# Introduction

Here are some general directions for the weekly laboratory part of Physics 182 and 202. The topics include electric and magnetic fields, DC and AC electrical circuits, magnetism, optics, diffraction & spectra, and nuclear half-life. The are a total of twelve experiments.

The rules for maintaining your lab notebook and writing lab reports are the same as for the first semester class.

**Materials** For each meeting of the laboratory, you should bring:

- This lab manual;
- Your laboratory notebook, as discussed below;
- A pen for writing in your laboratory notebook; Don't use pencil for this!
- A calculator;
- A physics textbook for looking up formulas and constants.

**Grading** Each lab's work is graded for ten points. The lab reports are due at the beginning of the next lab. The laboratory notebook will be collected and graded for ten points at the end of the course. The total for all the reports and the laboratory notebook will be reported to your lecture instructor at the end of the term.

**Attendance** Attendance is required for all laboratory activities. If you know of a conflict for a future meeting, arrange with the instructor to attend another section of the lab for that week. Any work to make up for an excused absence is to be determined by the instructor.

**Laboratory Notebook** You should bring to each meeting of the laboratory your laboratory notebook. The notebook must be a bound, quadrille (graph paper) book. If you have such a notebook from a previous laboratory with at least fifty blank pages, this should suffice for one semester of lab work. The first three pages should be reserved to enter your name, the course title, and a table of contents to be completed by the end of the semester. The entries for each session should begin on a new page, which begins with the title for the work. All observations and data are to be written in ink directly into the record as they are made—not copied from scraps of paper—into the notebook. Any measurement must include the appropriate units. If data are discarded, they are simply crossed out with a single $\times$ so that the stricken material is still visible. The last page on which data are recorded for the day should be signed and dated, then signed by the instructor before you leave for the day.

**Reports** Laboratory activities are to be submitted at the following meeting as a formal report. Work is which is submitted later than the due date will be assessed a penalty. Your report should be viewed as an opportunity to practice your writing skills. It should include the following sections:

**Abstract** Briefly describe the experiment and summarize your main results.

**Procedure** Write a short summary of the experimental set-up and the measurements performed.

**Data** Present your data in well organized form. Do not include large amounts of raw data if you include a graph or statistical analysis of that data.

**Analysis** Perform any calculations needed. This should be done first in your lab notebook and—when you get everything right—copied into your report. You may find it convenient to write this part of the report by hand.

**Conclusions** Summarize your most important results. When appropriate, compare them with the standard values and discuss any discrepancies. The conclusion should be quantitative and discuss differences in terms of standard deviations.

Be sure to include the names of your lab partners at the beginning of your report. Reports may be typed or neatly hand-written. Unless otherwise instructed, the first four sections of your report may be done as a group; however, each student must write his own conclusion.

To use your time efficiently in the laboratory, you should read the appropriate section of this lab manual before coming to lab. Think of questions to ask at the beginning of the session concerning procedures which are not clear. Look for questions in the lab manual which you will need to answer in your report.

Each member of the group is to take part in the work. The group is to share in all aspects of the work, including the calculation and analysis phase.

In grading your reports, your instructor will have several points in mind: Did this person participate and contribute in the lab phase of the work? Is the report well organized; is it easy to find the main items? Can the main result of the experiment be found quickly? Have all the parts of the experiment been treated and included? Is the writing reasonably free of grammatical and other writing errors? Was an error overlooked because data analysis was not begun before leaving the lab?

## Using the lab computers

For some of the experiments, we will use the lab computers to analyze our results. Here are a few general guidelines:

- If your computer shows a login screen, supply the user name `luser` and password `geneva`.
- Double-click on the `physics` icon to start up the physics program.
- When plotting, you can remove unwanted plots by placing the cursor over the plot and typing the letter `q`.

- The XTerm windows have a scrolling option.
- Do not turn the computers off.

## Physics 182/202 Schedule 2004

| Experiment | Tuesday | Thursday | Friday |
|---|---|---|---|
| 1 | Jan. 20 | Jan. 22 | Jan. 23 |
| 2 | Jan. 27 | Jan. 29 | Jan. 30 |
| 3 | Feb. 3 | Feb. 5 | Feb. 6 |
| 4 | Feb. 10 | Feb. 12 | Feb. 13 |
| 5 | Feb. 17 | Feb. 19 | Feb. 20 |
| 6 | Feb. 24 | Feb. 26 | Feb. 27 |
| 7 | March 2 | March 6 | March 7 |
| 8 | March 9 | March 13 | March 14 |
| 9 | March 23 | March 27 | March 28 |
| 10 | March 30 | April 1 | April 2 |
| 11 | April 13 | April 15 | April 16 |
| 12 | April 20 | April 22 | April 23 |

All laboratory notebooks and reports due one week after your last lab.

