NAME PERIOD DATE

12. ELECTROMAGNETIC INDUCTION

STRUCTURED

Driving Question | Objective

How is the average emf induced in a wire coil affected by the rate at which magnetic flux through the coil changes? Investigate how the rate of change of magnetic flux through a coil affects the magnitude and polarity of the average emf induced in it, and then determine a mathematical relationship between the two.

Materials and Equipment

- Data collection system
- PASCO Induction Wand[1]
- PASCO Rotary Motion Sensor[2]
- PASCO Variable Gap Magnet[3]
- PASCO Voltage–Current Sensor[4]
- PASCO 2-Axis Magnetic Field Sensor[5]
- PASCO Sensor Extension Cable[5]
- Table clamp or large base
- Support rod, 45-cm
- Right angle clamp
- Additional rod

[1]www.pasco.com/ap02
PASCO Induction Wand

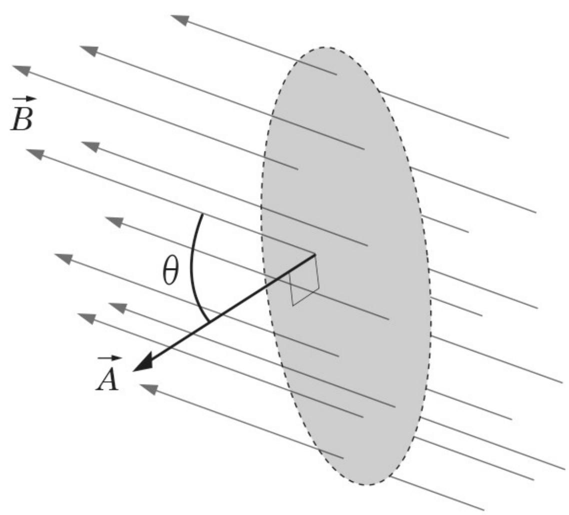
[2]www.pasco.com/ap20
PASCO Rotary Motion Sensor

[3]www.pasco.com/ap03
PASCO Variable Gap Magnet

[4]www.pasco.com/ap19
PASCO Voltage–Current Sensor

[5]www.pasco.com/ap35
PASCO 2-Axis Magnetic Field Sensor

Background



Magnetic flux Φ_B is a measure of the amount of magnetic field that passes through a given surface area. It is often referred to as a measure of relative magnetic field strength and can be demonstrated in a diagram as the density of magnetic field lines that pass through a given surface area.

If a uniform magnetic field $\vec{B}$ passes through a flat uniform surface, the equation for magnetic flux can be written:

$$\Phi_B = \vec{B} \cdot \vec{A}$$

$$\Phi_B = \left|\vec{B}\right| \cos\theta \left|\vec{A}\right| \qquad (1)$$

where $\vec{B}$ is the vector representing the magnitude and direction of the magnetic field at the surface, $\vec{A}$ is the normal vector to the surface with area A through which the magnetic field passes, and θ is the angle between the two vectors. For magnetic field lines that pass perpendicularly through the surface, Equation 1 can be simplified to:

$$\Phi_B = BA \qquad (2)$$

When the magnetic flux through a coil of wire changes ($\Delta\Phi_B$), an electromotive force (emf) is induced within the coil. This emf, in turn, generates current flow in the wire and a measureable emf voltage $\mathcal{E}$.

In this lab activity, you will explore how varying the rate of magnetic flux change $\Delta\Phi_B/\Delta t$ through a coil affects the average induced emf voltage $\mathcal{E}_{\text{ave}}$ in the coil, make conclusions about the directionality and magnitude associated with the average induced emf, and use your data to support those conclusions.

