Department of Physics

Magnetic fields and Faraday's Laws

1120 Lab 5R Simulation

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I Lab Objectives

- Identify the factors that affect the magnetic fields produced by a current-carrying solenoid.
- Identify the factors that affect the magnitude of the induced emf and the induced current in a coil.

Lab Materials

- Computer with internet access

Links for this lab

- Electromagnetism Physlet
- Faraday's Laws PhET Sim

II Theory

II.1. Magnetic field of a magnet

A magnet attracts magnetic materials like iron nails, when they are brought close to the magnet. When some iron filings are sprinkled around a bar magnet by placing it on a cardboard and then gently tapped, the iron filings settle forming a pattern as shown in Fig. 1.

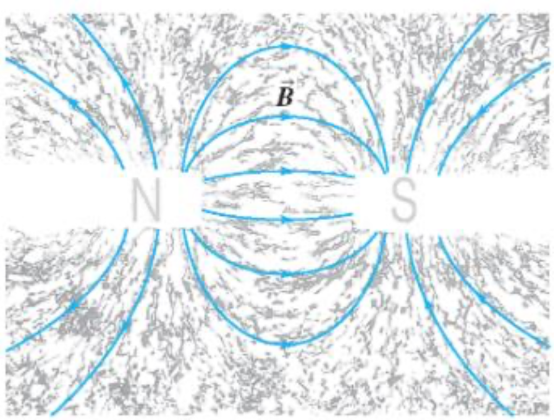

Figure 1: Iron filings forming a pattern around bar magnets.

A magnetic compass needle around a magnet at rest would show different directions in different locations, as shown in Fig. 2. All these observations are related to the magnetic field of a magnet. The magnetic field around a magnet is the space where the magnet influences magnetic materials or other magnets, i.e., a magnet attracts magnetic materials, and attracts or repels another magnet.

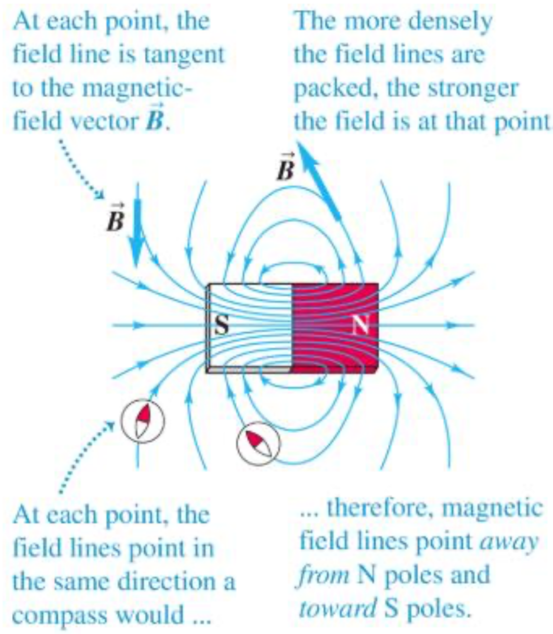

Figure 2: Magnetic compass needles placed around a bar magnet.

II.2. Magnetic field sources

The common sources of magnetic field seen around our homes or labs are bar magnets, rod magnets, magnetic strips in the refrigerator doors, etc. They are permanent magnets. Other sources of magnetic field are current carrying wires. One commonly used source of magnetic field is a current-carrying solenoid. Fig. 3 shows the magnetic field produced by a current-carrying solenoid at various points on its axis.

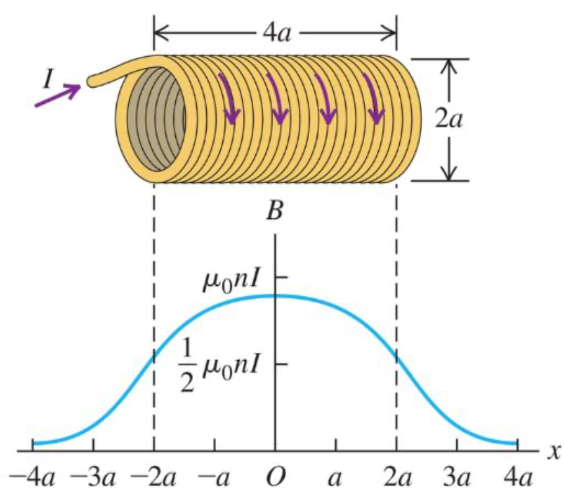

Figure 3: Magnetic field produced by a current-carrying solenoid along its axis.

