LAKE FOREST COLLEGE
Department of Physics

Physics 115 **Experiment #10: Solenoid Field and Faraday's Law** Spring 2025

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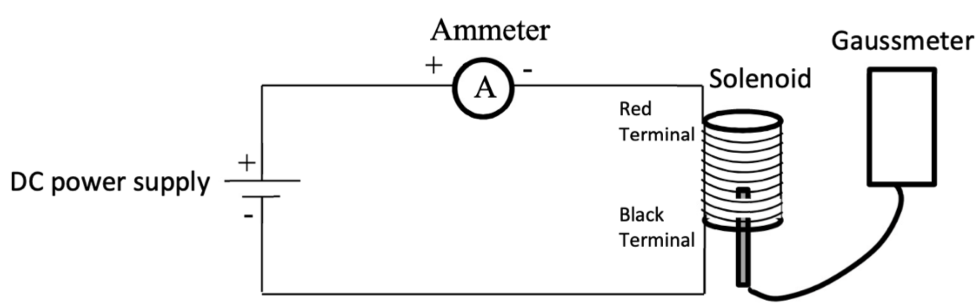
Preliminary Instructions
Create a folder for you and your lab partner on Teams. Save a copy of these instructions for each student to that folder. Include your name in the filename. As you edit this document put your text in a different color. Save one copy of the Excel template with both your and your partner's name included in the filename.

Experimental Purpose:
Determine the magnetic field in a solenoid and test the validity of Faraday's Law of Induction.

Background:
A voltage can be induced in a coil by a changing magnetic field in the coil, but not by a steady field in the coil. More exactly, a voltage is induced by a changing "magnetic flux" in the coil. A magnetic flux, Φ_B, is defined as the number of magnetic field lines passing through the coil, i.e. $\Phi_{\text{coil}} = N_{\text{coil}} B_z A_{\text{coil}}$ where N is the number of turns in the coil, and B_z is the magnetic field component perpendicular to the area, A, of the loop. Faraday's law states that the voltage induced in the coil is equal to the rate of change of the magnetic flux.

$$\text{Faraday's law: } \mathrm{E} = -\frac{\Delta\Phi_B}{\Delta t}; \left(\text{actually } \mathrm{E} = -\frac{d\Phi_B}{dt}\right)$$

Part I: The magnetic field of a solenoid.



1. Connect an ammeter in series with the solenoid and the DC power supply. Arrange your circuit such that positive current will flow clockwise around the solenoid as viewed from the end near the desktop computer.

2. Use the zero-gauss chamber to zero the Lakeshore gaussmeter.

3. Place the magnetic field probe at the center of the solenoid along the axis of the solenoid using the holder. Insert the probe into the end of the solenoid nearest the wall.

4. Measure the magnetic field component along the axis of the solenoid for five different currents in the solenoid including 0 A. Do not exceed 2 A.

5. A positive reading on the magnetic field sensor corresponds to a magnetic field that is directed into the probe. Confirm this direction using the 3D compass.

6. Reverse the leads at the power supply in order to run current through the solenoid in the other direction. Measure the component of the magnetic field for four different negative currents down to −2 A. Check the direction of the magnetic field using the 3D compass. **Insert the table here. Include a table caption.**

I (A)	B_z (mT)	B_z (T)
0.00	0.01	0.00001
0.25	0.45	0.00045
0.50	0.92	0.00092
0.75	1.34	0.00134
1.02	1.84	0.00184
1.25	2.22	0.00222
1.51	2.69	0.00269
1.75	3.11	0.00311
2.01	3.59	0.00359
-0.51	-0.93	-0.00093
-1.02	-1.78	-0.00178
-1.5	-2.66	-0.00266
-2.00	-3.55	-0.00355

Table 1. Current and Magnetic Field Measurements. The Magnetic Field of the solenoid was measured using a LakeShore Gaussmeter. Current was provided using a Topward DC Power supply and measured using a Fluke multimeter. The field of a positive current was measured up to 2A at increments of 0.25A. The field of a negative current was measured down to -2A at increments of -0.5A.

