{out}
- Calculate the percent difference
- repeat for *at least* one other combination of input and output coil packs.

Why is there a difference between your calculated and measured V_{out} numbers? Explain.

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