X. FARADAY'S LAW

f05.01

INTRODUCTION

The magnetic and electric fields are coupled; even though a static electric field can exist without a magnetic field (and vice versa) its impossible to change the magnetic field without changing (inducing) the electric field. The opposite is also true. We call this phenomenon **electromagnetic induction**. It was discovered in experiments made in the beginning of the XIX century by Michael Faraday and independently by Joseph Henry.

PURPOSE

Experimental verification of Faraday's Law of induction.

PRE-LAB ASSIGNMENTS

A. Readings:

Faraday's Law describes how changes in magnetic field induce electric field:

$$\oint \vec{E} \cdot d\vec{s} = \frac{d\Phi_B}{dt} \tag{1}$$

where Φ_B is the magnetic flux through any surface bounded by the closed path in the integral of the electric field. You may be confused at this point, since we previously learned that $\oint \vec{E} \cdot d\vec{s} = 0$ for any closed path. There is no contradiction. The latter is true in absence of time dependent magnetic fields ($d\Phi_B/dt = 0$).

Electric field induced by changes in magnetic field can be observed with help a conductor. Imagine conductive loop interrupted at one points (see Fig. 1). Since $\Delta V = -\int \vec{E} \cdot d\vec{s}$, the induced electric field will generate some potential difference between the two ends of the conductor:

$$\Delta V = -\frac{d\Phi_B}{dt} \tag{2}$$

This is how Faraday's Law is usually written.

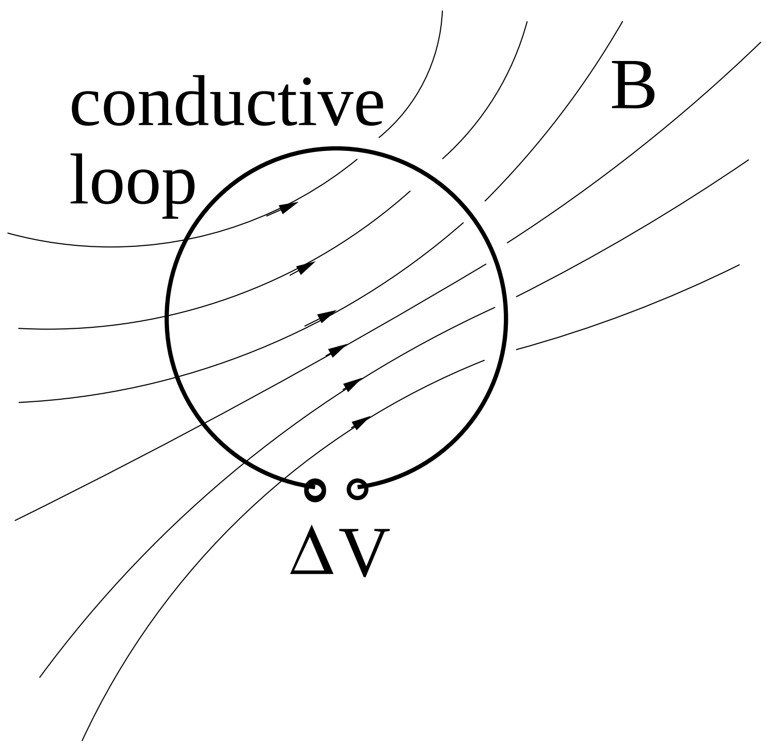

Figure 1. Potential difference is induced in conductive loop if the magnetic field flux through the loop changes with time.

We will use a solenoid for the conductive loop. Assuming that B is approximately constant across the solenoid we can write $\Phi_B \approx N\,A\,B$, where N is the number of turns in the solenoid and A is the area of one wire turn. Since N and A are constant:

$$\Delta V \approx -N\,A\,\frac{dB}{dt} \tag{3}$$

We will verify this formula experimentally.

B. Exercises:

Please answer the questions on Report Sheet X–1, which will be collected at the *beginning* of the laboratory session and graded by your instructor.

REPORT SHEET X–1

Date____________________ Name____________________

Instructor____________________

PRE-LAB EXERCISES

Exercise 1.

Let us assume that a permanent magnet creates magnetic field of 30 Gauss (= 0.003 Tesla) inside the solenoid with 3400 wire turns and cross-section area of about 0.006 m^2. If the magnetic field is constant, what is the potential difference induced between the two ends of solenoid wire?

Exercise 2.

