E&M Laboratory 1106, Summer 2025

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https://www.physics.smu.edu/tneumann/110X_Summer2025/

Lab 10 — Electromagnetic Induction in a Solenoid Max. points: 56

Your preparation: Work through before coming to the lab

- Prepare for the lab by thoroughly reading and understanding the measurement and analysis procedures on this worksheet. Photos of the equipment and further introductory material will be made available on https://www.physics.smu.edu/tneumann/110X_Summer2025/schedule-em/.
- Collect all your questions and ask your instructor at the beginning of the lab.
- Study the following topics in Halliday, Resnick, and Walker [1]: Understand the concept of a magnetic field and how it exerts a force on moving charges. Review the concept of a magnetic dipole moment and how a magnetic field exerts a torque on a magnetic dipole.

  Study Faraday's Law of electromagnetic induction, including the relationship between changing magnetic flux and induced electromotive force (EMF). Understand Lenz's Law and how it determines the direction of induced currents. Review the concept of magnetic flux and how it changes in different situations, such as a magnet moving through a coil.

  Understand the concepts of electrical power and energy dissipation in a resistor. Review Ohm's Law and how it relates voltage, current, and resistance.

Pre-lab: Upload to Canvas before coming to the lab

A reminder: Upload your answers as a text document (exported as PDF) to Canvas before the lab begins (Canvas uploads are no longer possible 30 minutes before the lab starts!).

Pre-lab 1 — 12 points

1. (1 point) State Faraday's Law of electromagnetic induction in your own words. Explain the relationship between a changing magnetic flux and the induced electromotive force (EMF).
2. (1 point) State Lenz's Law. How does it relate to the direction of the induced current in a coil?
3. (2 points) A cylindrical magnet is dropped through a solenoid. Describe how the magnetic flux through the solenoid changes as the magnet falls. Consider the different stages of the magnet's motion (approaching, inside, and leaving the solenoid).

4. (2 points) In the qualitative observations section, you will observe LEDs connected to the solenoid. Explain how the direction of the induced current in the solenoid will affect if an LED will light up.
5. (2 points) Consider the falling magnet and the solenoid. Describe the different forms of energy present in this system, and explain how these forms of energy change as the magnet falls through the solenoid.
6. (2 points) The copper collar is observed to slow down the falling magnet. Explain why this happens, referencing the concepts of induced currents and Lenz's Law.
7. (2 points) In the quantitative analysis section, you will plot the power dissipated in the resistor versus time as the magnet falls through the solenoid. Sketch a qualitative prediction of what you expect this plot to look like. Justify your prediction, considering how the induced current changes as the magnet moves.

Lab measurements and report: submission by end of class

A reminder: All measurements must be fully documented . The final report must be uploaded to Canvas *by the end of the class* exported as PDF with plots and tables from Excel or Capstone embedded as images. Canvas will stop accepting uploads 10 minutes after the class ends. If you have not fully completed your report, you must upload the documents as far as you have completed them for grading.

Measurement 1 *Qualitative Observations of Electromagnetic Induction* 13 points

Equipment: Solenoid, transparent plastic tube, cylindrical magnet (with red sticker marking the north pole), two connecting cables, copper collar, oscilloscope.

Important note: *Handle the magnets with extreme care, as they are very brittle and can easily break.*

1. (5 points) **General observations about Faraday's Law and Lenz's Law:**

   Begin by setting up the demonstration apparatus as illustrated in the introductory photo and connect the two LEDs to the solenoid. Your first task is to investigate the behavior of the LEDs as the magnet falls through the transparent tube. Initially, ensure the switch is in the **ON** position. Drop the magnet through the tube and carefully observe the LEDs. Note whether both LEDs flash, and if so, which one flashes first. Next, set the switch to the **OFF** position and repeat the drop. Again, observe which LED flashes.

   A crucial aspect of this experiment is to determine the relationship between the magnet's orientation and the LED behavior. Pay close attention to whether the LEDs flash when the north pole of the magnet is facing up versus when it is facing down. Recall that an LED will only illuminate when the current flows in the correct direction.

2. (3 points) Use the oscilloscope to examine the voltage across the LED as the magnet passes through the solenoid and take a screen capture on the oscilloscope. Discuss in how far the volt-

age measurement is consistent with an inductive rising and falling waveform and the flashing of the LEDs.

3. (5 points) **Effect of Copper Collar:** For the second part of this qualitative study, you will investigate the effect of the copper collar on the magnet's motion. Place the copper collar over the tube. Drop the magnet through the tube again, carefully observing its falling speed before, within, and after passing through the collar. Note whether the LEDs flash during this process, and if they do, how brightly they illuminate. In your report, provide a thorough explanation for why the copper collar significantly reduces the magnet's falling speed and why the LEDs' light is so faint in this configuration.