RELEVANT EQUATIONS

$$\Phi_B = BA \qquad (2)$$

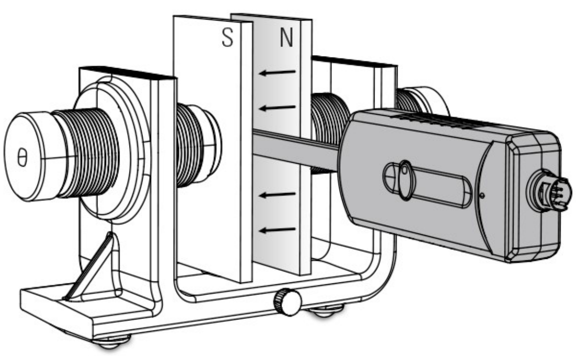
Procedure

Part 1 – Rate of Flux Change and Average Emf

SET UP: MEASURE MAXIMUM MAGNETIC FIELD MAGNITUDE

1. Place the variable gap magnet on the lab table, increase the gap spacing so you can insert the two flat iron pole plates (to provide a uniform magnetic field), and adjust either plate so that the gap between the pole plates is 2 cm.

2. Connect the magnetic field sensor to the data collection system using the sensor extension cable, and then create a digits display of perpendicular magnetic field strength.



3. Hold the sensor with its tip directly between the magnet pole plates. Turn the sensor so that the "perpendicular" measurement axis is aligned with, and in the same direction as, the magnetic field between the plates (from north pole to south pole), similar to the figure.

   NOTE: A diagram on the sensor case indicates the direction of the perpendicular axis.

COLLECT DATA: MEASURE MAXIMUM MAGNETIC FIELD MAGNITUDE

4. Start recording data. If the value is negative, rotate the sensor so the Tare button on the sensor faces the other pole plate. This should change the measurement polarity to positive. Measured values are positive when the perpendicular axis is in the same direction as the magnetic field (north pole to south pole).

5. Determine the magnetic field strength (magnitude) at the center between the pole plates on the magnet. Record this as the maximum magnetic field, in units of tesla, above Table 1 in the Data Analysis section below.

6. Stop recording data, disconnect the magnetic field sensor and extension cable, and delete any data on your data collection system.

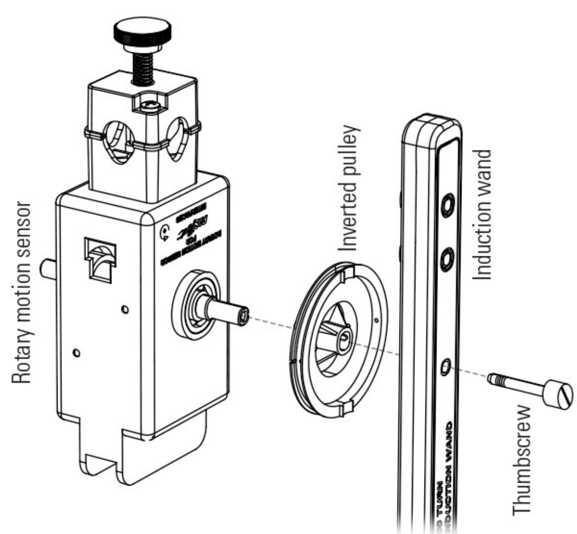
SET UP: MEASURE INDUCED EMF

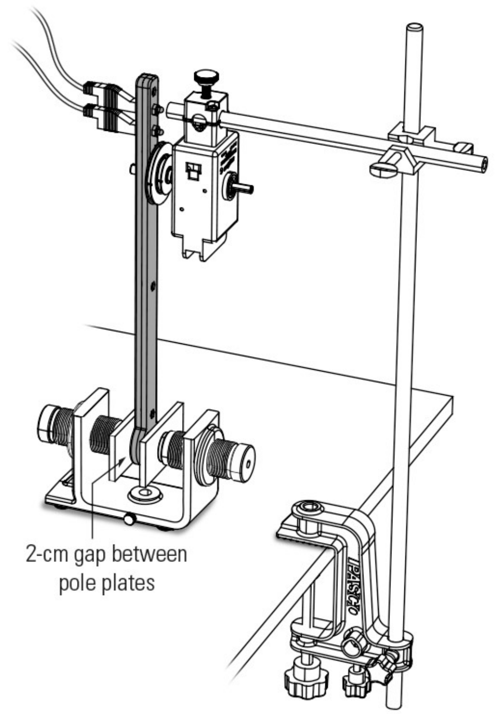
7. Assemble the equipment as shown in the figure:

    - Invert the pulley on the rotary motion sensor so the smallest pulley step faces the sensor. Use the thumbscrew accompanying the induction wand to attach the wand to the axle on the rotary motion sensor.