Let us now assume that the permanent magnet is suddenly moved away from the solenoid and the magnetic field drops from 30 Gauss to zero in 0.1 seconds. What is the average potential difference induced between the two ends of solenoid wire?

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LABORATORY ASSIGNMENTS

Materials Needed:

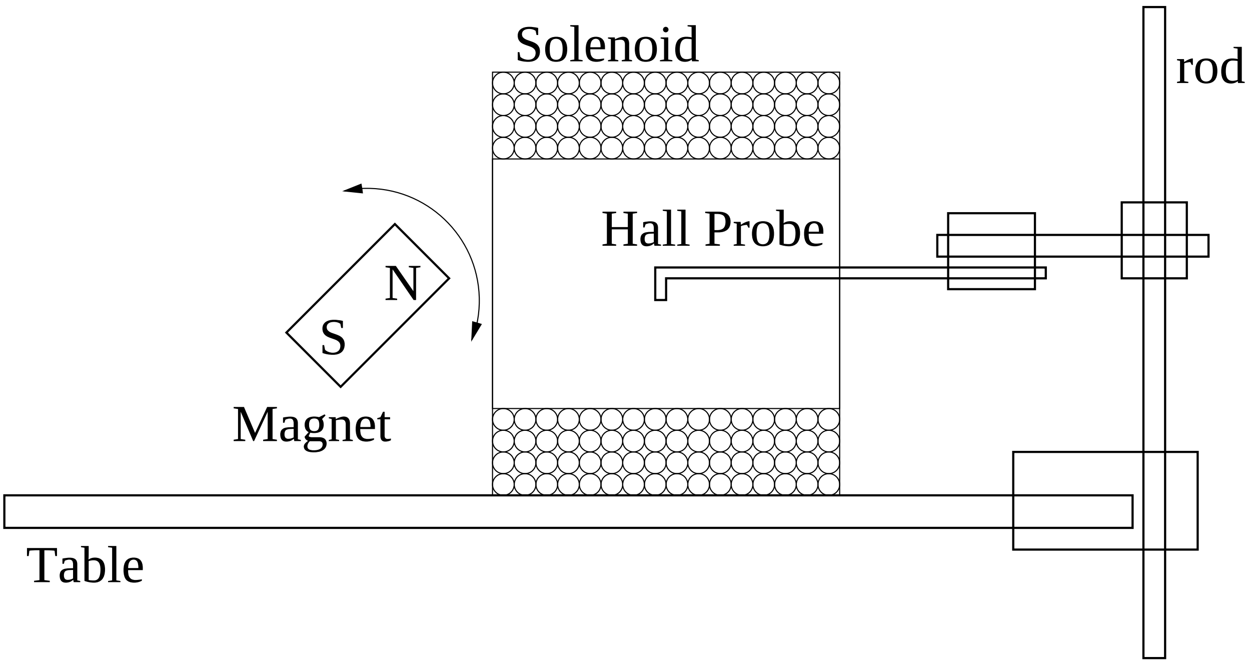
- Solenoid
- 2nd Solenoid (**D**)
- Power Supply (**D**)
- Large permanent magnet
- Hall probe
- Dual Channel Amplifier with one voltage probe
- ULI computer interface box
- Mounting fixtures
- Cables
- Voltmeter (for apparatus tests only)
- 4.5V Battery (for apparatus tests only)
- Ruler

Experiment A-D: *Verification of Faraday's Law*

The Task:

To observe linear dependence of induced ΔV on dB/dt. To measure the slope of the dependence and to compare it to the slope predicted by Faraday's Law.

Experiment A-C: *Verification of Faraday's Law using permanent magnet*



Side view of the apparatus in Experiment A.

Procedures

A-1. Mount the Hall probe in the middle of the solenoid (see above). Connect the Hall probe to DIN2 and the Dual Channel Amplifier with the voltage probe 1 to DIN1 of the ULI interface box. The Hall probe should be set to low sensitivity. Switch the interface box on. Start the computer, and click on the PHY222 icon to start the program. To load the proper initialization file, choose "Open..." from the "File" menu. Open the file "faraday" in PHY222 subdirectory. Test the voltage probe on a battery. Connect the voltage probe to the solenoid.

With the permanent magnet far away from the probe go to "Experiment" menu and select "Zero", then "Zero magnetic field" from the pop-out window.

There are four graphs in the program set-up. The upper (lower) left graph will display magnetic field (voltage) as a function of time. The upper right plot will show the voltage as a function of time derivative of the magnetic field. The lower right plot will show the voltage as a function of magnetic field itself.