# Contents

# Experiment 1

## The Electrical Field and the Permittivity Constant

The objectives for the experiment are:

1. to observe electrical fields in a two-dimensional space and
2. to measure the permittivity constant by observing the force between charged objects.

## 1.1 Field plotting

There are two equivalent methods for describing the electrical characteristics of space. The electric field $\mathbf{E}(\mathbf{x})$ describes the vector force experienced by a charge at some location $\mathbf{x}$. One can draw "electric field lines" which are curves that are everywhere tangent to $\mathbf{E}$. Equivalently, the electrostatic field $V$ describes the potential energy of a charge at each point relative to some reference point. The usual system for representing electrical potential energy is to define the energy for a standard unit charge (1 coulomb=1 C); the electrical potential thus has units of energy/charge or J/C, called the volt (V). If the electrical potential is everywhere defined in a space, the field can be derived from the potential function. Curves are often used to connect points with the same potential, called equipotential curves. The field is perpendicular to these curves, and its magnitude is inversely proportional to the distance between adjacent equipotential curves.

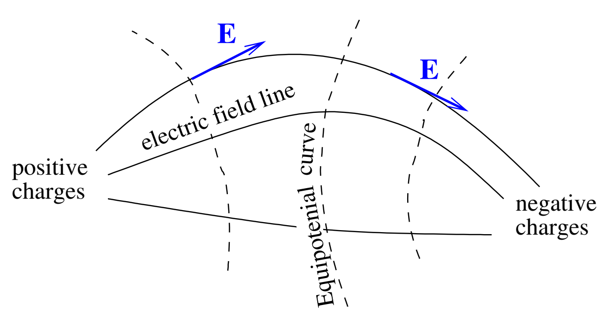



Figure 1.1: Equipotential curves and field lines

## Procedure

We will study the two-dimensional field found a shallow dish of water. The field is obtained by applying a potential difference to the two electrodes placed in the water. Connect the power supply and adjust the output so that there is a voltage of about 12 volts across the electrodes. Use the Tenma digital multimeter (DMM) to determine this voltage.

You need two pieces of graph paper. On both peices, draw matching coordinate axes. Take one piece and slide it under the dish of water: you will use this to measure the position of your probe.

On the other piece of graph paper, mark the positions of the two electrodes. Connect the negative (black) lead of the DMM to the negative output of the power supply. Next, use the positive (red) lead of the multimeter to determine the potential at various points in the dish and record the results on your graph paper. You should measure enough points so that you can construct five different lines of constant potential, or "equipotential lines." The lines should look something like the lines in Figure 1.2.

*Field curves* are lines which are drawn such that they are always perpendicular to the equipotential curves. Sketch three such curves on your graph paper. A field curve indicates the direction of the field at any point on the curve. The electric field $\mathbf{E}$ is the force experienced by a standard +1 C charge placed at that point. The units for $\mathbf{E}$ are N/C or V/m.

The magnitude of the field at some point on a field curve is determined as follows. If the point selected on the field curve is between two equipotential curves, estimate the distance along the field curve, in meters, between the equipotential curves. Divide the difference in potential for the two equipotential curves by the distance. For example, a point on a field curve lies between the 4 V and the 6 V equipotential curves; the distance between the equipotential curves as measured along the field curve is approximately 2.0 cm or 0.02 m. The field magnitude is then $(6-4)/0.02$ V/m or 100 N/C. Perform this analysis at some chosen point for each of your field curves.

The potential and field values can now be used to determine energy and force values. If we assume that electrons, with a charge $q$ of $-1.602 \times 10^{-19}$ C, are the mobile charges moving in the water, we can determine forces acting on the electrons and work done in moving the electrons from place to place. At a point where you have estimated the field $\mathbf{E}$, the force on the electron as $\mathbf{F} = q\mathbf{E}$. The direction of this force, for a negative charge, is the direction of the field curve moving from smaller to larger potentials. The work done in moving an electron from one equipotential curve $V_1$ to another $V_2$ is $q(V_2 - V_1)$. Calculate the force on an electron for each of your three points at which you estimated the field. Calculate also the work done in moving the electron along the field curve from one equipotential curve to the next equipotential curve as you pass through a point at which you have estimated the field. You should have three force and three work values from your calculations.