7. Use *Logger Pro* to plot the component of the magnetic field inside the solenoid as a function of the current in the solenoid. Include both positive and negative current points on the same plot. Fit the magnetic field inside the solenoid as a function of current to a straight line

($B_z = mI + b$) . A small environmental field may cause there to be a nonzero intercept, *b*. **Insert the graph here. Include a graph caption.**

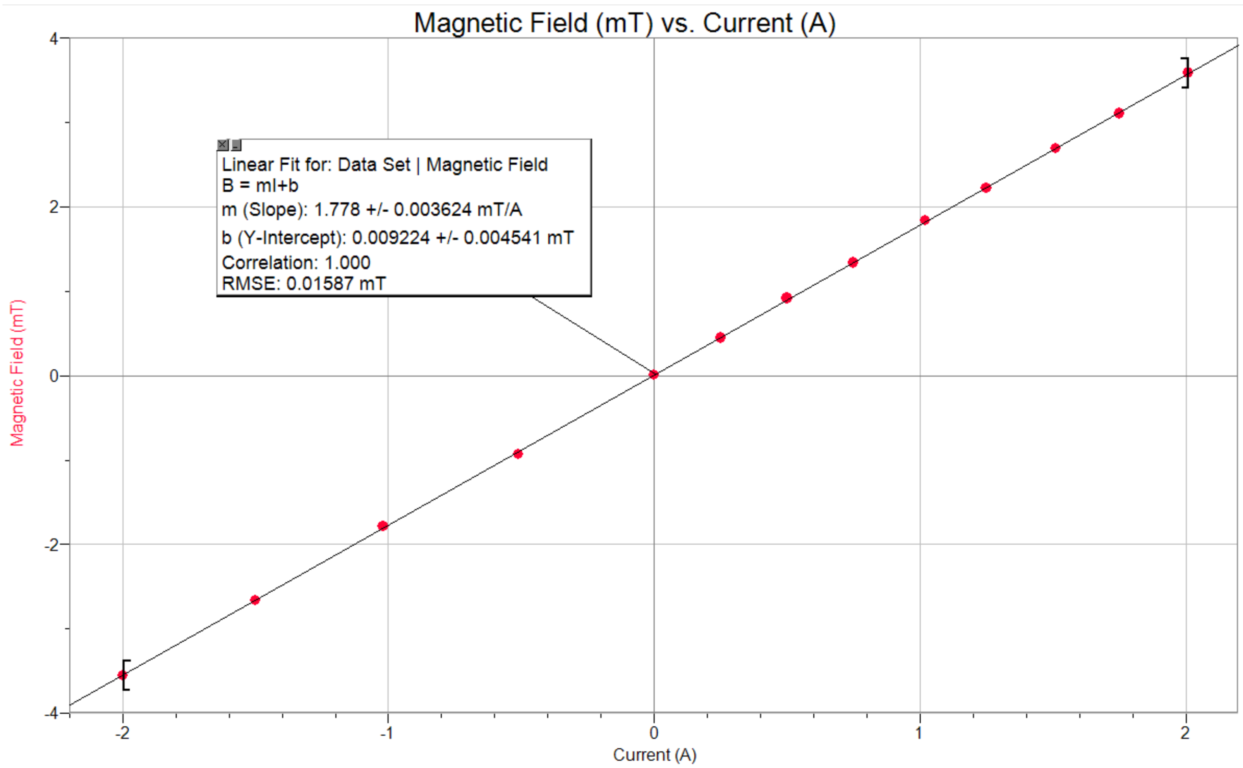


Figure 1. Magnetic Field vs. Current Graph. Current, in amps, is on the x-axis. Magnetic field, in milli-Tesla, is on the y-axis. A line was fitted to 13 measured data points. The slope of the line y=m(x)+b is equivalent to the equation $B_z = \mu_o N/L(I) + B_{oz}$.

8. Copy the fit parameters and their uncertainties into the spreadsheet. **Insert the table here. Include a table caption.**

	Measured slope of B_z vs I (T/A)
value	0.001778
abs unc	3.62E-06
rel unc (%)	0.20%

Table 2. Measured Slope of Magnetic Field vs Current. The slope comes from the linear fit LoggerPro graph. The slope, m, represents $\mu_o N/L$. The absolute uncertainty comes from the uncertainty of the slope.

9. Use the meterstick to measure the length of the solenoid. Note that this is the length of the wire windings, not the length of the plastic. Record your measurement and uncertainty in the spreadsheet. The absolute uncertainty is probably 1 mm.

10. The number of turns in the solenoid has been carefully determined and written on a notecard. Record this number and its uncertainty in the table.

11. For an ideal very long solenoid we expect that the magnetic field inside the solenoid should be $B_{\text{solenoid }z} = \dfrac{\mu_0 N_{\text{solenoid}} I}{L}$, where $\mu_0 = 1.25663706127 \times 10^{-6}\ \dfrac{\text{T}\cdot\text{m}}{\text{A}}$, N_{solenoid} is the number of turns of wire in the solenoid, and L is the length <u>of the windings</u> of the solenoid.