Measurement 2 *Quantitative Study of Electromagnetic Induction* Equipment: Solenoid, transparent plastic tube, cylindrical magnet, dual-beam photogate, Capstone software, digital multimeter (DMM), 5 Ohm (nominal) resistor, oscilloscope, USB drive. 16 points

1. (3 points) **Resistance Measurements:**

   Begin by preparing the apparatus for this quantitative measurement: First, remove the copper collar and disconnect the LEDs from the solenoid. Using the digital multimeter (DMM), carefully measure and record the resistance of both the solenoid coil and the 5 Ohm (nominal) resistor. Ensure that you document both resistance values in your lab report.

2. (7 points) **Velocity Measurements:**

   Next, connect the 5 Ohm resistor to the terminals of the solenoid coil. Activate the dual-beam photogate and prepare to measure the magnet's velocity as it falls through the tube.

   (a) Drop the magnet through the tube, and use the Capstone software to accurately measure its velocity as it exits the tube. Record this velocity.

   (b) Repeat the previous step at least five times, recording each velocity measurement.

   (c) Calculate the average velocity from your five trials.

   (d) Calculate the standard deviation of the mean of the velocity measurements. This will serve as your uncertainty in the velocity.

   Repeat the above steps with the coil open (no resistor connected). It is important to note that the magnet may occasionally bounce back up the tube after falling, generating a second measurement. Discard these data points, as the recorded speed will be significantly different from the free-fall velocity. Use the average velocity for the following calculations.

3. (5 points) **Voltage Measurements:**

   With the resistor still connected to the coil, drop the magnet through the tube again. This time, use the oscilloscope to measure the voltage across the resistor. Carefully observe the voltage waveform, paying particular attention to the characteristic dip and rise. Determine whether the leading pulse is positive or negative, and correlate this observation with the orientation of the magnet (north pole up or down) during the drop. Compare the oscilloscope screen capture obtained here with the one you obtained during the qualitative observations when the LED was in the circuit. Note any differences in the time separation between the two pulses and discuss the underlying reasons for this difference in your report. Finally, transfer the voltage versus time data to your computer using a USB drive for further analysis.

4. (1 point) **Magnet Mass:**

   Weigh the magnet using a suitable scale and record its mass.

Analysis 1 *Data Analysis and Interpretation* 15 points

1. (10 points) **Energy Calculations:**

   (a) **Electric Energy Induced:** The goal here is to calculate the total electric energy (E_{elec}) induced in the coil by the passing magnet. This will be done by integrating the power over time.

   (b) **Current Calculation:** First, determine the current ($I(t)$) in the coil at each time point using Ohm's Law. The voltage ($V(t)$) across the resistor is measured by the oscilloscope. The current is then given by:

   $$I(t) = \frac{V(t)}{R_{\text{resistor}}} \tag{1}$$

   where R_{resistor} is the resistance of the 5 Ohm resistor.

   (c) **Power Calculation:** Next, calculate the instantaneous power ($P(t)$) dissipated in the circuit at each time point. The total resistance of the circuit is the sum of the coil resistance (R_{coil}) and the resistor resistance (R_{resistor}). The power is given by:

   $$P(t) = I(t)^2 \cdot (R_{\text{coil}} + R_{\text{resistor}}) \tag{2}$$

   (d) **Power vs. Time Plot:** Create a plot of the calculated power ($P(t)$) versus time (t).

   (e) **Peak Observations:** Observe that both peaks in the power vs. time plot are positive.

   (f) **Peak Height Comparison:** Observe if the second peak is always higher than the first, regardless of the magnet's orientation. Discuss the reasons for these observations in terms of the changing magnetic flux and Lenz's law.

   (g) **Total Electric Energy:** Finally, calculate the total electric energy (E_{elec}) generated through induction by integrating the power over time. This can be approximated by summing the area under the power vs. time curve:

   $$E_{elec} = \int P(t)\,dt \approx \sum_i P(t_i)\Delta t_i \tag{3}$$

   where Δt_i is the time interval between measurements.

2. (5 points) **Kinetic Energy Comparison:**

   (a) **Kinetic Energy Difference:** Extract information about the difference in kinetic energy (ΔK) of the magnet from the speed measurements with and without the resistor connected. The kinetic energy (K) of the magnet is given by:

   $$K = \frac{1}{2}mv^2 \tag{4}$$

where m is the mass of the magnet and v is its velocity. The difference in kinetic energy is then:

$$\Delta K = K_{\text{open}} - K_{\text{resistor}} = \frac{1}{2}m(v_{\text{open}}^2 - v_{\text{resistor}}^2) \tag{5}$$

where v_{open} is the velocity with the coil open and v_{resistor} is the velocity with the resistor connected.

(b) **Energy Comparison:** Compare the electric energy generated (E_{elec}) with the kinetic energy loss (ΔK).

(c) **Conclusions:** Draw conclusions about electromagnetic induction and the efficiency of the energy conversion process. Discuss whether the electric energy generated is approximately equal to the kinetic energy lost by the magnet. Comment on dominant systematic or random uncertainties that affect your measurement and the ability to draw this conclusion.

References

[1] D. Halliday, R. Resnick, and J. Walker. *Fundamentals of Physics*. Fundamentals of Physics. John Wiley & Sons.