24. Faraday's Law of Induction

Objectives

In this experiment, students observe the electromotive force generated by passing a magnet through a coil. Students will explore the relationship between:

- The number of turns in the coil and the magnitude of the electromotive force
- The rate of change of the magnetic flux by virtue of the size of the magnetic field in motion and the magnitude of the electromotive force
- The rate of change of the magnetic flux by virtue of the speed of the magnet field in motion and the magnitude of the electromotive force

Procedural Overview

Students gain experience measuring a continuously changing voltage for a very short duration. This lab pays particular attention to the scientific method of isolating a variable. In each of three parts, students isolate and change a single variable to determine the effect it has on the outcome.

Time Requirement

- Preparation time — 10 minutes
- Pre-lab discussion and activity — 10 minutes
- Lab activity — 30 minutes

Materials and Equipment

For each student or group:

- Data collection system
- Voltage sensor
- Coils (3), 200-, 400-, and 800-turn
- Magnets (3), different strengths
- Rod stand
- Three-finger clamp
- Paper
- Tape
- Pen or pencil
- No-bounce pad (optional)

Concepts Students Should Already Know

Students should be familiar with the following concepts:

- Voltage or electromotive force
- Current
- Magnetic fields
- Acceleration due to gravity

Related Labs in This Guide

Labs conceptually related to this one include:

- Voltage: Fruit Battery/Generator

Using Your Data Collection System

Students use the following technical procedures in this activity. The instructions for them (identified by the number following the symbol: "�") are on the storage device that accompanies this manual. Choose the file that corresponds to your PASCO data collection system. Please make copies of these instructions available for your students.

- Starting a new experiment on the data collection system �(1.2)
- Connecting a sensor to your data collection system �(2.1)
- Changing the sample rate �(5.1)
- Starting and stopping data recording �(6.2)
- Displaying data in a graph �(7.1.1)
- Adjusting the scale of a graph �(7.1.2)
- Displaying multiple data runs in a graph �(7.1.3)
- Adding a note to a graph �(7.1.5)
- Drawing a prediction �(7.1.12)
- Saving your experiment �(11.1)

Background

Michael Faraday (1791–1867) discovered a relationship between a changing magnetic flux Φ (magnetic field strength), and the potential within a conductor ε:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \qquad \text{(Eq. 1)}$$

Known as Faraday's Law, this relationship summarizes how a voltage (potential ε) may be generated by a change in the electromagnetic environment (such as changing the magnetic field strength). It is defined by two key elements: the number of turns in a coil N, and the change in magnetic flux Φ. The negative sign indicates that the induced electromotive force (emf) always opposes the change in magnetic flux. Magnetic flux is related to the strength of the magnetic field B, the area enclosed by the wire loop A, and the angle between them θ.

$$\Phi = BA\cos\theta \qquad \text{(Eq. 2)}$$

Because the size of the coil used in this activity is fixed and students will be dropping the magnet through the coil perpendicular to the plane of the wire loops in the coil (for which the cosine θ term in Eq. 2 equals 1) we can say that the flux is proportional to the strength of the magnetic field B.

Students will investigate the rate of change of flux by using magnets of different strength and increasing the rate at which the magnet passes through the coil. We will use three different coils to see what effect the different number of turns in a coil has on the induced electromotive force.

Pre-Lab Discussion and Activity

For the demonstration station:

- Data collection system
- Voltage sensor
- 800-turn coil
- Projection system recommended
- Magnet
- DC voltage supply
- Magnetic field sensor
- Patch cord, 4-mm banana plug (2)

Connect the DC power supply directly to the coil using the banana plug patch cords. Demonstrate with a magnetic field sensor that, when the power is "off," the magnetic field strength is zero, and when the power is "on," a field is present and stable. Use the magnetic field sensor to show that a stable field is also present around your magnet.

Connect the voltage sensor directly to the coil. Place the magnet in the center of the coil and hold it in place. Begin collecting or monitoring voltage data and show that the voltage produced by the static magnetic field is zero. This can also be accomplished with a demonstration multi-meter or voltmeter.

Challenge your students to predict what will happen when you pull the magnet out of the coil.

Teacher Tip: Accept all answers, and write ideas on the board or overhead projector, keeping them displayed during the activity.