A-2. Our goal is to create changes in magnetic field penetrating the solenoid. Magnetic field will be created by the permanent magnet in front of the solenoid. In this experiment we will generate changes in the magnetic field by changing the magnet orientation. Collect data while flipping the magnet back-and-fourth in your hand **as fast as you can** (e.g. alternate the magnet orientation between the horizontal and vertical direction). Get as close to the solenoid as you can without obstructing the flipping motion. The data collection may seem to pause after a few seconds before reaching 10 seconds on the time axis. The data collection is actually not interrupted but there is some delay in graphing the data. Just wait and the graphs will be completed.

You should be able to induce ΔV up to at least $0.5V$. If you don't reach this kind of potentials, may be you are not flipping the magnet fast enough or the magnet is too far from the probe. Once you are satisfied with your measurement copy Potential vs. dB/dT graph onto Report Sheet X–2. Indicate ranges of the horizontal and of the vertical axes.

Faraday's Law leads to Eq. 3, and therefore, predicts that this graph should be linear. However, Eq. 3 has only approximate nature since it assumes that magnetic field is the same at any point inside the solenoid. Due to this approximation you are likely to observe a family of curves creating a thick line rather than a perfect, narrow line. Any discrete steps in your curves are due to the limited measurement precision.

Note that unlike ΔV vs. dB/dt, ΔV dependence on B does not have much regularity.

A-3. In this step we will measure slope of ΔV dependence on dB/dt and compare it to the slope expected from Faraday's Law. Select the ΔV vs. dB/dt graph by clicking on it. Go to "Analyze" menu and click on "Linear Fit". Default precision of the displayed fitted slope is not sufficient for this experiment. Double-click on the box displaying the fitted parameters. Change "Decimal Places" from 3 to 4 in the pop-out window. Click

OK to close. You will need to repeat this procedure whenever you fit a slope. Copy the fitted slope to Report Sheet X–2.

According to Equation 3 the slope predicted by Faraday's Law is given by $N\,A$. Number of wire turns in the solenoid (N) is given on the solenoid label. Calculate area of one turn from $\pi\,R^2$, where R is the radius of the wire loop. Use a ruler to measure R for the **inner layer** of wire winding. If R is in meters then $N\,A$ will be in SI units which for ΔV vs. dB/dt slope are $Volt/(Tesla/sec)$. Since we measured slope in $Volt/(Gauss/sec)$ you need to divide $N\,A$ by 10,000 to obtain the expected slope in the same units. Report your calculations in Report Sheet X–2.

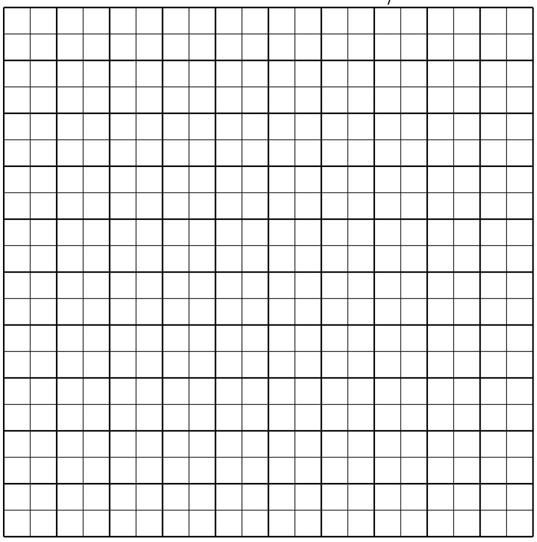
REPORT SHEET X–2

Date____________________ Name____________________

Instructor____________________ Partner(s)____________________

A-2,3. Potential vs. dB/dt

ΔV (V)



dB/dt (Gauss/sec)

fitted slope $m_{measured} =$ $(V/(Gauss/sec))$

A-2.
Is the induced potential difference ΔV approximately linearly dependent on dB/dt as predicted by Faraday's Law?

☐ yes ☐ no

A-3.

$N =$

$R =$ (m)

$A = \pi R^2 =$ (m^2)

$m_{expected} = N\,A/10\,000 =$ $(V/(Gauss/sec))$

Does your measured slope roughly agree with the slope expected from Faraday's Law?

