MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

8.02 **Spring 2005**

Experiment 9: Faraday's Law of Induction

OBJECTIVES

1. To become familiar with the concepts of changing magnetic flux and induced current associated with Faraday's Law of Induction.

2. To see how and why the direction of the magnetic force on a conductor carrying an induced current is consistent with Lenz's Law. Lenz's Law says that the system always responds so as to try to keep things the same.

OUTLINE

This experiment consists of three parts:

1. Prediction of the magnetic flux through a closed contour and the direction of the induced current in a wire along this contour associated with the change of this flux with time as the wire moves, using Faraday's Law.

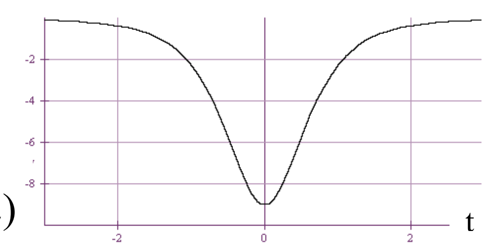
2. Qualitative measurement of the current and flux, and the relationship between these two.

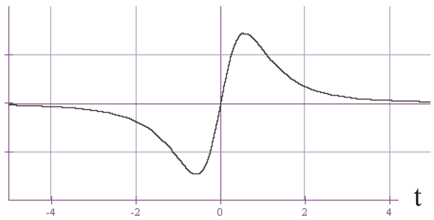
3. Qualitative determination of the direction of the force on a current-carrying conductor due to the induced current in a magnetic field.

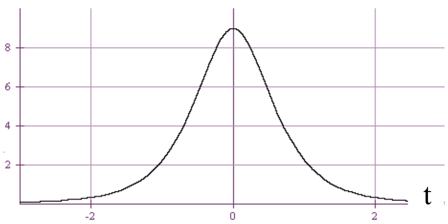
Part 1: Predictions of Magnetic Flux and Induced Current

The questions for Part 1 refer to the four graphs below. Each graph is a qualitative depiction of some physical quantity as a function of time.
To answer the questions, refer to the numbers that label each of the graphs.
Enter your predictions on the tear-sheet at the end of these instructions.

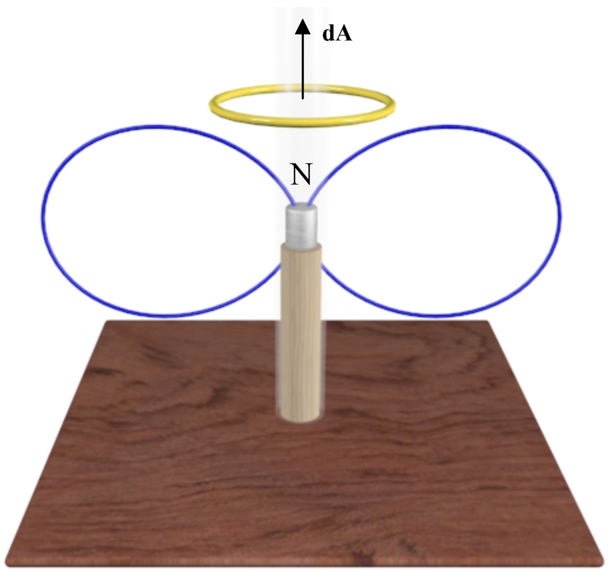
(1)


(2)


(3) 

(4) 

In this exercise we predict the time dependence of the current in a coil as the coil is moved up and down past a stationary permanent magnet. The coil and magnet are arranged as in the figure below. The North Pole of the magnet is on the top.



Prediction 1-1: Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed. Predict the shape of a graph of the *magnetic flux through the loop* as a function of time, taking the direction of $d\vec{\mathbf{A}} = dA\,\hat{\mathbf{n}}$ for the loop as upward.

Prediction 1-2: Suppose you move the loop from well *above* the magnet to well *below* the magnet at constant speed. Predict the shape of a graph of the *current through the loop* as a function of time, taking the positive direction for current in the loop to be counter-clockwise when viewed looking down on the apparatus from above.

Prediction 1-3: Now suppose you move the loop from well *below* the magnet to well *above* the magnet at a constant speed. Predict the shape of a graph of the *magnetic flux through the loop* as a function of time, taking the direction of $d\vec{\mathbf{A}} = dA\,\hat{\mathbf{n}}$ for the loop as upward.

Prediction 1-4: Now suppose you move the loop from well *below* the magnet to well *above* the magnet at constant speed. Predict the shape of the *current through the loop* as a function of time, taking the positive direction of current in the loop as counter-clockwise when viewed looking down on the apparatus from above.

Part 2: Measurements of Induced Voltage, Induced Current and Flux

Download the **exp09.ds** *DataStudio* file from the "Current Assignment" Web Page. The activity is already set up to graph induced current and magnetic flux as functions of time. Take the coil of wire from your experimental set-up, connect it to the Current Sensor and connect the Current Sensor to Analog Channel "A" on the *Science Workshop 750 Interface* (these last two steps may be done for you already).