Quickly pull the Magnet out of the coil, and discuss the result relative to the student predictions.

Lab Preparation

These are the materials and equipment to set up prior to the lab.

Although this activity requires no specific lab preparation, allow 10 minutes to assemble the equipment needed to conduct the lab.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Be careful with magnets. Strong magnets can disrupt electronic devices and severely pinch any skin that comes between them.
- Especially keep magnets away from computer hard drives, USB drives, or videotapes.

Sequencing Challenge

The steps below are part of the Procedure for this lab activity. They are not in the right order. Determine the proper order and write numbers in the circles that put the steps in the correct sequence.

1	3	5	4	2
Connect the Voltage Sensor to the Data Collection System.	Drop the magnet through the coil, and then stop data collection.	Compare the voltage produced by the 200-turn coil to that produced by the 400 turn coil on the graph.	Remove the 200-turn coil and replace it with the 400 turn coil.	Begin collecting data with your Data Collection System.

Procedure with Inquiry

After you complete a step (or answer a question), place a check mark in the box (☐) next to that step.

Note: Students use the following technical procedures in this activity. The instructions for them (identified by the number following the symbol: "�") are on the storage device that accompanies this manual. Choose the file that corresponds to your PASCO data collection system. Please make copies of these instructions available for your students.

Part 1 – As the coil turns: same magnet, different coils

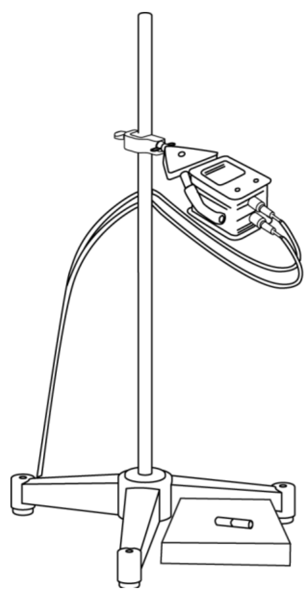
In the first part of this lab, we determine if passing a magnet through a coil of wire gives rise to a voltage (or electromotive force), and whether the number of turns in the coil *N* has any effect on the amount of voltage as predicted in Faraday's equation.

Note: For the best comparison, always be sure to use the same orientation of the magnet when dropping it through the coil.

Set Up

1. ☐ Start a new experiment on the data collection system. �(1.2)

2. ☐ Mount the 200-turn coil to the rod stand using the three-finger clamp, approximately 40 cm above the lab table.



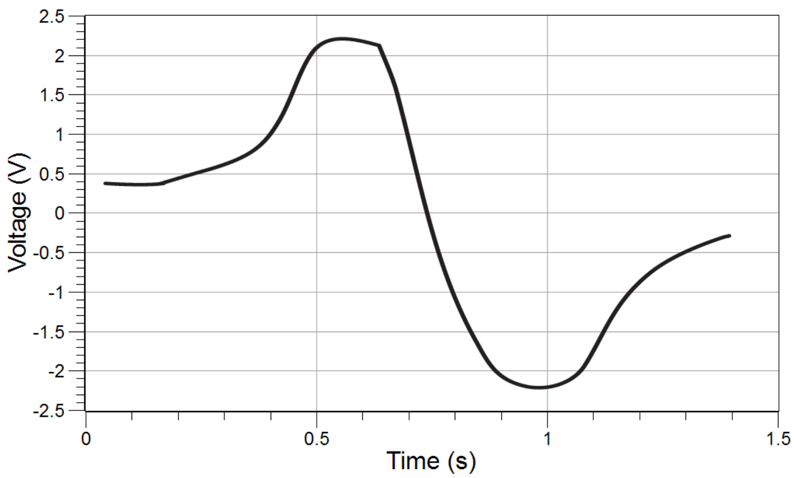
3. ☐ Connect the voltage sensor to the coil. If you are using a no-bounce pad, place it below the coil.

4. ☐ Connect the voltage sensor to the data collection system. �(2.1)

5. ☐ Display a graph of Voltage versus Time data on your data collection system. �(7.1)

6. ☐ Set the sampling rate of your data collection system for at least 1000 samples per second. �(5.1)

7. ☐ Given the bipolar nature of a magnet, try to predict the shape of the Voltage versus Time curve using the data collection system, and sketch your prediction on the graph below. �(7.1.12)



8. ☐ If a changing magnetic field causes charges to move in a conductor, and charges moving in a conductor give rise to a magnetic field, what do you think the orientation of the induced magnetic field would be relative to the original changing magnet field?