A sheet of idealized field curves and equipotential curves is shown in Figure 1.2; it gives the theoretical predictions for a two-dimensional space between two charged circles. You can compare your results with this figure to determine how well the theory compares with the electrical characteristics that you observe. The theory assumes that the space is infinite in extent; the dish of water has finite size: large errors occur when you approach the edge of the dish. More meaningful results will be obtained if you limit your observations to a circle with a diameter of 5 to 6 inches centered on the center of the dish.

In your conclusion, compare the theoretical and observed equipotential curves, and discuss your

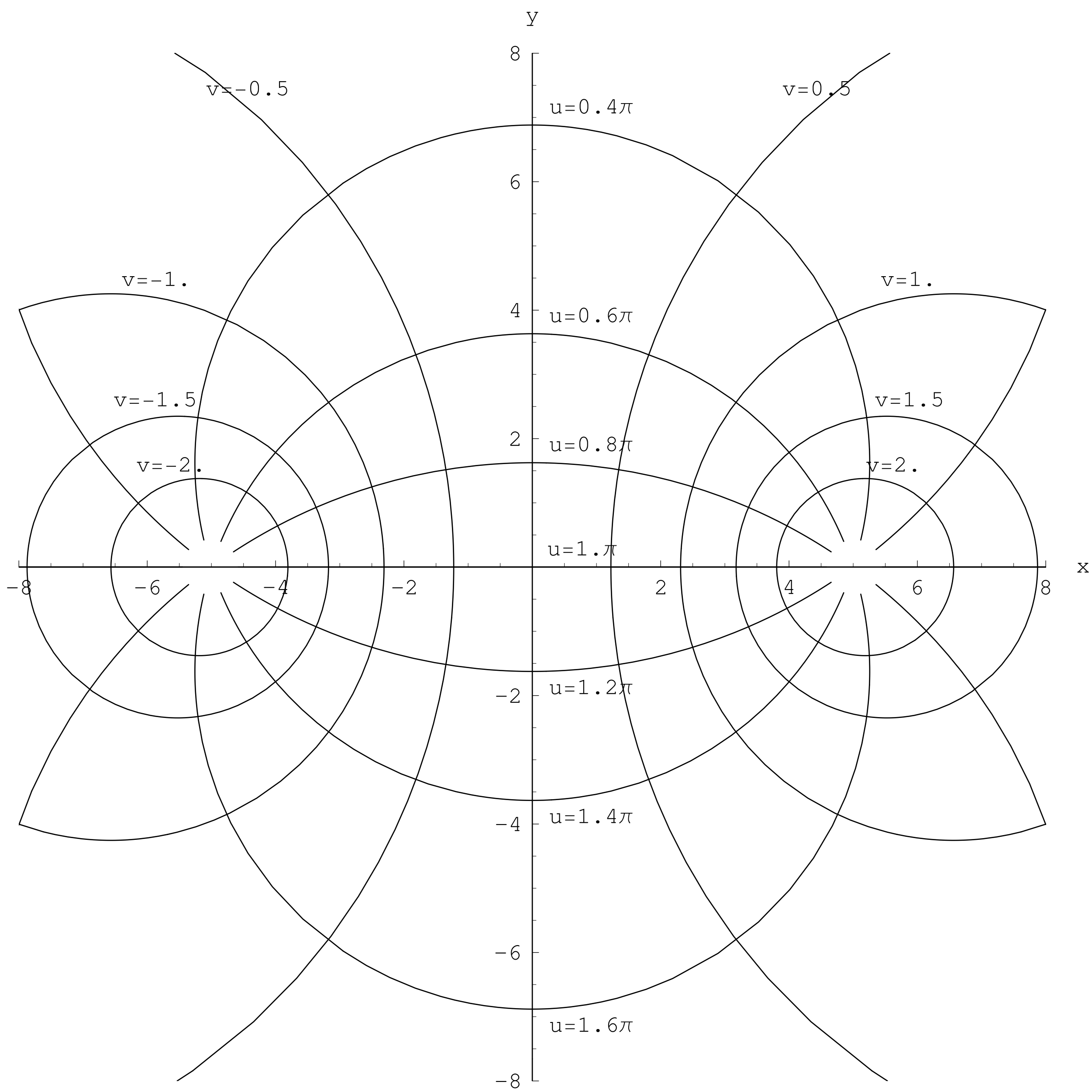



Figure 1.2: Equipotential lines and field lines for two point-charges in two dimensions. These lines can be expressed in terms of "Bipolar Coordinates." The conversion between Cartesian $(x, y)$ and Bipolar $(u, v)$ coordinates plotted above is given by: $x = \dfrac{5\sinh v}{\cosh v - \cos u}$ and $y = \dfrac{5\sin u}{\cosh v - \cos u}$.