Recall the convention for the Current Sensor and *DataStudio*, that the direction of positive current *through the Current Sensor* is from red to black. To allow the correct interpretation of the sign of the current, carefully examine the way the wire loops in your coil. The leads should be connected so that they lead from the black terminal on the Current Sensor to the coil, around the coil in a counterclockwise direction as viewed from above and then back to the red terminal on the Current Sensor. There is an arrow on the Current Sensor to remind you of this convention.

Perform the two motions indicated above, and check your Predictions 1-1 through 1-4 for the current *and* the magnetic flux.

The *DataStudio* activity is set to sample data for a time interval of 2 seconds at a rate of 100 samples per second (100 hertz). A recommended procedure is to start with the coil at the top of the plastic tube, begin taking data by pressing Start, and moving the coil downward as evenly (uniform speed) as you can over the interval of 2 seconds. Then repeat, moving the coil up. *DataStudio* should plot the two measurements on the same axes, allowing fairly easy comparison. Make the scale fit each of the graphs in the window by clicking on the icon at the upper left of the graph window. If something doesn't work right the first time, or even the second, go to Experiment from the main menu and select Delete ALL Data Runs.

Another suggestion is to lift or lower the alligator clips that are connected to the coil as you move the coil up or down; this will prevent having the clips come off the wire coil or hitting the magnet (the clips are magnetic).

Question 1 (*answer on your tear-off sheet at the end*): Did your predictions agree with your measurements?

A Note On How We "Measure" Magnetic Flux:

When you use the *DataStudio* Activity, the top panel of the graph window will show the measurement of $I(t)$, and the bottom panel will be labeled "Field Flux". Here we explain how the values displayed on the bottom panel computed. We know from Faraday's Law that when an ohmic resistor of resistance R coincides with the loop that bounds the surface through which the magnetic flux is determined for Faraday's Law,

$$I\,R = -\frac{d}{dt}\Phi_{\text{mag}}\,,$$

and since we measure $I(t)$,we can compute $\Phi_{\text{mag}}(t)$ by numerically integrating;

$$\Phi_{\text{mag}}(t) = -R\int_0^t I(t')\,dt'\,.$$

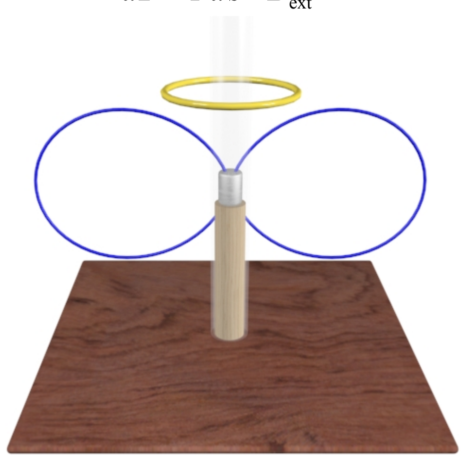
The *DataStudio* software is capable of integrating $I(t)$ and displaying the integral at the same time that $I(t)$ is measured, and the integral is what is displayed in the bottom plot.

Question 2 (*answer on your tear-off sheet at the end*): Note that no matter how quickly or slowly you move the coil up and down past the magnet, as long as you go from far above to far below, or from far below to far above, *the magnitude of the flux function will always attain the same maximum value in the process*.
Why?

Part 3: Feel the ($I\,d\vec{\mathbf{s}}\times\vec{\mathbf{B}}$) Force!

The force on a segment $d\vec{\mathbf{s}}$ of a wire carrying current I in a magnetic field $\vec{\mathbf{B}}_{\text{ext}}$ is given by

$$d\vec{\mathbf{F}} = I\,d\vec{\mathbf{s}}\times\vec{\mathbf{B}}_{\text{ext}}$$



Note that $d\vec{\mathbf{s}}$ here has a physical meaning: the direction of the current flow. In the two preceding figures, the positive direction for current flow was determined purely mathematically by our choice of direction for $d\vec{\mathbf{A}} = dA\,\hat{\mathbf{n}}$. Note also that $\vec{\mathbf{B}}_{\text{ext}}$ is the magnetic field produced by external currents somewhere else, such as the atomic currents in the permanent magnet; it is *not* the magnetic field of the wire segment itself.
Enter your predictions on the tear-sheet at the end of these instructions.

Prediction 3-1: Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *above* the magnet, should the direction of the magnetic force point up or down?

Prediction 3-2: Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *below* the magnet, should the direction of the magnetic force point up or down?

Prediction 3-3: Suppose you move the loop from well *below* the magnet to well *above* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *below* the magnet, should the direction of the magnetic force point up or down?

Prediction 3-4: Suppose you move the loop from well *below* the magnet to well *above* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *above* the magnet, should the direction of the magnetic force point up or down?