The new field should have the opposite orientation of the changing magnetic field.

Teacher Tip: This could also be expressed as resisting or opposing the change of the original field.

Collect Data

9. ☐ Hold the magnet just above the coil opening.

10. ☐ Start collecting data with the data collection system. �(6.2)

11. ☐ Drop the magnet through the coil, and then quickly stop collecting data. �(6.2)

12. ☐ Annotate your data run with the number of turns in the coil you used. �(7.1.5)

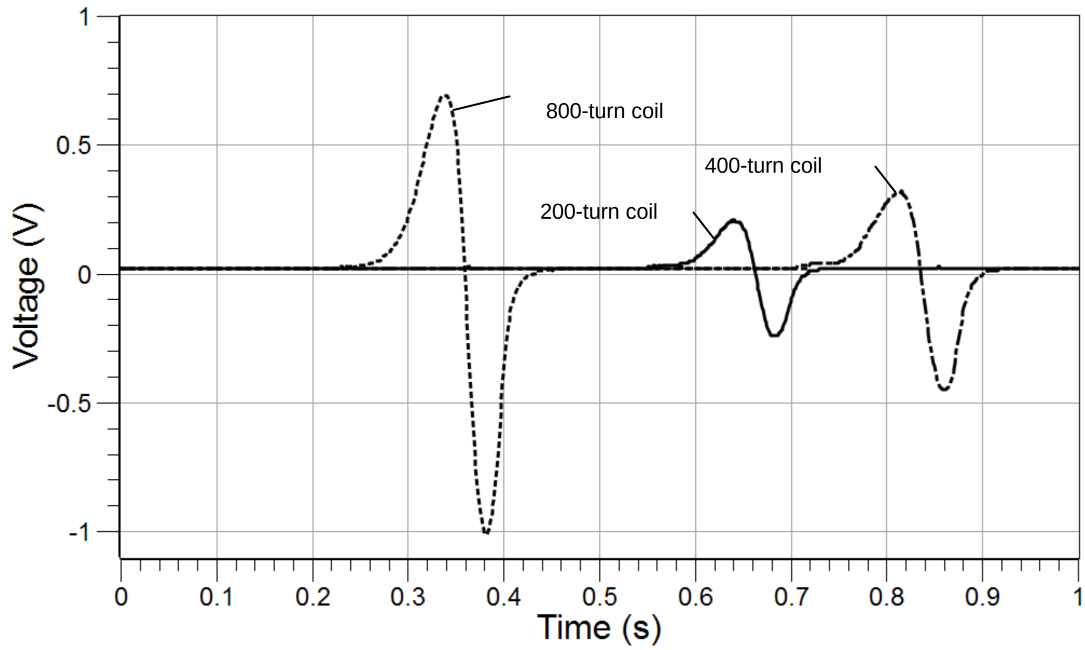
13. ☐ Replace the coil with the next in the series, and repeat the data collection steps for each coil.

Analyze Data

14. ☐ Display all three data runs on the graph on your data collection system. �(7.1.3)

15. ☐ Adjust the axis of your graph to focus on the portions of the graph where the greatest change in voltage takes place. �(7.1.2)

16. ☐ Sketch your graph below, and be sure to indicate which run corresponds to which coil.



17. ☐ Describe one of the major differences between the data runs.

The peak voltage increases as the number of turns in the coil increases

18. ☐ Describe the relationship between the number of turns in the coils and the peak voltages you observed.

The peak voltage appears to be proportional to the number of turns in the coil.

Part 2 – More magnets: same coil, different magnets

The second part of Faraday's equation refers to the rate of change in magnetic flux. From our observations of magnets, different types of material produce different strengths of magnetic field. Try at least three magnets of different strengths to see if the strength of the magnet makes a difference. Use only one of the coils, and drop the magnets from the same height each time.

Set Up

19. ☐ Use the same set up for this part as in Part 1, but use only the 200-turn coil.

Collect Data

20. ☐ Hold the first magnet just above the coil opening.