12. **Explain why the slope of B_z vs I for a long solenoid equals $\mu_0\ N_{\text{solenoid}} / L$.**

The slope is $\mu_o N/L$ because it is the coefficient of current and current is the x value. y=m(x)+b is equivalent to the equation $B_z=\mu_o N/L(I) + B_{oz}$. Where y is B_z, x is I, and b is B_{oz}, so m = $\mu_o N/L$.

B_{oz} is the background field that comes from the earths magnetic field and other magnetic field in Lillard.

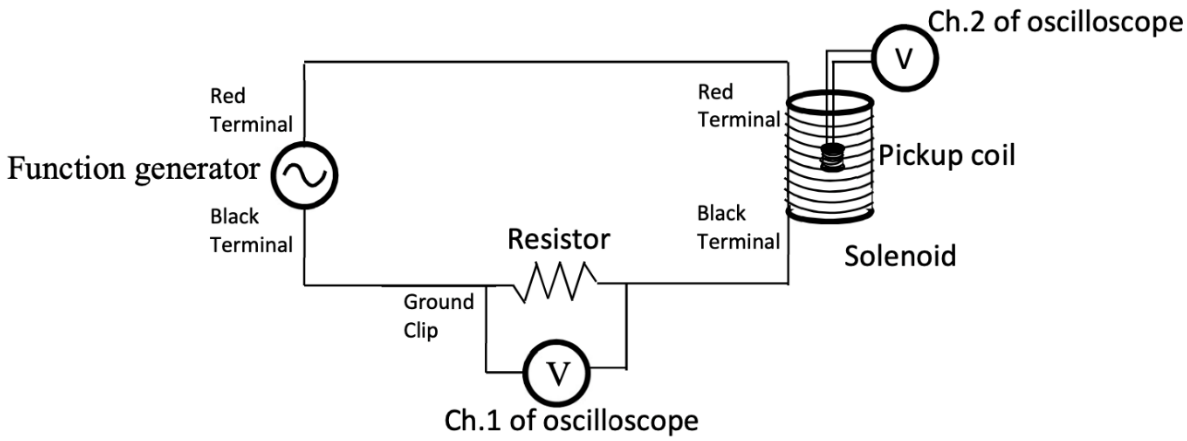
13. Predict the slope of B_z vs. I. Compare your fitted slope to your prediction. **Insert these tables here. Include table captions.**

	m₀ **(T·m/A)**	***N*****solenoid**	***L*** **(m)**	**Predicted slope of *B*z vs *I* for a long solenoid (T/A)**
value	1.2566E-06	799.4	0.562	0.001787
abs ubc	2.00E-16	0.5	0.001	4.30E-06
rel unc (%)	0.000000016%	0.063%	0.18%	0.24%

ratio test for slopes
1.2

Table 3. Measured vs Calculated Magnetic Field Magnitude. The predicted slope was calculated using the equation m = $\mu_o N/L$ where μ_o is the permeability constant, N is the number of loops of the solenoid, and L is the length of the solenoid. The calculated value agreed with the measured one according to the ratio test.

Part II: Induced emf



14. Connect the function generator, resistor, and solenoid in series. Connect the channel 1 voltage probe of the oscilloscope across the resistor. Measuring the voltage across this resistor will allow us to determine the current in the solenoid and the magnetic field inside the solenoid. Its resistance is written on its aluminum base. Record the resistance and its uncertainty in your Excel table. Note: $1.005(3)\ \Omega = (1.005 \pm 0.003)\ \Omega$

Note: The ground clip of the oscilloscope must be at the same point in the circuit as the ground of the function generator. The instructor can help you with this subtle point.

15. A custom manufactured pickup coil will detect the induced emf. The coil is made with $N_{\text{coil}} = 200 \pm 1$ turns of 30 AWG wire wound on a cylinder. The diameter of the coil is $d_{\text{coil}} = 32.1 \pm 0.2$ mm. Calculate the area of the coil and its uncertainty. **Insert the table here. Include a table caption.**

	d_{coil} (m)	A_{coil} (m^2)	N_{coil}	R (Ω)
value	0.0321	0.000809	200	1
abs unc	0.0002	1.01E-05	1	0.01
rel unc (%)	0.62%	1.25%	0.50%	1.00%

Table 4. Induced EMF Calculations. The diameter of the solenoid was given. The area of the solenoid was calculated using the equation $A = \pi(d/2)^2$. The relative uncertainty of the solenoid area was calculated by doubling the relative uncertainty of the diameter. N_{coil} is the number of wire loops around the solenoid, this value was given. The resistor with resistance R was in series with the solenoid.