If the length of a solenoid is much longer than it's diameter, we approximate it as an infinitely long solenoid. The magnetic field magnitude along the axis of an infinitely long solenoid is

$$B = \mu_o nI \tag{1}$$

where $\mu_0 = 4\pi 10^{-7}\frac{H}{m}$ (Henry per meter) $= 4\pi 10^{-7}\frac{T*m}{A}$ is called the magnetic permeability of vacuum, n = N/L (total number of turns/length) is the number of turns per length in the solenoid, and I is the current flowing through the solenoid.

If the length of the solenoid is short compared to the diameter, the magnetic field should be determined experimentally.

II.3. Magnetic field lines

A magnetic field line is a smooth closed curve, comes out of a magnet through its North pole and enters the magnet through its South pole as shown in Fig. 4 (left). A current-carrying solenoid produces magnetic field like that of a bar magnet as shown in Fig. 4 (right).

Figure 4: Magnetic field lines around a permanent magnet (left) and a current-carrying solenoid (right).

Magnetic field lines map the magnetic field of a magnet. The field lines are crowded where the field is strong, and far-separated in the regions of weak magnetic field. The tangent at any point to a field line give the direction of the magnetic field at that point [Fig. 5 (in the left)]. As there is a unique field direction at any point in space, two magnetic field lines cannot intersect each other. The Earth has its own magnetic field (Fig. 6). Its magnetic field is created by the currents in the Earth's molten core.

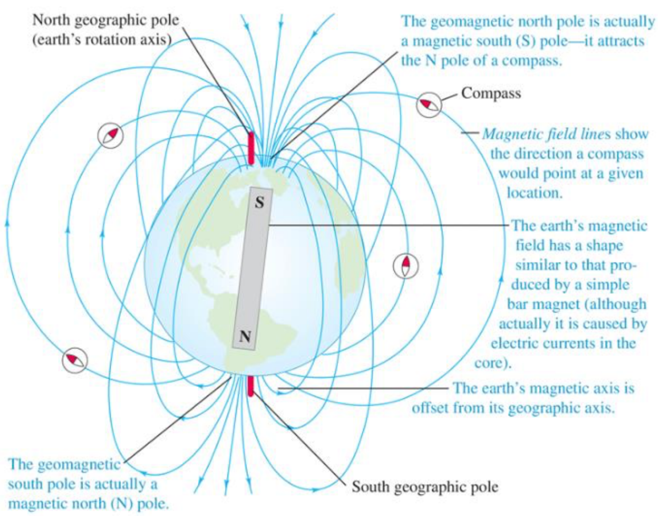

Figure 5: Diagram of Earth's magnetic field.

II.4. Magnetic flux

The total number of field lines passing perpendicularly through a given area represent the magnetic flux qualitatively (Fig. 6, left). Quantitatively, magnetic flux ϕ_B passing through a surface area is defined as follow

$$\phi_B = \overrightarrow{B} \cdot \overrightarrow{A} = BAcos\phi \tag{2}$$

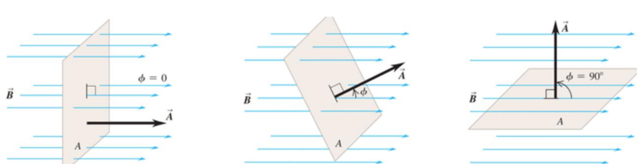

Figure 6: Magnetic flux passing through a surface when the surface is orientated at various angles relative to the magnetic field.

Where B is the magnitude of the magnetic field vector $\overrightarrow{B}$, A is the magnitude of the surface area vector $\overrightarrow{A}$, and ϕ is the angle between the direction of $\overrightarrow{B}$ and that of $\overrightarrow{A}$. The SI unit of magnetic flux is the weber (Wb). 1Wb = 1 Tesla meter squared ($T \cdot m^2$).

Fig. 7 shows how the magnetic flux passing through a surface changes when the orientation of the surface relative to the magnetic field is changed.

II.5. Faraday's laws of electromagnetic induction

When there is a change in magnetic flux linked with a coil, an electromotive force (emf) is induced in it (Fig. 8). The induced emf is directly proportional to the time rate of change of flux linked with the coil. Mathematically,

$$\epsilon(t) = -\frac{d\phi_B}{dt} \tag{3}$$

where $\eta(t)$ is the induced emf in volts (V), and it is a function of time.