21. ☐ Start collecting data with the data collection system. �(6.2)

22. ☐ Drop the first magnet through the coil, and then quickly stop collecting data. �(6.2)

23. ☐ Annotate your data run with the identifier for the magnet you used. �(7.1.5)

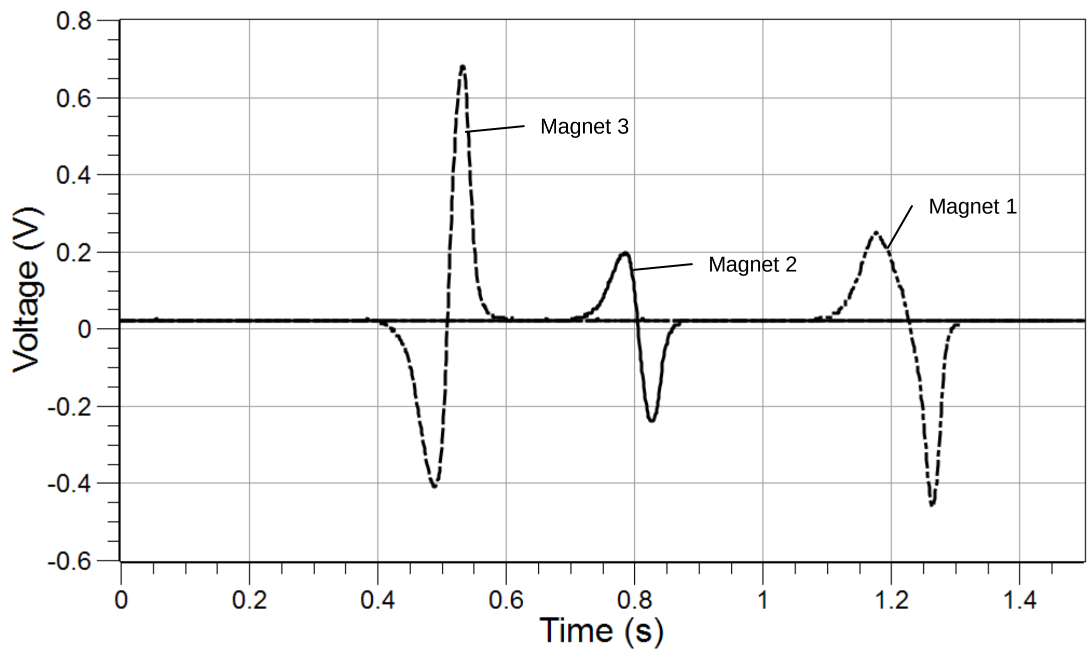
24. ☐ Repeat the data collection steps for each of the magnets, dropping the magnets from the same height each time.

Analyze Data

25. ☐ Display all the data runs on the graph on your data collection system. �(7.1.3)

26. ☐ Adjust the axis of your graph to focus on the portions of the graph where the greatest change in voltage takes place. �(7.1.2)

27. ☐ Sketch your graph below, and be sure to indicate which run corresponds to which magnet.



28. ☐ Describe one of the major differences between the data runs.

The peak voltage increases with stronger magnets.

29. ☐ Describe the relationship between the strength of the magnets used and the peak voltages you observed. What would you measure to better understand the relationship?

The peak voltage appears to be proportional to the strength of the magnet used, but measuring the strength of the magnets would give a better understanding of the relationship.

