Electromagnetic Induction

Produced by the Physics Staff at Collin College

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**Purpose**

In this experiment, you will investigate electromagnetic induction in solenoids and paired wire coils. You will also investigate electromagnetic permeability by noting the effects of different materials on the induced magnetic field of a coil.

**Equipment**

- Pasco coil set
- Iron, brass, and aluminum rods
- Low-voltage dc power supply or dry cell
- SPST switch
- Four clip leads
- Solenoid
- One bar magnet
- Magnetic compass
- Galvanometer
- Large resistor (10kΩ – 100kΩ)

**Theory**

Electric and magnetic phenomena are closely related. A moving electric charge (an electric current) creates a magnetic field, and a magnetic field exerts a force on a moving electric charge. These phenomena were discovered in 1820. Natural curiosity then compelled scientists to ask, “If an electric current produces a magnetic field, is it possible that a magnetic field can produce an electric current?”

Ten years later the American scientist Joseph Henry and the English scientist Michael Faraday independently found that it was indeed possible. Henry actually made the discovery first but Faraday published his results earlier and investigated the subject in more detail. Faraday discovered that under certain conditions a magnetic field does produce an electric current in a conductor. This phenomenon is expressed in Faraday’s famous Law of Induction, which today is the basis of the generation of most of the electricity used in the world.

Our understanding of the mutual relationship between electricity and magnetism is among the most significant discoveries in physics during the last century and a half. Danish scientist Hans Christian Oersted made the first discovery in 1820. He discovered that a magnetic field exists in the space around an electric current.

He further noted the relationship between the direction of the current and the direction of the magnetic field: the force lines form concentric circles around the current-carrying conductor. The magnetic field vector at any point is tangent to the circle at that point. The direction of the magnetic field is given by right-hand rule: Grasp the conductor in your right hand with your fingers encircling it and your thumb extended in the direction of the current. Your fingers indicate the direction of the magnetic lines (Figure 9.1).

![Figure 9.1](image-url)
Michael Faraday reasoned that if a wire carrying a current produced a magnetic field, then a magnetic field around a wire should produce a current in the wire. However, Faraday met with failure when he attempting to reverse Oersted’s experiment. He found no effect with a stationary magnet or magnetic field.

After a lengthy series of experiments he found the essential condition for producing a current from a magnetic field. There must be relative motion between the conductor and the field. Figure 9.2 illustrates Faraday’s breakthrough experiment. He connected a helical coil of wire to a galvanometer and brought a bar magnet near the coil. With no relative motion between the magnet and the coil, the galvanometer read zero, indicating no current.

![Figure 9.2](image)

However, when he moved the magnet toward the coil, a current appeared in the coil and the galvanometer deflected to the right. As the magnet approached, the magnetic field that it creates in front of it became stronger and stronger. It was this changing magnetic field that produced the current.

A current also appeared when he moved the magnet away from the coil, but the direction of the current was reversed and the galvanometer deflected to the left. In this case, the magnetic field in the coil became weaker as the magnet moved away. Once again, the changing magnetic field at the coil generated a current.

A current would also be created if he held the magnet stationary and moved the coil because the field lines in the coil would change as he moved the coil toward or away from the magnet. Only relative motion between the magnet and coil is needed to generate a current. It does not matter which one moves as long as magnetic field through the coil is changing.

The current in the coil is called an *induced current* because it is induced by the changing magnetic field. Since a current in a circuit is normally produced by a source of emf, the coil itself behaves as if it were a source of emf. It is called an *induced emf*. Thus, a changing magnetic field induces an emf in the coil, and the emf creates the current. His investigations led Faraday to the conclusion that the important factor in electromagnetic induction was the time rate of change of magnetic field lines (flux) through the coil. The induced emf $\varepsilon$ is therefore given by

$$\varepsilon = -\frac{d\Phi}{dt}$$

*Equation 9.1*

where $\Phi$ is the total magnetic flux through the coil.
Often the magnetic flux passes through a coil of wire containing more than one turn. If the coil consists of \( N \) turns all the same area, and if the same flux passes through each turn, the total induced emf is found experimentally to be \( N \) times that induced in a single loop. So the average induced emf is

\[
\varepsilon = -N \frac{d\Phi}{dt}
\]

*Equation 9.2*

Equation 9.2 is known as Faraday’s Law of Induction.

Since the magnetic flux is defined as the total number of magnetic field lines passing through a surface.

\[
\Phi = BA \cos \theta
\]

*Equation 9.3*

Where \( B \) is the magnetic field vector, \( A \) is the cross sectional area of the loop, and \( \theta \) is the angle between the magnetic field and a line perpendicular to the plane of the loop.