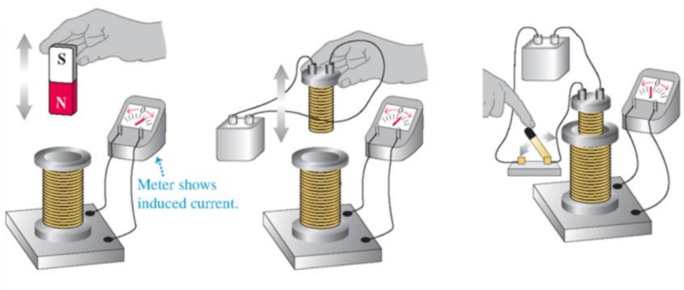

Figure 7: Faraday's law experiments (a) a magnet is moved up and down close to a coil, (b) a current-carrying coil is moved up and down around another coil, and (c) a circuit with battery is suddenly switched on. In each case, there is induced emf in the lower coil.

II.6. Lenz's Law

Lenz's law: The negative sign in Eq. (3) is related to the Lenz's law which states that the direction of any magnetic induction effect is such as to oppose the cause of the effect. Fig. 9 shows self-explanatory diagrams for the application of Lenz's law.

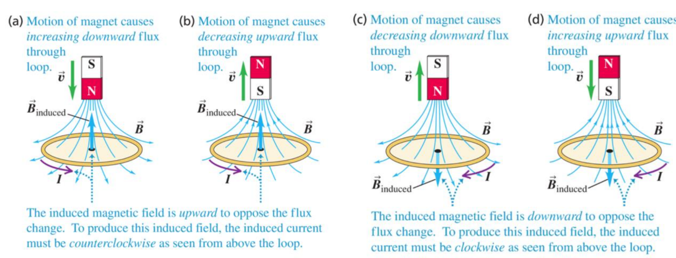

Figure 8: Applications of Lenz's law to determine the direction of induced current

If a coil has N turns the induced emf increases by this factor:

$$\epsilon(t) = -N\frac{d\phi_B}{dt} = -N\frac{d}{dt}(BAcos\phi) \tag{4}$$

Eq. 4 shows that the magnitude of the induced emf depends on several factors. What are those factors? How do they affect the induced emf in a coil?

For example, does an increase in number of windings in a coil increase or decrease the induced emf? What it the effect on induced emf due to an increase or decrease of the magnetic field? How about area?

If the resistance of the coil and a circuit connected with the coil is R as shown in Fig. 10, the induced current flowing through the resistance is given by Ohm's law:

$$I = \frac{\epsilon(t)}{R} \tag{5}$$

On what factors does the induced current depend?

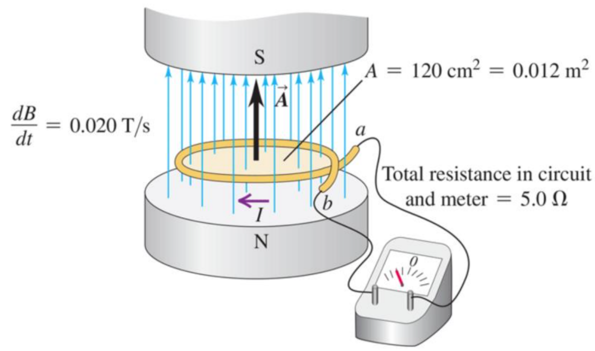

Figure 9: Induced current in a loop due to electromagnetic induction

Question 1 **Introduction**

Please write an introduction section based on the results you have collected today. For reference on what it should look like please consult the Generic Deliverables at this link.

III Procedure

Watch a short video in the following link before you start working on PART-A of the Worksheet. https://www.youtube.com/watch?v=I
Open the following physlet animation window here in which a slinky (stretchable) solenoid is shown. Set the length of the solenoid to the maximum, and current to zero.