☐ yes ☐ no

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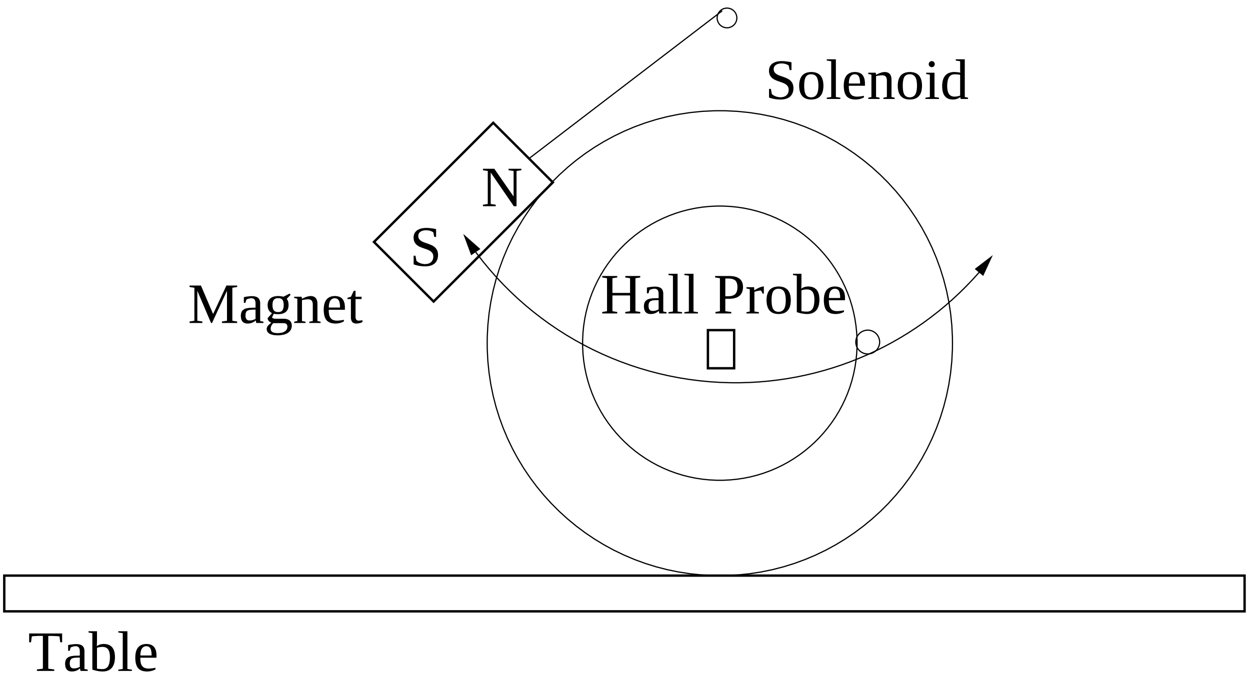
B. This time generate changes in the magnetic field by swinging the permanent magnet on a string in front of the solenoid (see below). Try to maximize speed of the magnet in front of the solenoid. For example, shorter string will result in shorter time period of your pendulum. Fit the slope. Note that the expected slope is still the same as calculated in the previous experiment. Report your results in Report Sheet X–3.



Front view of the apparatus in Experiment B.

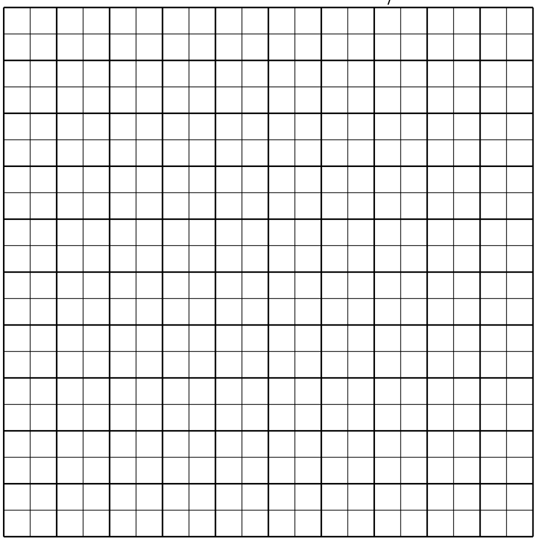
REPORT SHEET X–3

Date____________________ Name____________________

Instructor____________________ Partner(s)____________________

B. Potential vs. dB/dt

ΔV (V)