    - The gap between the pole plates on the magnet should be 2 cm wide.

    - Adjust the height of the rotary motion sensor and the position of the variable gap magnet so the center of the coil at the bottom end of the induction wand can swing freely between the pole plates on the magnet, but hangs freely and motionless exactly between the poles on the magnet.





8. Connect the voltage sensor leads to the top end of the induction wand: connect the red lead to the top port, connect the black lead to the bottom port.

    NOTE: Do not allow the voltage sensor cords to impede the swing of the induction wand.

9. Connect the voltage sensor and rotary motion sensor to the data collection system.

10. Create one graph display with two *y*-axes versus time: one *y*-axis showing voltage from the voltage sensor, and the second *y*-axis showing angle (°) from the rotary motion sensor. Lock the graph so that both *y*-axes share the origin.

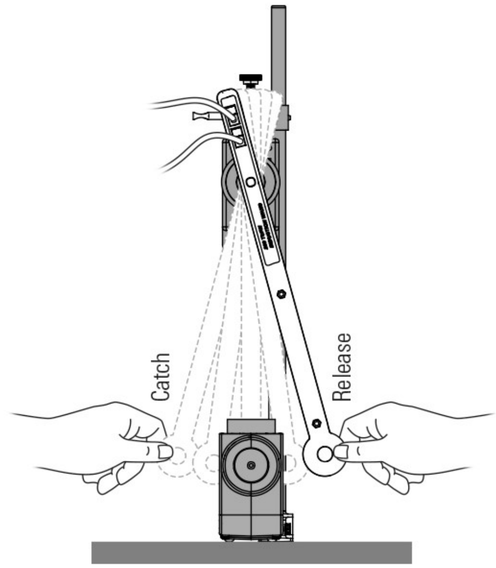
11. Set the sample rate on the data collection system to 250 Hz.

12. In your data collection system's sensor settings, configure the rotary motion sensor to *NOT* automatically zero the sensor's measurements on start. Then, with the wand hanging freely and motionless between the poles on the magnet, on the data collection system select the "Zero Sensor Now" button to associate the current position of the wand to an angular position of 0° for all trials.

COLLECT DATA: MEASURE INDUCED EMF

13. Start recording data, and then rotate the wand to the right (counterclockwise) approximately 30°. Hold it in place for a short moment and then release it to swing freely, once, through the pole plates on the magnet.

    Catch the wand on the other side of the magnet before it swings back through the pole plates.



14. Stop recording data.

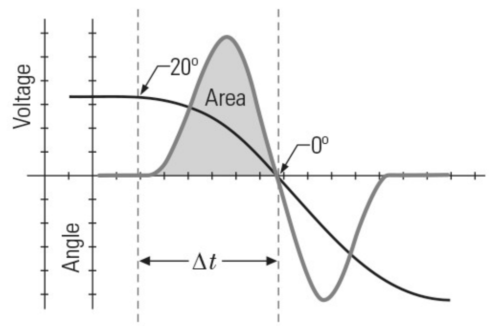
15. Repeat the data collection steps four additional times, each time rotating the wand in the same direction and increasing the rotation angle by approximately 15°. When you are finished, you will have a total of five trials of data.

16. Use the tools on your data collection system to obtain the following values in each trial:

    a. The area under your voltage versus time curve between the angles 20° and 0° (the area may be positive or negative). Record each area value for the corresponding trial in Table 1.

    b. The change in time Δt between the angles 20° and 0°. Record each Δt value for the corresponding trial in Table 1.

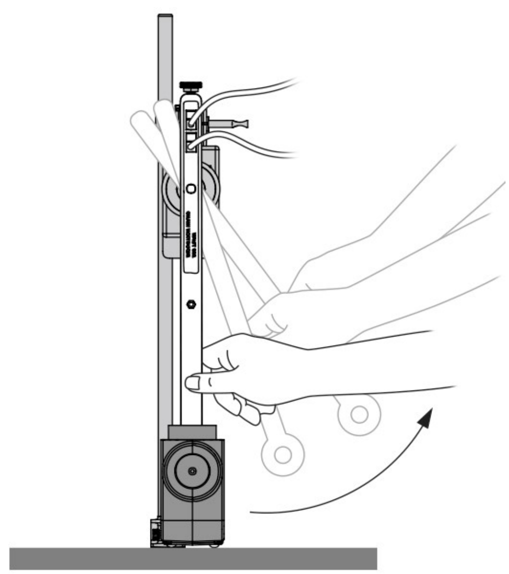
    NOTE: Each trial may not have angle or voltage data points that align exactly with 20° or 0°. In this case, use the data points closest to 20° or 0°.