Question 2 *Keeping the length fixed at maximum, vary the current I = 1A, 2A, ..., using the slider in the current bar, and observe the magnetic fields B produced. Record 10 values of I and the corresponding magnetic fields in Table 1. Please include this table in your worksheet.*

Table for question 2		
Currents (A)	Magnetic field (T)	Ratio of B to I (B/I)
$I_1 = 1A$	$B_1 =$	$\frac{B_1}{I_1} =$
$I_2 = 2A$	$B_2 =$	$\frac{B_2}{I_2} =$
$I_3 = 3A$	$B_3 =$	$\frac{B_3}{I_3} =$
$I = ...$	$... =$	$\frac{...}{...} =$
$I_{10} = 10A$	$B_{10} =$	$\frac{B_{10}}{I_{10}} =$

Question 3 *Transfer the data to Python.*[a] *Plot a graph of B and I. Insert the best fit line to the data, and include that slope of your line in your caption.*

Follow all the figure and caption guidelines, which are reiterated in the Appendix. Include your graph and caption on your worksheet.

[a]If you do not wish to use Python you can use any other programming language (R, Matlab, C++, etc) you wish. You are not, however, allowed to use Excel or Google Sheets

Question 4 *Divide the slope of the B-I curve you obtained in question 3 by* μ_0 *(introduced in equation 1) and record in your worksheet. What physical quantity does this ratio give? What are it's SI units?*

Open the following physlet animation window (which is the same as before), here in which a slinky (stretchable) solenoid is shown.

Set the current at 1A in the current bar. Drag the slider in the length bar and observe how the magnetic field varies with the length. Based on your observations answer the following questions.

III.1. Faraday's Laws

Open a PhET simulation in the following link here.

Question 5 *Drag the bar magnet with your computer mouse close to the coil and leave it there motionless.*

Move the magnet with its North pole closer to the coil, at different speeds (i) toward and (ii) away from the coil?

Question 6 *Repeat question 5 by flipping the pole of the magnet. You can do this by using the flip button located close to the lower part of the simulation window.*

Question 7 *Click on the icon with two coils located close to the lower part of the simulation window. Repeat question 5 and question 6.*

Question 8 **Results**

Please write a results section based on the data you have collected today. For reference on what it should look like please consult the Generic Deliverables at this link.

Question 9 **Conclusion**

Please write a conclusion section based on the results you have collected today. For reference on what it should look like please consult the Generic Deliverables at this link.

IV Acknowledgement

This lab was first developed by Dr. Rudra Kafle to replace the on-site labs for D term, 2020 due to the COVID-19 Emergency. They have been iterated upon by Dana, who takes full credit for any mistakes therein.

V Appendix

The Figures and Caption Rules

There are a few very important aspects to creating a proper figure and caption. If you follow these rules, not only will you get points on your physics lab grades, you will impress your instructors and peers in the future.

The Caption

- The caption should start with a label so you can reference the figure from other places in your paper/report. For this course you should use "Figure 1", "Figure 2", etc.
- The caption should allow the figure to be standalone, that is to say, by reading the caption and looking at the figure, it should be clear what the figure is about and why it was included without reading the whole paper.
- The caption should contain complete sentences and be as brief as possible while still conveying your information clearly (this is not always easy).
- Please add captions to your tables as well, otherwise we will not know what we are looking at.

The Figure

- **Make sure that the resolution is high enough to not be pixelated at its final size.**
- Check that any text is readable at the final size (Using a smaller graph in Logger Pro will cause the text to be larger in relation to the graph when inserted into another program).
- For graphs, ensure that the axes are labeled (including units) and that there is a legend if you have multiple data sets on the same graphs.

Tables

- The first row of the table should be a header, where each item is labeled with what is contained in that row. If it is a physical measurement it should have the correct units.

- For tables include a short caption of what is contained in the table, or what was examined.
- The caption should start with a label so you can reference the figure from other places in your paper/report. For this course you should use “Table 1”, “Table 2”, etc. For an example of a good table caption please see Figure 10.

Table 1. Baseline characteristics of study participants

Variables	Intervention group (n=14)	Control group (n=15)
Women (no [%])	7 (50)	5 (33)
Median age (range)	22.0 (19 – 58)	21.0 (18 – 70)
First winter in icy conditions (no [%])	—	1 (7)
Previous falls on ice (no [%])	8 (57)	11 (73)
≥ 1 fall this winter (no [%])	4 (29)	7 (50)
Injury from fall this winter (no [%])	1 (7)	—
Time been walking this route (no [%]):		
<6 months	3 (21)	2 (13)
6–12 months	9 (64)	9 (60)
>12 months	2 (14)	4 (26)

Figure 10: An example table from the paper Lianne Parkin, Sheila M Williams, and Patricia Priest, “Preventing Winter Falls: A Randomised Controlled Trial of a Novel Intervention” 122, no. 1298 (2009): 9.