calculated field values, forces, and work done on an electron. You should submit your graph paper with your lab report.

## 1.2 The electrostatic balance: determination of $\epsilon_0$

The fundamental equation for electrical interactions is Coulomb's Law:

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 r^2} \ ,$$

where

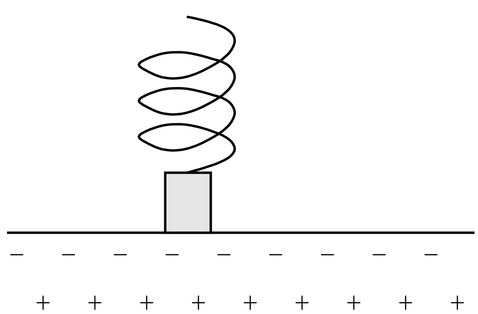
$F$ is the force of attraction or repulsion by one charge on the other (N),

$q_i$ is one of the charge magnitudes (C),

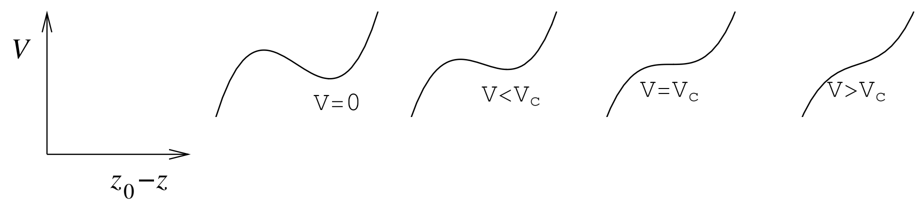
$r$ is the distance between the centers of the charges (m), and

$\epsilon_0$ is a constant called the permittivity of the vacuum $\left(\frac{\mathrm{C}^2}{\mathrm{N \cdot m}^2}\right)$. The permittivity of air has about the same value as the permittivity of the vacuum.

The electrostatic balance consists of two metal plates, one fixed to a base, the other suspended a small distance above it on a soft spring. A high voltage power supply, 0–400 V, forces + and - charges onto the opposite plates, causing them to attract each other.




The force of attraction causes the spring to stretch and the suspended plate moves closer to the fixed plate. As a result of being closer, the power supply can now put more charge on the plates, causing them to attract with greater force, and bringing the plates even closer to each other. For a given distance of separation, it is observed that small voltages from the supply do not give enough charge to the plates to overcome the restraining force of the spring; the plates come a little closer together, but remain separated. As the voltage is increased, the equilibrium distance between the plates decreases but remains at some equilibrium value. At some critical voltage, the charges are sufficient to cascade onto the plates without limit, allowing the plates to move without stopping at any mechanical equilibrium: the plates now come gently together. The total potential energy for the system is displayed here at various applied voltages to show that the minimum, required for stable equilibrium, disappears when the voltage $V$ exceeds some critical value $V_c$:




Because the distance of separation between plates is too small to measure accurately, a set of indirect observations is made to replace a direct measurement of the distance. If a tiny mass is placed on the upper plate before any voltage is applied, the spring stretches slightly. Increasing the voltage from the supply now results in the plates coming together at a lower voltage than was observed without the help of the added weights pushing the plates together. Repeating this observation with various added weights gives data for critical voltage vs. added weight; this can be analyzed to determine the force of attraction between the charges and, ultimately, the value of $\epsilon_0$, the permittivity of the vacuum.

## Procedure

1. If the plates are not parallel, you may need to add a 1 g or 2 g weight on the upper plate. This is to be moved around on the plate to tilt it so that it is as parallel to the lower plate as possible.

2. The starting separation of the plates is usually about 3–4 mm; if your plates are not at this separation, have the instructor adjust them.