Equation 9.3 shows that a change in flux can result from changes in quantities other than the magnetic field. Substituting Equation 9.3 into Equation 9.2 gives

\[
\varepsilon = -N \frac{d\Phi}{dt} = -N \frac{d(BA \cos \theta)}{dt}
\]

*Equation 9.4*

Equation 9.4 shows that there are three quantities that can change with time to produce an induced emf: the magnitude of the magnetic field \( B \), the area of the coil \( A \), and the angle \( \theta \).

Expand this equation to get

\[
\varepsilon = -N \left[ (A \cos \theta) \frac{dB}{dt} + (B \cos \theta) \frac{dA}{dt} + BA \frac{d(cos \theta)}{dt} \right]
\]

*Equation 9.5*

The first term in the bracket is the change in flux due to a time-varying magnetic field (with area and orientation of the coil constant). A time varying magnetic field is easily obtained by varying the current producing it, as in the case with an alternating current.

The second term is the change in flux due to a time varying coil area (with constant magnetic field and constant orientation). This could occur if the diameter of the coil was changing with time.

The third term is the change in flux due to a change in orientation of the coil with time (with constant magnetic field and constant coil area). This could occur if the coil is rotated in a uniform magnetic field.

Since the total flux depends on all three factors, the induced emf is due to either a single factor or a combination of two or three factors. In this experiment you will be concerned with the effect of only the first term in Equation 9.5, i.e., the flux change due to a time-varying magnetic field.

The negative sign in Equation 9.2 expresses another important law of electromagnetic induction. Russian Physicist Heinrich Lenz discovered what determines the polarity of the induced emf. He found that the polarity (direction) of the emf is such that the magnetic flux
created by the induced current opposes the *change in flux* causing the emf. (Use the right hand rule to determine the direction of the magnetic flux created by the induced current).

This means that the induced current creates a magnetic field which (a) adds to the original magnetic field if the original field is decreasing, or (b) subtracts from the original magnetic field if it is increasing. Either way, the induced magnetic field tends to oppose the change in the original field. This rule is known as Lenz’s law.

Consider what would happen if Lenz’s law were not true, but was just the reverse. Then the induced current would produce a flux in the same direction as the original change. This greater change in flux would induce an even larger current which would cause a still greater change in flux, and so on. The current would continue to grow indefinitely, producing more power, even after the original effect ended. This would violate the conservation of energy principle.

The magnetic field along the axis of a solenoid carrying current $I$ is given by

$$B = \mu_0 n I$$  \hspace{1cm} \text{Equation 9.6}$$

where $n$ is the number of turns per unit length ($N/L$) and $\mu_0$ is the permeability of free space (or air), indicating that the solenoid is filled with air. If the solenoid is filled instead with a material having a magnetic permeability $\mu$, the $\mu_0$ in Equation 9.6 is replaced by $\mu$. The permeability of a substance expresses its magnetic characteristics. A substance having a large value of permeability (e.g., iron) can be used to increase the magnetic field in a solenoid.

**Procedure**

The direction of the current in a circuit is indicated by the right or left deflection of the galvanometer. To establish which direction of the galvanometer deflection is due to a known current direction, connect one terminal of the dry cell (or 1.5 – 3.0 volt dc power supply) to one terminal of the galvanometer and the other voltage source terminal through a large resistance to the other galvanometer terminal (Figure 9.3). Use a large value of resistance to minimize the current.

From the known polarity of the source, relate the galvanometer deflection to the direction of current flow. Conventional current (assuming positive charge carriers in the copper wire) flows out of the positive source terminal.

Galvanometer deflections to the right are called positive and deflections to the left are negative. You should have a conventional current entering the positive galvanometer terminal causing a positive deflection.
A. Current Induced by Moving Bar Magnet

1. Connect the galvanometer to the terminals of a large coil as shown in Figure 9.4.

2. Use the compass to determine the polarity of the bar magnet. Investigate the effect (how much and which direction the galvanometer deflects) of moving the magnet in and out of the coil (a) fast and slow, and (b) with N and S poles leading. Record your results in Table 9.1.

B. Electromagnet Field

3. Set up a coil circuit as shown in Figure 9.5 with the switch $S$ open. Select a coil large enough to insert the bar magnet into. Close the switch and use the compass to investigate the magnetic field around the coil. Make a sketch (on a separate sheet of paper) of the magnetic field pattern (including polarity) in your lab report.

C. Current Induced by Varying Magnetic Field

4. Set up the primary and secondary coil circuits as shown in Figure 9.6 with the switch $S$ open. Insert the primary coil into the secondary coil.

5. Record (in Table 9.2) the magnitude and direction of the galvanometer deflection when you (a) close the switch, and (b) when you open the switch.

6. Insert the aluminum rod into the primary coil and repeat step 5. Record the galvanometer deflection, noting any difference in magnitude from that in step 5.

7. Repeat step 6 with the brass rod then with the iron rod.

8. Estimate the relative permeabilities of the three rods.