ELECTROMAGNETIC INDUCTION

OBJECTIVE: The object of this experiment is to study the laws of electromagnetic induction (Faraday's law and Lenz's law).

THEORY: Electromagnetic induction is the process in which a magnetic field causes or *INDUCES* an electric field. However, a "static" magnetic field will not do this; it takes a *CHANGING* magnetic field. A changing *B*-field can be produced in several ways: (1) the current producing the *B*-field can change, (2) the source of the field (electromagnet or permanent magnet) can be in motion, or (3) the frame of reference in which the *B*-field is being observed can be in motion. The induced electric field exists only while the change is occurring. If there is no change, then there is no induction.

When there are conductors present, the induced electric field is usually described in terms of an induced electromotive force (EMF). If the conductors form complete circuits, then the induced EMF's produce induced currents. Faraday's law of induction relates the induced electric field to the changing magnetic field. For the case of a circuit, Faraday's law can be written as

$$EMF = \frac{d\Phi}{dt},$$

where Φ is the magnetic flux through the circuit. When the *B*-field is uniform and at right angles to the area *A* bounded by the circuit, then the flux is simply *B A*. (For non-uniform fields, the flux must be calculated by integration.)

Often it is useful to distinguish between the case where the *B*-field passes through the area *A* in one direction (e.g., left to right) and the case where it passes through in the opposite direction (e.g., right to left). This can be done by letting the flux be positive in one case (it doesn't matter which) and negative in the other case. When this is done, a reversal of the field direction or a rotation of the circuit by 180° relative to the *B*-direction will cause a sign change in the flux through the circuit.

Often a minus sign is used in the Faraday's law equation which gives information about the direction of the induced E-field and thus the sign (polarity) of the resulting induced EMF. When currents are possible, Lenz's law can be used to predict the current direction. A useful version of Lenz's law is:

> ***The induced current will appear in such a direction that the magnetic flux of the field caused by that current will try to cancel the flux change that produced the current in the first place.***

In other words, the magnetic effects of the induced current opposes the change in conditions which produced it.

For this experiment, the secondary (yellow) coil and the meter comprise the circuit in which the induced EMF and induced current appear. The many turns in the coil magnify the small effects that would be observed with only a single turn.

PROCEDURE:
(In order to be sure that your observation of an effect was correct, you should repeat any step in this procedure as many times as you need to.)

I. Bar magnet at rest inside the coil.

1. Place the bar magnet inside the secondary coil (yellow coil with many turns) with the North pole inside.
2. Connect the multimeter in DC volt mode across the terminals of the secondary coil and note any voltage that occurs as the last connection is made.
    a. Was there a (non-zero) reading? _____
    b. Was your observed result expected? Explain.

II. Bar magnet moved.

1. Move the magnet (with the **North** pole in the secondary coil) about half way **out** of the coil and then **remove** the rest quickly (with a jerk).
    a. Which sign did the voltmeter give (+ or -)? _____
    b. Which way did the INDUCED magnetic field generated by the INDUCED voltage point (i.e., which end of the secondary coil was the North pole)? _____
    c. Did this induced field oppose or support the field of the bar magnet? _____
    d. Comment on this observation in relation to Lenz's Law.

2. Does the speed at which you remove the magnet affect the **sign** (polarity) of the induced voltage? _____

3. Does the speed at which you remove the magnet affect the maximum **size** of the induced voltage? _____

4. Now **insert** the magnet (North pole in) about half way into the coil with a quick movement.
    a. Which sign did the voltmeter give (+ or -)? _____
    b. Which way did the INDUCED magnetic field generated by the INDUCED voltage point (i.e., which end of the secondary coil was the North pole)? _____
    c. Did this induced field oppose or support the field of the bar magnet? _____
    d. Comment on this observation in relation to Lenz's Law.

5. Use your knowledge of the *B*-field around a bar magnet to answer the following.
    a. Did you increase or decrease the flux through the coil in step 1 of this section? _____
    b. Did you increase or decrease the flux in step 4? _____
    c. Write a statement relating flux increase and decrease to voltmeter sign for your setup.