3. Rotate the lower plate on its center pivot to make the edges of the two plates parallel.

4. All measurements must be made with an absolute minimum of vibration. One team member may need to be assigned the responsibility to brush elbows and heads of forgetful team members from the table during measurements. Even vibrations from the floor cause erratic results; if the marching band is practicing in the hall, slip them a little money and tell them to go to a movie.

5. Try gradually increasing the voltage from the supply. One team member should observe the separation of the plates. Observe the voltage when the plates come together.

6. The plates should come together at a voltage between 350 and 400 V.

    - If this voltage is less than 350 V, call the instructor to adjust the apparatus.
    - If the plates do not come together at 400 V, turn down the voltage and try adding a fractional weight, such 100 mg. This will lower the critical voltage. If you need to add more than 300 mg, call the instructor to adjust the apparatus.

    Do not include any added masses in your data; they are considered to be part of the initial mass of the upper plate.

7. Using increments of 20–30 mg, measure the voltage at which the plates come together, tabulating the voltage vs. added weight. When the voltage falls below 180V, the series of measurements is complete. Good results require at least 8 points. If you have fewer points, try adding some different increments to get more data in the range of 180 to 400 V.

8. Record the spring constant $k$ of your spring and the area $A$ of the upper plate.

## 1.3 Calculations

When increased mass helps to stretch the spring, the power supply does not have to supply as much charge to pull the plates together. However, the mathematical dependence between the critical voltage and the added mass is far from obvious. One can find the voltage that will just cause the total potential energy to fail to have a minimum, as illustrated above. Note that the total potential energy includes contributions from gravitational attraction on the upper plate, spring pulling on the upper plate, and the electrical attraction by charges in the lower plate. The mathematical condition to be met is that this total potential function is to have an inflection point. If you are a calculus buff, your blood is now racing with anticipation, but you will not get any satisfaction here.

The equation relating the critical voltage and the added mass is

$$V_c^{2/3} = -\frac{2g}{3\left(k^2\epsilon_0 A\right)^{1/3}}\, m + \frac{2}{3}\left(\frac{k}{\epsilon_0 A}\right) z_0 \,, \tag{1.1}$$

Notice that a plot of the 2/3 power of the critical voltage vs. added mass should give a straight line. It is the slope of this plot which we can analyze to solve for $\epsilon_0$. The slope will be negative: we are interested only in its magnitude. Setting the measured slope equal to the expression for the slope in Equation (1.1) gives

$$\epsilon_0 = \frac{8g^3}{27k^2 A\,|\text{slope}|^3} \,. \tag{1.2}$$

In your lab record, extend your data tables to include added mass converted from mg to kg, as well as the 2/3 powers of your observed voltages. Use the `physics` program, menu `Math`, menu `Linear Regression`, to plot $V^{2/3}$ vs. $m$ in kilograms; use the slope and its standard deviation to find $\epsilon_0$ and its standard deviation. Compare your result for $\epsilon_0$ with the value given in your textbook.

The associated relative error for $\epsilon_0$ is

$$\frac{\sigma_{\epsilon_0}}{\epsilon_0} = \sqrt{9\left(\frac{\sigma_g}{g}\right)^2 + 4\left(\frac{\sigma_k}{k}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2 + 9\left(\frac{\sigma_{\text{slope}}}{\text{slope}}\right)^2} \,. \tag{1.3}$$

You will need to estimate the error associated with each term in Equation (1.3). Then, you can use Eqn. (1.3) to estimate the standard deviation for $\epsilon_0$. Which term in Equation (1.3) is the largest source of error for $\epsilon_0$?

# Experiment 2

# Direct Current and Resistors

The objectives for this experiment are:

1. to become familiar with simple DC equipment and
2. to study properties of resistors.

## 2.1 Introduction

A simple analog for electrical circuits is hydraulics, the motion of water through a pipe:

- Voltage, with units of volt (V) or J/C, is the analog of pressure causing fluid to flow through a pipe.
- Current, with units of ampère (A) or C/s, is the flow rate.
- The flow characteristics of a pipe or partially closed valve are expressed by the ratio of pressure difference to resulting flow rate, giving the resistance of the conducting device.

Resistance has the unit, ohm ($\Omega$) or V/A. For many conducting devices the flow rate is proportional to the pressure difference, or the current is proportional to the voltage difference across the terminals of the resistor. Such devices are called Ohm's law resistors:

$$V = IR$$

where $V$ is voltage, $I$ is current, and $R$ is resistance. The SI units (V, A, $\Omega$) are chosen to make this equation correct without any proportionality constant being inserted.