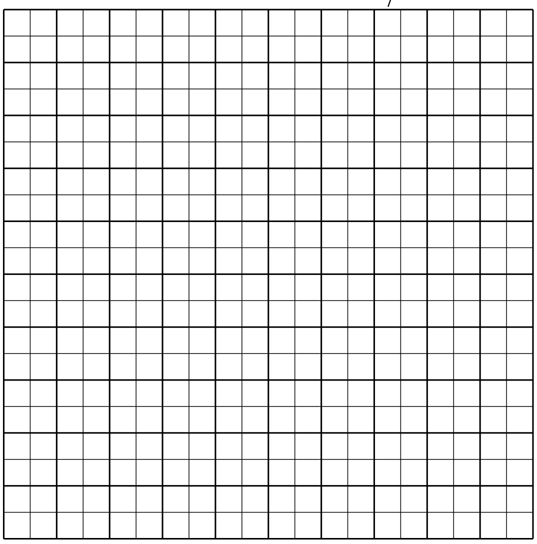


dB/dt (Gauss/sec)

fitted slope $m_{measured} =$ $(V/(Gauss/sec))$

C. Potential vs. dB/dt

ΔV (V)



dB/dt (Gauss/sec)

fitted slope $m_{measured} =$ $(V/(Gauss/sec))$

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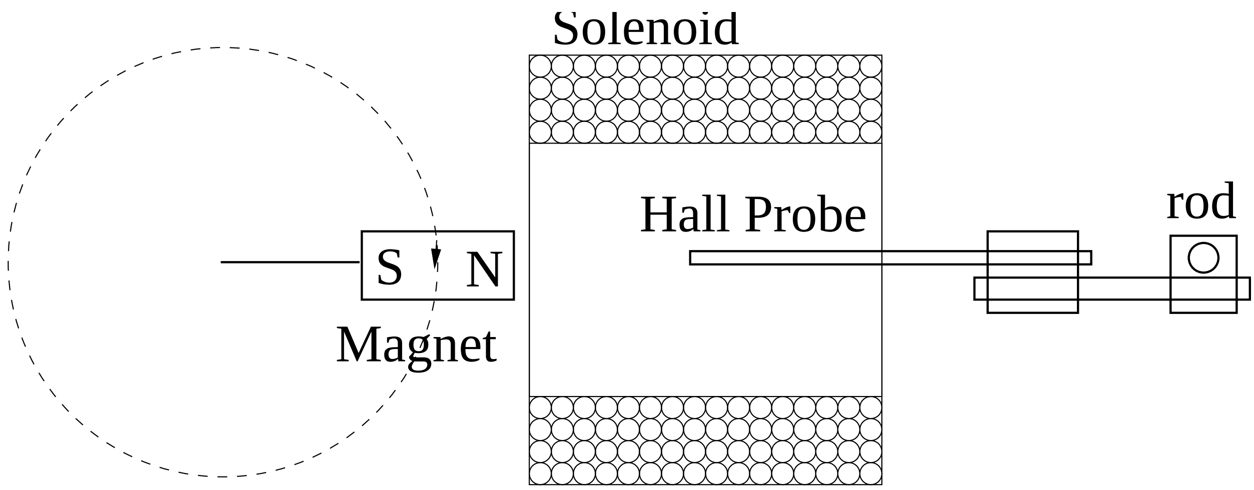
C. Generate changes in the magnetic field by making fast horizontal circles with the permanent magnet held by the string in front of the solenoid (see below). Report your results in Report Sheet X–3.