Part 2 – Emf Direction

SET UP

17. Keep the equipment setup identical to that of the previous part, and create a new graph display of only voltage versus time. Hide any data so that your graph is blank.



COLLECT DATA

18. With the wand hanging freely and motionless between the poles of the magnet, begin recording data.

19. Using your hand, and without taking your hand off the wand, quickly rotate the wand to the right, moving the coil completely out from between the magnet plates. Hold it in place, and then stop recording data.

20. Again, with the wand hanging freely and motionless between the magnet poles, begin recording a second run of data: quickly rotate the wand to the left, out from between the magnet plates, and hold it in place.

21. Stop recording data and sketch a copy of your *voltage* versus *time* graph, with these two runs, in the blank Graph 2 axes in the Data Analysis section. Be sure to label both axes with the correct scale and units.

22. Hide your data so the voltage versus time graph is blank.

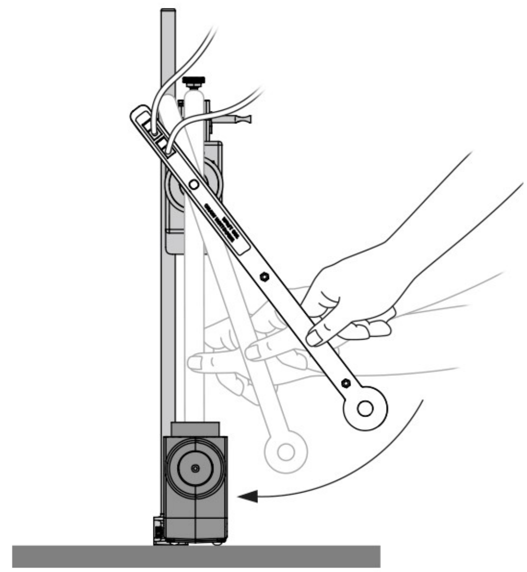
23. Use your hand to rotate the wand to the right and hold it in place so that the coil is completely out from between the magnet plates.

24. Begin recording data, and without the wand leaving your hand, quickly rotate it back and stop when the wand is vertical and the coil is directly between the centers of the pole plates on the magnet.

25. Stop recording data.

26. Use your hand to rotate the wand to the left and hold it in place so that the coil is completely out from between the magnet plates and then repeat the two previous data collection steps.

27. Stop recording data. Sketch a copy of your graph with these two runs into the blank Graph 3 axes in the Data Analysis section. Be sure to label both axes with the correct scale and units.



Data Analysis

Part 1 – Rate of Flux Change and Average Emf

Maximum magnetic field (T): ______________________________

Table 1: Determination of the average induced emf and the rate of magnetic flux change

Trial	Release Angle (approximate) (°)	Area Under Curve (V·s)	Δt (s)	$\mathcal{E}_{ave}$ (V)	$\Delta\Phi/\Delta t$ (T·m²/s)
1	30				
2	45				
3	60				
4	75				
5	90				

1. Calculate the average induced emf $\mathcal{E}_{ave}$ for each Part 1 trial. Record your results in Table 1.

$$\mathcal{E}_{ave} = \frac{\text{Area under voltage versus time curve}}{\Delta t}$$

2. The following information will help with the calculation of the total change of magnetic flux through the coil:

   Assuming the magnetic field was always perpendicular to the plane of the coil as it swung in each trial, and the area of the coil A is constant, then according to Equation 2, the equation describing the total change in magnetic flux $\Delta\Phi_B$ in each trial is:

   $$\Delta\Phi_B = \Delta BA$$

   $$\Delta\Phi_B = \Delta B\pi r^2 \quad (3)$$

   where ΔB is the total change in magnetic field amplitude experienced by the coil and r is the radius of the coil.