Part 3 – The faster the flux: one magnet, one coil, and different speeds

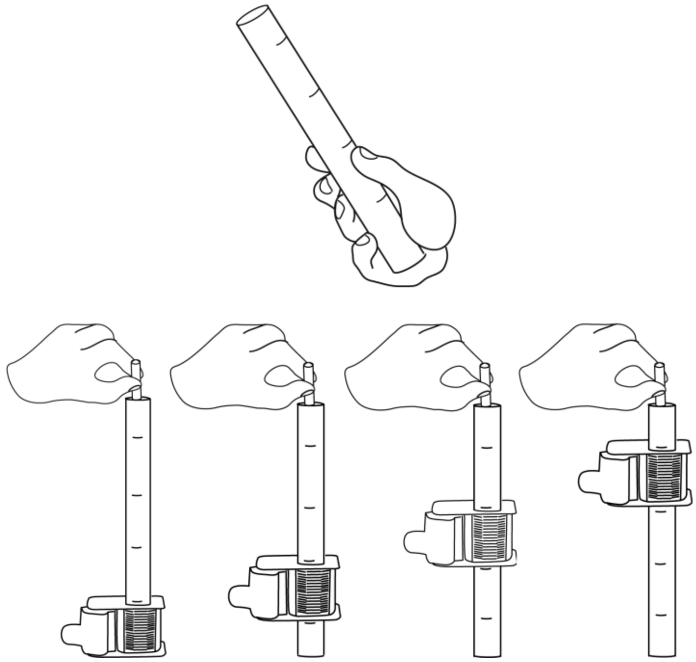
If the strength of the magnet affects the change in flux, how about the speed at which the magnet passes through the coil? The farther an object falls in a gravitational field, the faster it travels. If the magnet passes through the coil faster, it is reasonable that the magnetic flux in the coil is changing faster. Use one of your coils to find out.

Set Up

30. ☐ Use the same set up for this part as Part 1, but using only the 200-turn coil and a single magnet.

31. ☐ Roll up a piece of paper into a tube, and tape it securely. The tube should be wide enough to allow your magnet to pass through freely, but narrow enough to fit inside the coil.

32. ☐ Mark four equally spaced positions on the tube and slide the tube into the coil so that the first mark is showing just above the coil opening.



Collect Data

33. ☐ Hold the magnet just above the tube opening.

34. ☐ Start collecting data with the data collection system. �(6.2)

35. ☐ Drop the magnet through the tube/coil, and then quickly stop collecting data. �(6.2)

36. ☐ Annotate your data run indicating the height from which the magnet was dropped (for example,1st Mark)

37. ☐ Slide the tube down into the coil until the next mark on the tube is just above the opening of the coil.

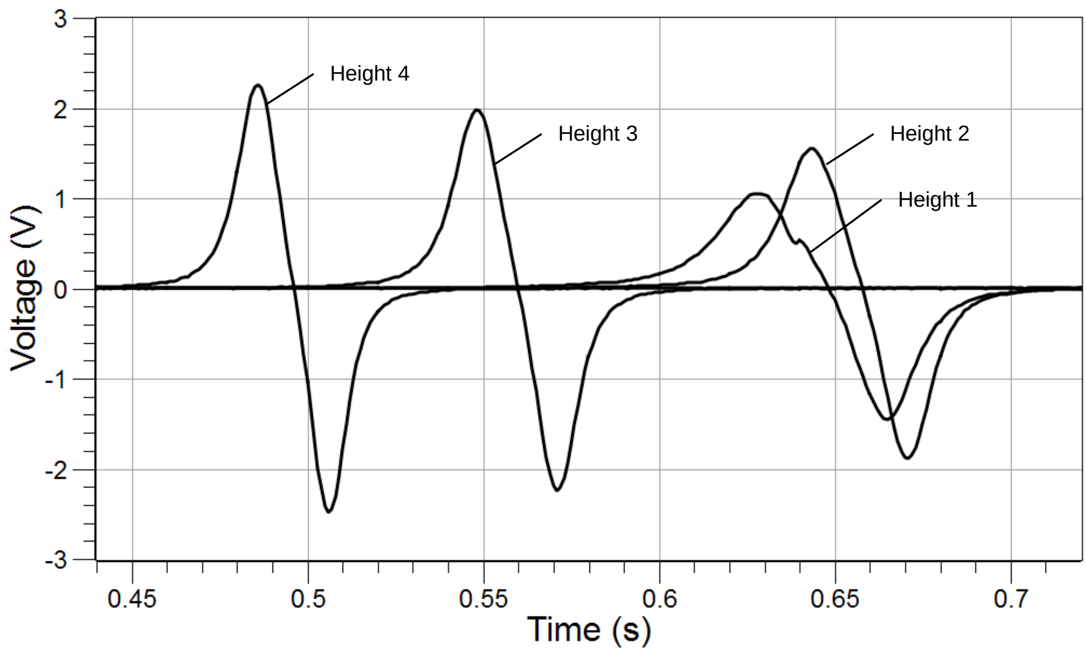
38. ☐ Repeat the data collection steps for each mark on the side of the tube.