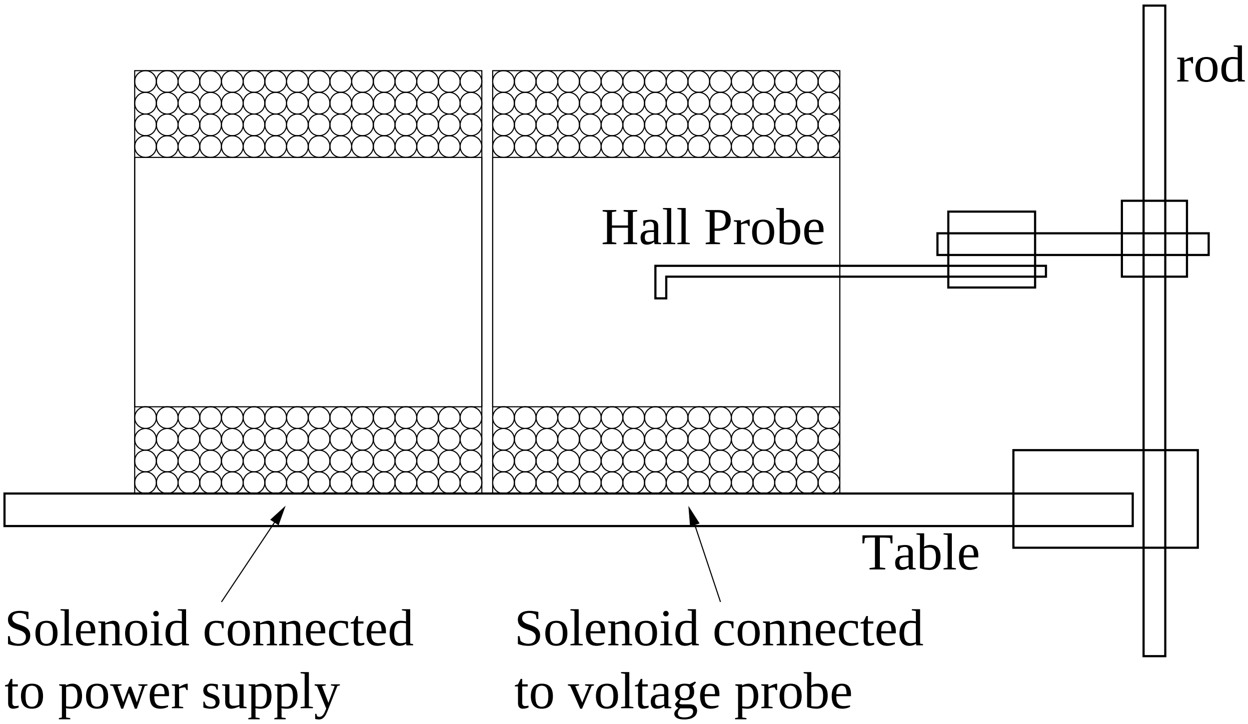
Top view of the apparatus in Experiment C.

Experiment D: *Verification of Faraday's Law using two solenoids*

Procedures

D-1. Instead of permanent magnet we will use second solenoid connected to the power supply to generate magnetic field. Position the second solenoid as shown below. Varying supplied voltage to the second solenoid changes magnetic field in our initial solenoid connected to the voltage probe and with the Hall probe inside. Using knob of the power supply to vary the magnetic field does not produce good results since variation of the field is slow (you can try it). To produce faster variation switch the power supply off and turn the knob on the power supply all the way to the right and leave it at this maximal setting. Wait a few seconds. Start collecting data with the power supply off. Then switch it on. This will cause sudden change of magnetic field from zero to its maximal value. After a second or so, switch the power supply off. You will observe magnetic field decaying exponentially with time. After a couple of seconds you can switch the power supply on and off again.

The graph of ΔV vs dB/dt will be asymmetric since magnetic field rises in this set-up much faster than diminishes. Fit the slope. Report your results in Report Sheet X–4.



Side view of the apparatus in Experiment D.

D-2. Copy all measured slopes from the previous report sheets into the summary table in Report Sheet X–4. Compare them to the expected value which you calculated in Report Sheet X–2.

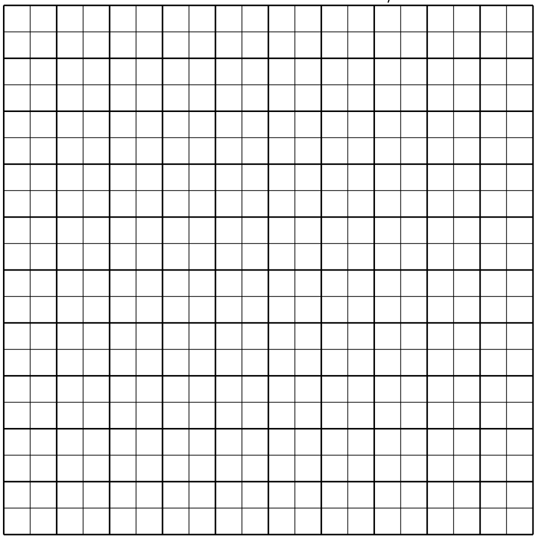
REPORT SHEET X–4

Date______________________ Name______________________

Instructor______________________ Partner(s)______________________

D. Potential vs. dB/dt

ΔV (V)



dB/dt (Gauss/sec)

fitted slope $m_{measured} =$ $(V/(Gauss/sec))$

Experiment	Slope of ΔV dependence on dB/dt (V/(Gauss/sec))
A. Flipping permanent magnet	
B. Swinging permanent magnet	
C. Circulating permanent magnet	
D. Two solenoids	
Expected slope	