TESTING THE PREDICTIONS

First, take off your wristwatch. Second, connect the leads to the coil, forming a closed loop (you can use a clip from the Current Sensor leads for this, but take the Current Sensor out of the circuit). Move the coil up and down over the magnet. Can you detect any magnetic force? Try moving the coil more quickly. However, the quicker you move the coil, the more force *you* have to apply to the coil, and the harder it might be to detect the magnetic force.

Question 3 (*answer on your tear-off sheet at the end*): Were you able to verify your predictions?

To obtain a more easily detected magnetic force, we need induced currents that are larger than those which can be produced in the coil. The aluminum sleeve that is part of the apparatus is conducting but non-magnetic.

Verify the "non-magnetic" property of aluminum part by holding the sleeve near the magnet and noting the absence of attraction.

Now, try moving the sleeve up and down on the Plexiglas tube past the magnet, and verify your predictions and summary above. Feel the $I\, d\vec{\mathbf{s}} \times \vec{\mathbf{B}}_{\text{ext}}$ force!

Hold the sleeve at the top of the plastic column, and let it drop. When you let the sleeve drop, the magnetic force opposed gravity (the external force).

Part 4: The Structure of Space and Time

Einstein starts his 1905 paper on special relativity with the following paragraph (see "On The Electrodynamics of Moving Bodies" by A. Einstein)

"It is known that Maxwell's electrodynamics--as usually understood at the present time--when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighborhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighborhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise--assuming equality of relative motion in the two cases discussed--to electric currents of the same path and intensity as those produced by the electric forces in the former case."

What he is saying is that it doesn't make any difference in the current you observe as to whether the magnet is stationary and the coil moves or the coil is stationary and the magnet moves. Check to see that this is correct. That is, hold the coil stationary and move the magnet through it, and see if you observe the same current signature as in the above experiments.

Chose one:

_____Current depends on relative velocity of coil and magnet only (Einstein right)
_____Current depends on whether the magnet is at rest and the coil moves or vice versa (Einstein wrong)

In the last class before the exam review, we will show you why this observation led Einstein to deduce the nature of space and time—i.e., space contraction, time dilation, and all those other weird things. It all grew out of classical electromagnetism.

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Tear off this page and turn it in at the end of class.

Note:
Writing in the name of a student who is not present is a Committee on Discipline offense.

Experiment Summary 9: Faraday's Law of Induction

Group and Section ____________________________ **(e.g. 10A, L02: Please Fill Out)**

Names _____________________________________

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Part 1: Predictions of Magnetic Flux and Induced Current

The curves from which you choose are reproduced here:

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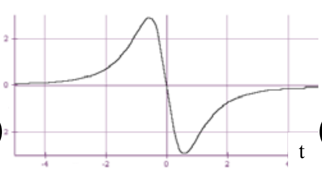

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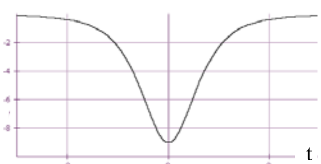

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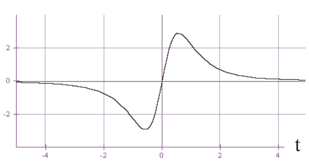

(4)


Prediction 1-1: Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed.
The graph of the *magnetic flux through the loop* as a function of time would most closely resemble: Curve ______

Prediction 1-2: Suppose you move the loop from well *above* the magnet to well *below* the magnet at constant speed.
The graph of the current as a function of time would most closely resemble Curve _____.

Prediction 1-3: Suppose you move the loop from well *below* the magnet to well *above* the magnet at a constant speed.
The graph of the *magnetic flux through the loop* as a function of time would most closely resemble: Curve ______

Prediction 1-4: Suppose you move the loop from well *below* the magnet to well *above* the magnet at constant speed.
The graph of the current versus time would most closely resemble: Curve _____.

Part 2: Measurements of Induced Current and Flux
Question 1: Did your predictions agree with your measurements?

Question 2: Note that no matter how fast or slow you move the coil up and down past the magnet, as long as you go from far above to far below, or from far below to far above, the *flux function will always attain the same maximum value in the process*. Why?

Part 3: Feel the ($I\, d\vec{\mathbf{s}} \times \vec{\mathbf{B}}$) Force!

Prediction 3-1: Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *above* the magnet, should the direction of the magnetic force point up or down? ______ up ________ down

Prediction 3-2: Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *below* the magnet, should the direction of the magnetic force point up or down? ______up ________down

Prediction 3-3: Suppose you move the loop from well *below* the magnet to well *above* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *below* the magnet, should the direction of the magnetic force point up or down? ______ up ________down

Prediction 3-4: Suppose you move the loop from well *below* the magnet to well *above* the magnet at a constant speed. From your predictions above of the direction of current flow when the loop is *above* the magnet, should the direction of the magnetic force point up or down? ______up ________down

Question 3: Were you able to verify your predictions?

Part 4: The Structure of Space and Time

_____Current depends on relative velocity of coil and magnet only (Einstein right)
_____Current depends on whether the magnet is at rest and the coil moves or vice versa (Einstein wrong)