We will often express resistances in terms of kilo-ohms, $1000\,\Omega = 1\,\mathrm{k}\Omega$. As a shorthand notation, one often drops the the "$\Omega$." Thus, $2.5\,\mathrm{k} = 2.5\,\mathrm{k}\Omega = 2500\,\Omega$.

## 2.2 Electrical Equipment

### 2.2.1 Power Supply

The simplest source for electrical energy in this experiment would be flashlight batteries, but these are expensive and not very reliable or flexible. Instead, we will use a power supply. One important advantage of the power supply is that it can be adjusted to deliver any of several voltage values required in the experiment by adjusting a voltage control knob. The current is delivered to an external circuit through the red (positive) and black (negative) leads attached to the terminals.

### 2.2.2 Digital Multimeter

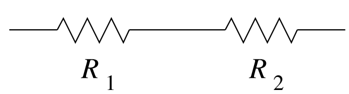
The Tenma Digital Multimeter (DMM) will be used in several experiments for measuring voltage (electrical potential difference) or resistance for several of the experiments. The rotary selection knob should be in the OFF position when the meter is not in use, in the V position for measuring voltage, or the Ω position for measuring resistance. The meter is auto-ranging, avoiding the necessity for selecting appropriate ranges. The digital readings are generally to four figures. The units used must be noted from the display. Resistance values may be displayed as ohms Ω , kilo-ohms kΩ, or mega-ohms MΩ. Two precautions should be observed in using the DMM:

1. The selector knob should be placed in the OFF position when not in use, especially at the end of the day.
2. When making resistance measurements, the meter is not to be connected to any circuit to which the power supply is connected. Failure to observe this precaution is likely to destroy the meter.

## 2.3 Simple resistive circuits

### 2.3.1 Series composite

If we have two resistors in series



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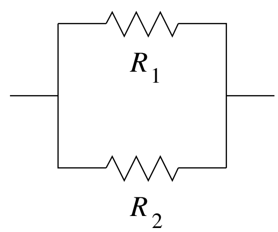
the total resistance is $R_1 + R_2$. If you have more resistors in series, the total resistance is just the sum of all the resistors.

- Turn the DMM rotary knob to the V position.
- Connect the power supply to the four resistors in series: the red lead to pin M1a and the black lead to pin M1e.
- Select roughly 10 V on the power supply and record the actual voltage as measured by the DMM.
- Measure the voltage difference across each of the four resistors. Use Ohm's law to find the associated current going through that resistor. You might want to set up a table in your lab manual to organize your results.
- Using the law for series resistors, we can check our results. Find the total resistance of all of the resistors and divide the total voltage by the total resistance. Do you obtain the same current for all these calculations?

- Disconnect the DMM and the power supply from the circuit.
- Use the DMM to measure the resistance of each of the resistors as well as the total resistance. How close are your answers to the values marked on the resistors?

### 2.3.2 Parallel composite

For two resistors in parallel

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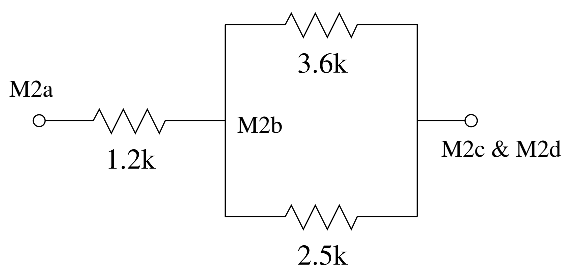
the total resistance is $\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}}$. Now, construct the following circuit:

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- Use an alligator clip lead to connect M2c to M2d.
- Connect the power supply to the circuit: the red lead to M2a and the black lead to M2d.
- Use the DMM to measure the voltage produced by the power supply.
- Now, measure the voltage across the 1.2 k resistor.
- Then measure the voltage across the 3.6 k and 2.5 k resistors.
- Disconnect the power supply.

The power supply causes a current to flow in the 1.2 k resistor, then this current splits into two currents in the parallel combination of 3.6 k and 2.5 k. Use Ohm's law to find the current going through each of the resistors. Does this current equal the sum of the other two resistor currents? Find the equivalent resistance for the 3.6 k and 2.5 k resistors.