16. Insert the coil into the end of the solenoid nearest the computer. Position the pickup coil in the center of the solenoid with the axes of the two coils aligned.

17. Attach the cable of the pickup coil to channel 2 of the oscilloscope.

18. Turn on the oscilloscope. It measures voltage as a function of time. The settings should be Channel 1: 500 mV/div (x10), Channel 2: 50 mV/div (x1), Time base: 2.50 ms/div, 20 MHz bandpass filter on both channels, averaging 64 cycles.

19. Turn on the function generator and set it to give a triangle wave with a frequency of 50 Hz and an amplitude of 10.0 V. The oscilloscope simultaneously displays voltages across the resistor and the pickup coil.

20. Download the data from the oscilloscope to the computer using the *Open Choice* application. Make sure the USB0 instrument is attached; Ch 1 & 2 are selected; select "Waveform Data Capture" and "Get Data" and "Save As" to a CSV file in your folder.

21. Open the CSV file using *Excel*. Columns D & E are the time and voltage data for Ch 1, respectively. Columns J & K are the time and voltage for Ch 2. Note that columns D and J are identical.

22. Open the *Logger Pro* file "Faraday's Law Graphs" on the desktop. Copy and paste the time, channel 1 (V solenoid), and channel 2 (emf) columns from Excel into *Logger Pro*. Note there are 2500 points. <u>Use tiny solid circles for the data points</u>.

23. Select an upward sloping straight line portion of the voltage across the resistor. Fit this region to a straight line using the linear fit function of *Logger Pro*. The slope gives the rate of change of the potential across the resistor, $\Delta V_1 / \Delta t$. The absolute uncertainty in the slope may be larger than the fitting uncertainty because of the slight curvature of the waveform.

24. Use $\Phi_{\text{coil}} = N_{\text{coil}} B_z A_{\text{coil}}$, $B_z = mI + b$, $V_1 = IR$, $\mathrm{E} = -\frac{\Delta\Phi_{\text{coil}}}{\Delta t}$, and $V_2 = \mathrm{E}$ to derive an expression for the predicted induced voltage in the pickup coil. Your answer should be

$$V_2 = -N_{\text{coil}}\, m \frac{1}{R} \frac{\Delta V_1}{\Delta t} A_{\text{coil}}. \qquad \text{Eq. 1}$$

Insert your derivation here.

$$\Phi_{coil} = NB_zA = N(mI + b)A = N\left(m\frac{V_1}{R} + b\right)A$$

$$E = -\left(\frac{\Delta\Phi}{\Delta t}\right) = -\left(\frac{Nm\frac{\Delta V_1}{R}A}{\Delta t}\right) = -Nm\frac{1}{R}A\left(\frac{\Delta V_1}{\Delta t}\right)$$

Figure 2. Voltage Equation Derivation. Φ is the magnetic flux, N is the number of turns, B_z is the magnitude of the magnetic field, A is the area of the solenoid, R is the resistance, and M is the slope of the line calculated in part 1.

25. Use the above expression with your positive slope measurement to calculate the predicted induced emf and its absolute uncertainty. Employ the *m* value from step 7. Both absolute and relative uncertainties are always positive. Use absolute value when necessary.

26. Over the same time region as your straight line fit of the voltage across the resistor, determine the mean reading of the pickup coil induced voltage using the statistics function of *Logger Pro*. Compare your measured value to your prediction using a ratio test.

27. Repeat your measurements and predictions for a downward sloping straight line region of the voltage across the resistor. **Insert the graph and the tables here. Include captions.**