Python

According to IEEE Spectrum, Python is the most popular programming languages. Python is a free, general purpose, cross discipline programming language that has moved to the forefront of many disciplines.

If you decide to use Python your TA’s will help you troubleshoot your code. While they might be able to help you troubleshoot when you use a different program or code, be aware of the fact that they are not familiar with all programming codes. There are many languages (R, Matlab, Opal, Julia, etc.) out there that are just as useful as Python, but we have chosen to use Python here. You may use any programming language you wish, but not Excel or Google Sheets.

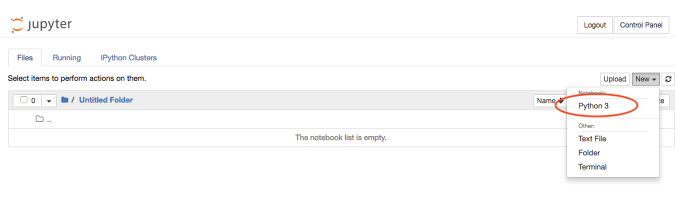

Figure 11: Navigate to `jupyterhub.wpi.edu/hub/login` and sign in with your WPI email address and password, choose an instance to spawn (either is fine) and create a new Python 3 file as shown here

We have set up a Jupyter notebook you may use. The website is https://jupyterhub.wpi.edu/hub/login.[1] There are many ways to learn Python, including reading a book, asking a friend, working through examples, or googling furiously when problems arise. We encourage you to discover which approach works best for you. Going forward this class will provide basic Python examples, but feel free to iterate upon the template we provide. What we provide is a stripped down version, and elaboration is encouraged. See this Github repository for our examples. We hope at the end of this term you will be able to add to your resume ”Proficient in Python”.

Jupyter uses a cell based system and evaluated variables carry over to the next cell. There are a few different types of cells, Figure 12 shows 2 kinds, the code cell, which we will be using most of the time, and the markdown cell, which you can use to add nicely formatted notes to you file.

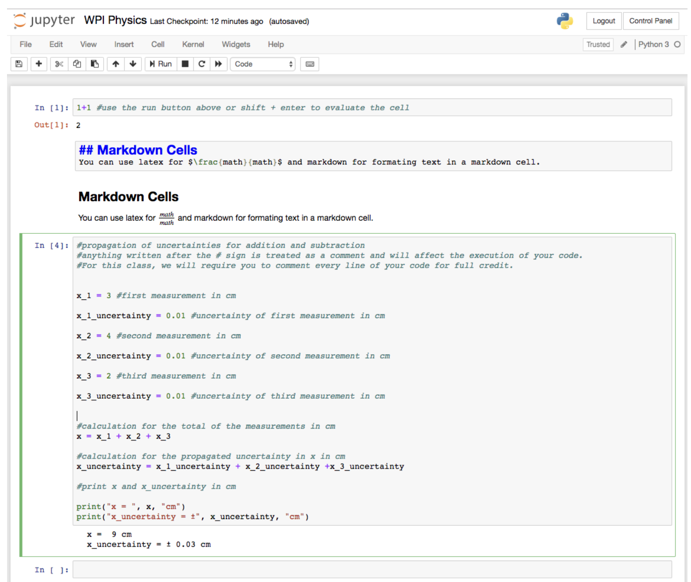

Figure 12: Above is the code that you could use use to propagate uncertainty for values that are added or subtracted. Always remember to comment your code.

If you prefer to work through a book or examples we recommend Mark Newman’s book, which is available for free on his website [1]. Chapter Two is a basic introduction to the syntax for Python. Chapter Three covers graphs and visualizations, and we hope you will look into it if you learn best from a book. If you wish to get a head start in this class we recommend reading this book.

If you wish for a more advanced textbook there is a compilation of free online computational physics books here.

[1] If you cannot log in please email WPI’s IT department, and they will be happy to help polite students. The first thing they will tell you, however, is to check to make sure you don’t have to change your password and try a VPN if you are off campus.

References

[1] Mark Newman. *Computational Physics with Python.* CreateSpace Independent Publishing Platform, 2012.