   If we assume the magnetic field magnitude was zero for angles greater than 20° and maximum at an angle of 0° (between the pole plates) in each trial, the total change in magnetic field magnitude for all trials is:

   $$\Delta B = B_f - B_i = B_{max} - 0 = B_{max}$$

   Plugging the result for ΔB back into Equation 3 gives the equation for the total change in magnetic flux through the coil for all trials:

   $$\Delta\Phi_B = B_{max}\pi r^2 \quad (4)$$

   where B_{max} is the measured maximum magnetic field value and r is the radius of the coil (in the case of the PASCO Induction Wand, r = 0.0125 m).

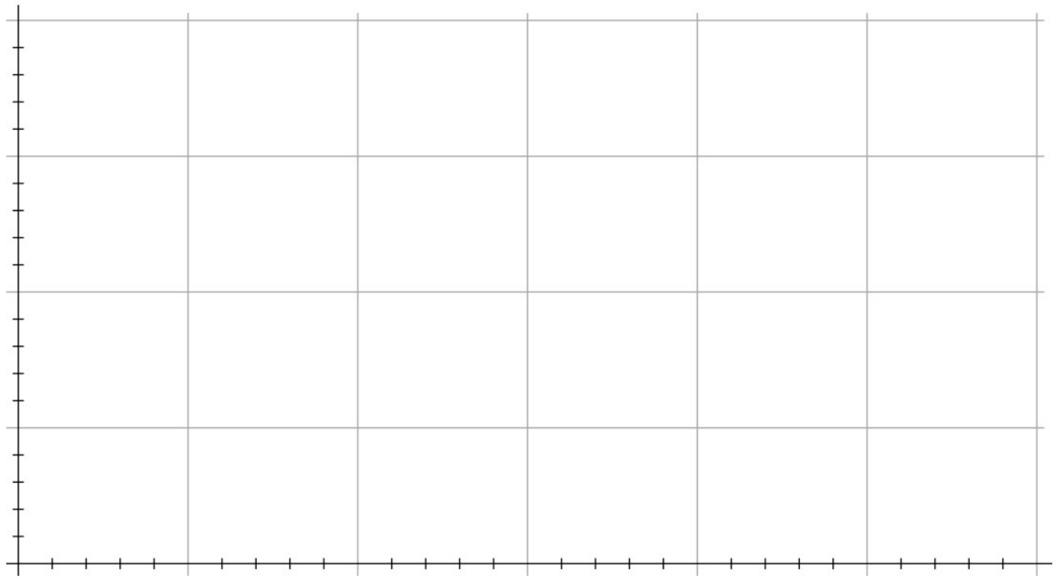
   Using the above information, calculate the total change in magnetic flux $\Delta\Phi_B$ through the coil for all trials. Record your value here:

   $\Delta\Phi_B$ (T·m^2): ________________________________

3. Calculate the rate of magnetic flux change $\Delta\Phi_B/\Delta t$ for each trial using the $\Delta\Phi_B$ value from the previous question and the elapsed time Δt values from Table 1. Record the results for each trial in Table 1.

4. Plot a graph of *average induced emf* $\mathcal{E}_{ave}$ versus *rate of magnetic flux change* $\Delta\Phi_B/\Delta t$ in the blank Graph 1 axes. Be sure to label both axes with the correct scale and units.