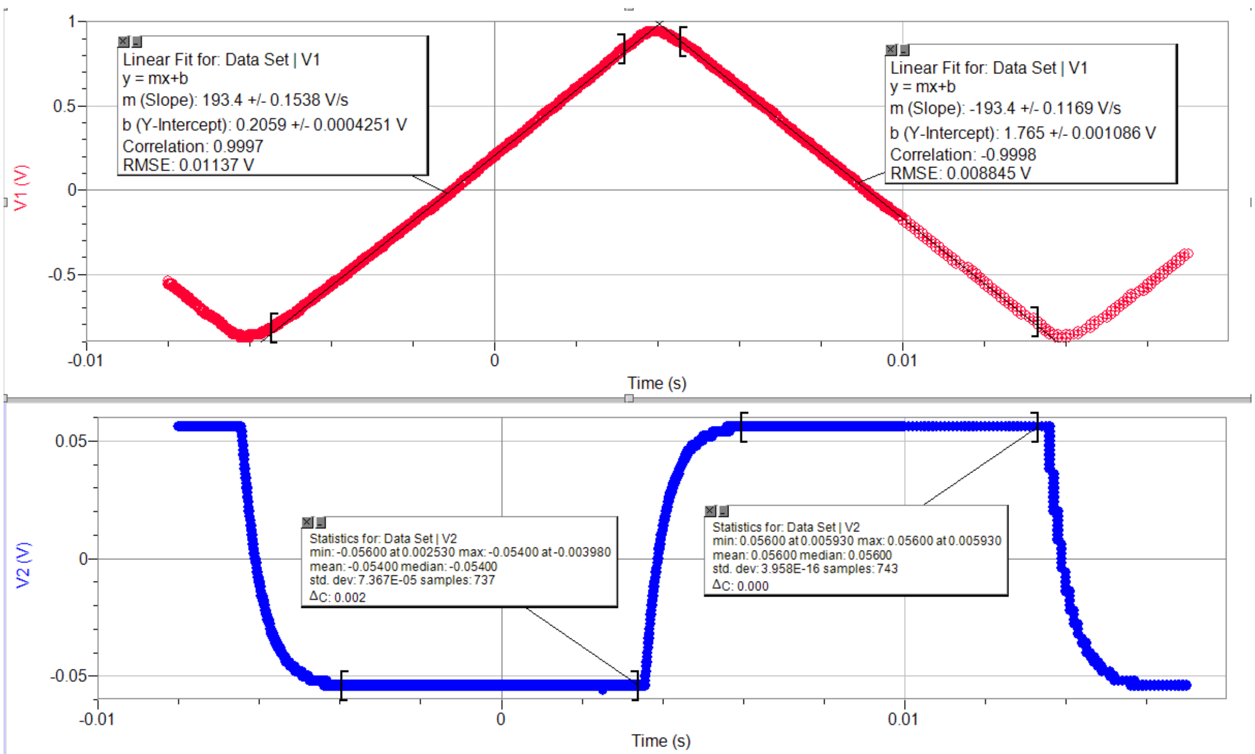


Figure 3. Voltage Graph. The data points come from the change in voltage over time as measured by a Tektronix oscilloscope. The slope of the top line is the $\Delta V_1/\Delta t$ and the mean of the bottom line is V_2.

Upward sloping region

	Measured DV_1/Dt (V/s)	Predicted V_2 (V)	Measured V_2 (V)	ratio test
value	193.4	-0.0557	-0.0540	0.94
abs unc	0.1538	0.0017	7.37E-05	
rel unc (%)	0.1%	3.0%	0.14%	

Downward sloping region

	Measured DV_1/Dt (V/s)	Predicted V_2 (V)	Measured V_2 (V)	ratio test
value	-193.4	0.0557	0.0560	0.20
abs unc	0.1169	0.0017	3.96E-16	
rel unc (%)	0.1%	3.0%	0.0000000000%	

Table 5. Calculated Measured and Predicted Voltages The predicted voltages were calculated using the equation derived above. Measured dv/dt and V_2 were measured using a Tektronix oscilloscope. In both upwards sloping region and downward sloping region, the calculated agreed with the measured according to the ratio test.

Conclusion:

The magnetic field of a solenoid has a linear relationship with current when slope is equal to $\mu_o N/L(I)$. When N = 799.4±0.5 loops and L= 0.562±0.001m then the coefficient of current, I, is 0.001787±0.0000043T/A. This agrees with the measured value of 0.001778±0.0000036 T/A according to the ratio test.
Faraday's Law states that the EMF is the negative rate of change on the magnetic flux. This is confirmed because changing the voltage in the inner solenoid which changes the flux, creates a voltage. The calculated produced voltage of -0.0557±0.0017V agrees with the measured voltage of 0.0540±0.000074V according to the ratio test. The calculated voltage of 0.0557±0.0017V agrees with the measured voltage of 0.0560±(3.9×10^{-16}) V according to the ratio test.

Final remarks
Adjust the formatting (pagination, margins, size of figures, etc.) of this report to make it easy to read. Save this report as a PDF document. Upload it to the course Moodle page. Double check that your Excel sheet, graphs, and Logger Pro files are saved in your folder on the Team. Clean up your lab station. Put the equipment back where you found it. Make sure that you logout of

Moodle and your email, then log out of the computer. Check with the lab instructor to make sure that they received your submission before you leave. Check with the lab instructor to make sure that they received your submission before you leave.