6. Next with a quick movement **insert** the **South** pole of the magnet (as in step 4) and note the sign of the induced voltage.

a. Which sign did the voltmeter give (+ or -)? _____

7. Quickly **remove** the **South** pole of the magnet.
    a. Which sign did the voltmeter give? _____

8. Are the observations of steps 6 and 7 consistent with your statement in step 5 and Lenz's Law? _____ Explain.

III. Electromagnet moved.

The primary coil, which fits inside the secondary, functions as an electromagnet. It produces a *B*-field with geometry similar to that of a permanent bar magnet, but the field magnitude is proportional to the current and the field direction reverses if the current direction is reversed.

1. From an inspection of the direction of the windings of the primary (blue, fewer turns, thicker) coil, determine which of its two terminals should be connected to the positive terminal of the power supply in order to make the bottom of the primary coil a North magnetic pole. (HINT: Consider the primary coil to be a solenoid.)

2. Connect the primary coil to a power supply with a switch in series so that the current to the coil can be turned on and off by closing and opening the switch. Leave the secondary coil connected to the voltmeter.

3. Place the primary coil (blue) inside the secondary (yellow) coil.   Close the switch and adjust the voltage control to the **lowest possible setting** that will give about 1 amp in the primary coil.

4. **Remove** the primary coil (electromagnet) from the secondary coil with a small jerk.
    a. What is the sign of the induced voltage on the voltmeter? _____
    b. Is this consistent with what happened when you removed a North pole from inside the secondary coil in Part II? _____

    _____
5. **Insert** the primary coil (electromagnet) into the secondary coil with a quick movement.
    a. What is the sign of the induced voltage on the voltmeter? _____
    b. Is this what you expected? _____

IV. Current in the electromagnet switched off and on.

1. Set the current in the primary coil to about 1 amp as in Part III. Place the primary coil inside the secondary coil.

2. **Open** the switch. What is the sign of the induced voltage on the voltmeter? _____

3. **Close** the switch and again record the sign of the induced voltage._____

4. Explain why opening and closing the switch causes the sign of the induced voltage on the voltmeter to change and why it gave the signs that it did. Your explanation must contain the words and phrases: *current in the primary coil, magnetic field, magnetic flux, secondary coil, flux increases, flux decreases, induced voltage.*

V. Effect of an iron core on the induced EMF.

1. Close the switch and set the power supply current at 0.5 amps using **the voltage control knob**. Disconnect the voltmeter from the secondary coil and replace the meter with the analog galvanometer. (The galvanometer is basically an ammeter.)

2. Open and close the switch and note the size of the induced current. Now place the **iron** (heavier) rod completely inside the primary coil. Open and close the switch again.
   a. Has the size of the induced current significantly increased? _____
   b. Explain this observation.

3. Remove about a fourth of the iron rod from the coil. Open and close the switch and note the size of the induced current. Repeat with about half of the rod removed and again with about three quarters removed.
   a. What happens to the size of the induced current as more of the iron rod is removed from the coil? _____
   b. Is this consistent with the preceding observation made in step 2? _____

4. Replace the iron rod with a **pencil** and repeat step 2.
   a. Do you still get a significant increase in the induced current over what you had originally with just air inside the coil? _____

5. Replace the pencil with the **magnesium** rod and repeat step 2. (The magnesium rod is much lighter in weight than the iron bar).
   a. Do you still get a significant increase in the induced current over what you had originally with just air inside the coil? _____
   b. Does a magnet attract the **iron** bar? _____
   c. Does a magnet attract the **pencil**?
   d. Does a magnet attract the **magnesium** bar? _____
   e. Explain how all of these observations made in steps 4 and 5 relate using the principles of electromagnetic induction.

VI. Effect of increasing current

1. Use the same circuit as in part V with the **iron** rod in completely inside the primary coil. See what the level of current in the electromagnet (primary coil) does to the induced current in the secondary coil as you open and close the switch to the electromagnet. Record your observations.
    a. Does the induced current in the secondary coil depend on the amount of current in the electromagnet? _____

2. If a more detailed study where made, we would find that the induced current in the secondary coil depends linearly on the electromagnet current. Explain this linear dependence in terms of Faraday's Law and other relevant relationships.