Analyze Data

39. ☐ Display all the data runs on the graph on your data collection system. �(7.1.3)

40. ☐ Adjust the axis of your graph to focus on the portions of the graph where the greatest change in voltage takes place. �(7.1.2)

41. ☐ Sketch your graph below, and be sure to indicate which run corresponds to which height.



42. ☐ Describe one of the major differences between the data runs.

The peak voltage appears to increase with the speed of the magnet through the coil

43. ☐ Describe the relationship between the height at which the magnet fell above the coil and the peak voltages you observed. What would you measure to better understand the relationship?

The peak voltage appears to be proportional to the speed the magnet travels through the coil, but measuring the speed of the magnet as it passes through the coil would give a better understanding of the relationship.

44. ☐ Save your experiment and clean up according to your teacher's instructions. �(11.1)

Analysis Questions

1. How does your prediction compare to the actual Voltage versus Time graph?

Answers will vary.

Synthesis Questions

Use available resources to help you answer the following questions.

1. Based on your observations in this lab, describe the characteristics of an electric coil generator that you would optimize to get the most electromotive force out?

To produce the largest electromotive force, the generator would need to have as many coil turns as possible, have the strongest magnets available, and move as fast as possible.

2. You may have noticed that the second peak of the voltage curve is always in the opposite direction of the first peak. However, you may not have noticed that it is also a slightly higher peak. Can you describe why that might be?

The peak was higher because the magnet is speeding up as it falls, making the top part of the magnet travel faster as it passes through the coil.

Multiple Choice Questions

Select the best answer or completion to each of the questions or incomplete statements below.

1. The electromotive force (emf) produced from dropping a magnet through a coil is a form of energy transformation. What kind of transformation is it?

- **A.** Thermal energy is transformed into electrical energy.
- **B.** Mechanical energy is transformed into thermal energy.
- **C.** **Kinetic energy is transformed into electrical energy.**
- **D.** Electrical energy is transformed into thermal energy.

2. If a generator with a 200-turn coil produced 120 V of electromotive force, how much would it produce if it was upgraded to an 800-turn coil?

- **A.** 40 V
- **B.** **480 V**
- **C.** 220 V
- **D.** There is not enough information to draw a conclusion.

3. The equation for Faraday's Law includes a negative sign on one side. What does it represent?

- **A.** Magnetism is an inherently negative force.
- **B.** Opposites attract.
- **C.** The emf generated seeks to reinforce the change in magnetic field.
- **D.** **The emf generated seeks to oppose the change in magnetic field.**

Key Term Challenge

Fill in the blanks from the list of randomly ordered words in the Key Term Challenge Word Bank.

1. Faraday's Law defines the relationship between the number of turns in a **coil** N, and the rate of change in **magnetic flux** Φ. Magnetic flux is related to the strength of the magnetic field, the area enclosed by the wire loop, and the angle between them. Because of the geometry of the experiment, we can say that the flux is proportional to the strength of the magnetic **field**.

Extended Inquiry Suggestions

Project: Build a Generator

Provide your students with raw parts (such as magnets, wire, etc.), and have them build a small generator. In groups of 3 to 5 students, ask them design and build a generator. Ask them to present their work to the class and include a live demonstration of the device.

Introducing area under a curve

Ask your students to repeat the experiment using one magnet and one coil of their choosing. On the graph of Voltage versus Time, have them use their data collection system to explore the area under the curve. �(9.7)

What are the units for the area under the curve?

Volt-seconds (v•s)

What does this represent?

The volt-second is also known as the weber and is a unit of magnetic flux

Demonstration

Use a hand-cranked generator to show how physical motion can be used to produce an electromotive force, and induce current to power a circuit.

Also, a discussion of electrical transformers could help here. You can discuss the electrical grid and how voltages are adjusted for domestic use and long-distance transmission. A great demo to enhance this discussion would be a "Jacob's Ladder," which transforms voltage from 120 V AC up to 10,000 V AC which is then high enough to jump a small gap and form the infamous "rising spark" so common to old sci-fi movies.

Other relevant applications worth mentioning are:

How does a "hybrid" car save so much money on gas?

Induced current from mechanical braking sets up an induced current that recharges electrical batteries, which becomes usable energy.