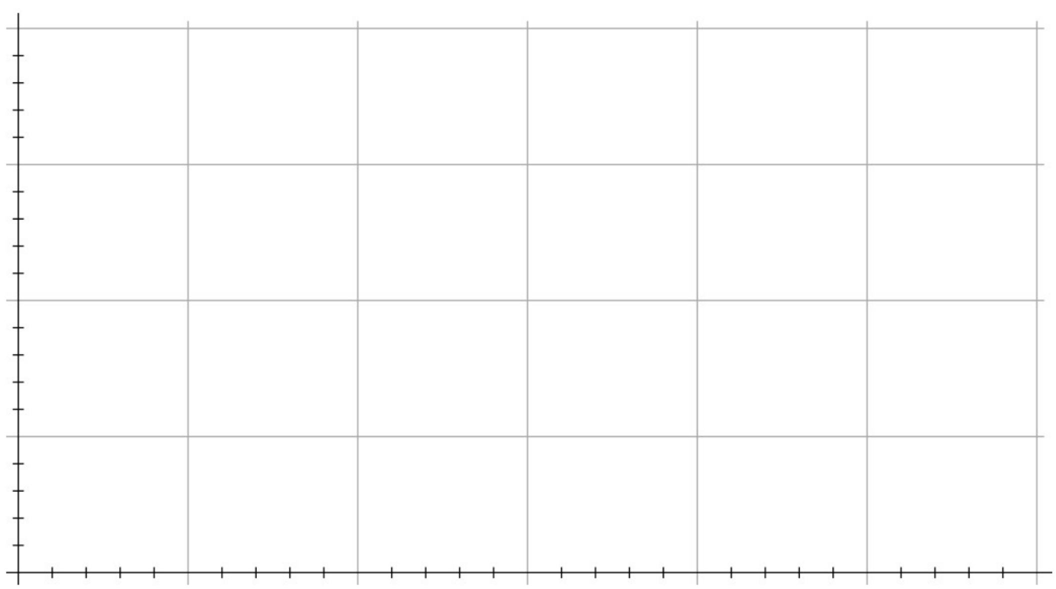
Graph 1: Average induced emf versus rate of magnetic flux change through a coil with fixed radius



5. Based on Graph 1, how is the average induced emf related to the rate of flux change $\Delta\Phi_B/\Delta t$ through the coil (proportional, inverse, squared, et cetera)?

Part 2 – Emf Direction

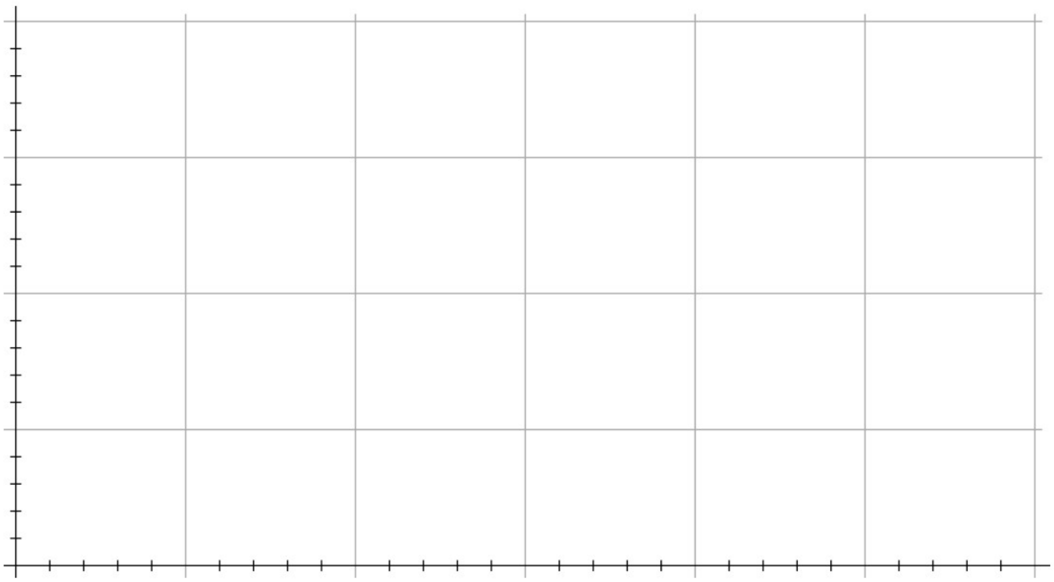
Graph 2: Induced emf by moving the coil out of a magnetic field



6. As the coil was moved away from the magnet, was the amount of magnetic flux passing through the coil increasing or decreasing? How do you know?

7. Was the induced emf positive or negative as the coil was moved away from the magnet? Did it make a difference if it was moved to the left versus to the right?

Graph 3: Induced emf by moving the coil into a magnetic field



8. As the coil was moved toward the magnet, was the amount of magnetic flux passing through the coil increasing or decreasing? How do you know?

9. Was the induced emf voltage positive or negative as the coil was moved toward the magnet? Did it make a difference if it was moved toward the center from the left versus from the right?

Analysis Questions

1. In this experiment, what steps did you take to change the magnetic flux through the coil of wire?

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2. Did the rate of magnetic flux change $\Delta\Phi_B/\Delta t$ affect the induced emf in the coil? If yes, how did it affect it?

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3. Faraday's Law of Electromagnetic Induction is written:

$$\mathcal{E}_{\text{ave}} = -N\frac{\Delta\Phi_B}{\Delta t} \tag{5}$$

where N is the number of turns in the coil. How does your data support Faraday's Law?

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4. How was the emf different when the magnetic flux through the coil was increasing versus when it was decreasing?

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5. The negative sign in Faraday's Law is due to Lenz's Law, which states that the emf induced in a coil will generate current in the coil that produces a magnetic field opposing the change in flux. How does your data support Lenz's Law?

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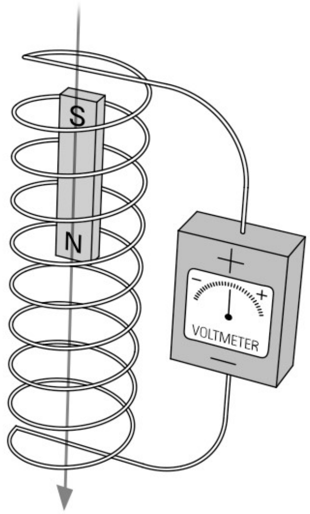
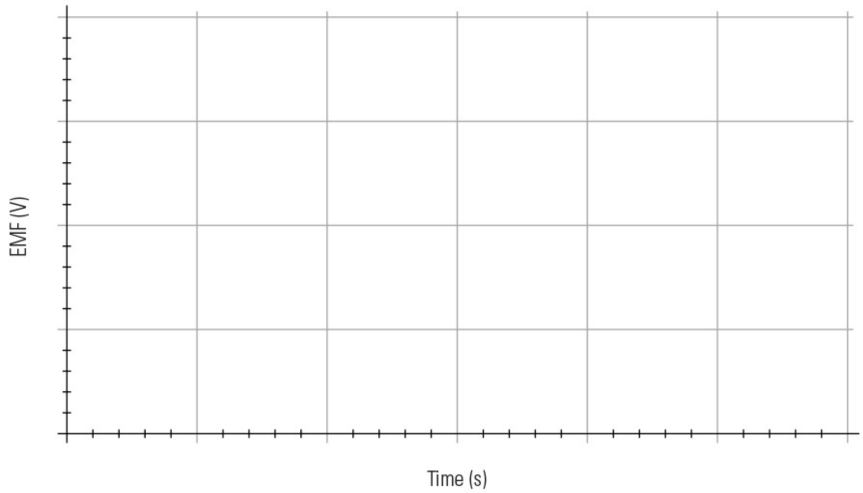
Synthesis Questions

1. A 4-cm long bar magnet is dropped from 2 cm above a coil of wire. If the falling bar magnet passes through the coil, north pole first (as in the diagram below), what would the graph of emf versus time look like? Sketch your answer in the blank graph axes below, starting from the time at which the magnet is dropped, and ending after the magnet has fallen out of the coil.





2. A round coil of wire with 10 turns sits in a uniform magnetic field whose field lines pass perpendicularly through the coil area. The magnetic field magnitude increases at a constant rate from 1 T to 10 T over some amount of time. This produces an average 4 V emf voltage in the coil over that time.

   a. What would be the average emf voltage if the same coil experienced the same constant change in magnetic field magnitude but in half the time? Explain your answer.

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   b. What would be the average emf voltage if the coil had 30 turns instead of 10 and experienced the original change in magnetic field magnitude over time? Explain your answer.

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   c. What would be the average emf voltage if the coil experienced the original change in magnetic field magnitude over time, but with a radius twice as large? Explain your answer.

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d. What would be the average emf voltage if the number of turns and radius of the coil were unchanged but the magnetic field magnitude changed at a constant rate from 10 T to 1 T over the same amount of time? Explain your answer.

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