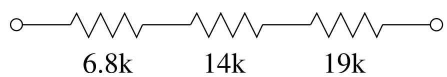
This equivalent resistance is now in series with the 1.2 k resistor. To obtain the total resistance of the entire circuit, add the equivalent resistance (of the parallel resistors) to 1.2 k. Use Ohm's law and the equivalent resistance of the entire circuit to find the total current going through the circuit. How does this compare with the currents found above?

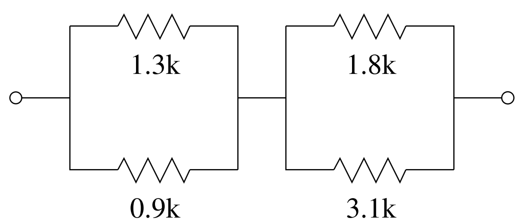
### 2.3.3 Composite Resistances

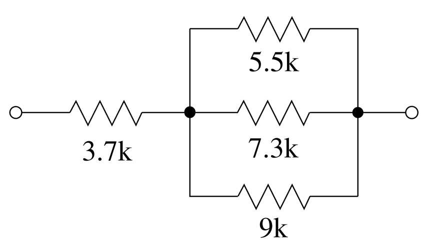
Similar results can be obtained by using the resistance mode of the DMM. In this mode the meter supplies a current to the circuit to which it is connected, and measures voltage. With the help of Ohm's law, the DMM uses the current and voltage to find the resistance of the circuit.

- For these experiments do not use the power supply!
- Put the DMM in the Ω position.

Construct each of the following circuits and measure the total resistance with the DMM. Next, analyze each circuit with the series-parallel rules to predict the total resistance? How good is the agreement?

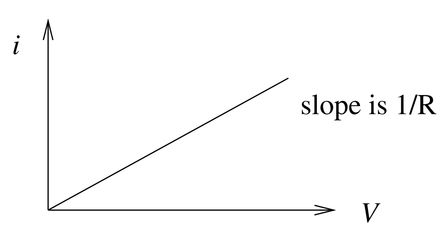



## 2.4 Nonlinear resistance

The resistors we have been using so far have been designed so that the measured resistance is the same, no matter how much current is going through them. If one were to plot the current flowing through the resistor as a function of the voltage across it, one would obtain a straight line:

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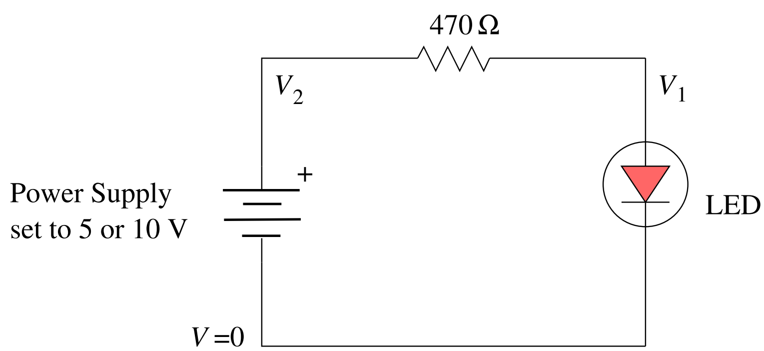
One says that the resistors have "linear" behavior. Other components, however, may have a resistance that is a function of the voltage. We will look at two examples of this behavior.

## LED

Locate the light emitting diode (LED) on your circuit board.

- Use the DMM to measure the reistance of this diode (The result should be very large).
- On the circuit board with the diode, find a resistor that is about 1000 Ω and measure the exact value of its resistance.
- Set your DMM back to the voltage scale.
- Set up the following circuit:




with the power supply set to about 5 V.

- Measure $V_1$ and $V_2$ with the multimeter.
- Use Ohm's law and the measured value of the resistor to calculate the current going through circuit. Then, use $V_1$ and the current to find the resistance of the LED.
- Change the power supply voltage to about 10 V, measure $V_1$ and $V_2$, and find the resistance of the LED again.

Compare your two results for the resistance with the resistance as measured directly by the DMM. Does the resistance go up or down as the voltage across the diode is increased?

## Light Bulb

Now, repeat the experiment using the light bulb instead of the LED (first, measure the resistance with the DMM. . . ). If you want to see the light bulb shine brightly, you can use 10 and 20 V as your two power supply voltages. Compare your two results for the resistance with the resistance as measured directly by the DMM. Does the resistance go up or down as the voltage across the light bulb is increased?

# Experiment 3

# Direct Current Circuits

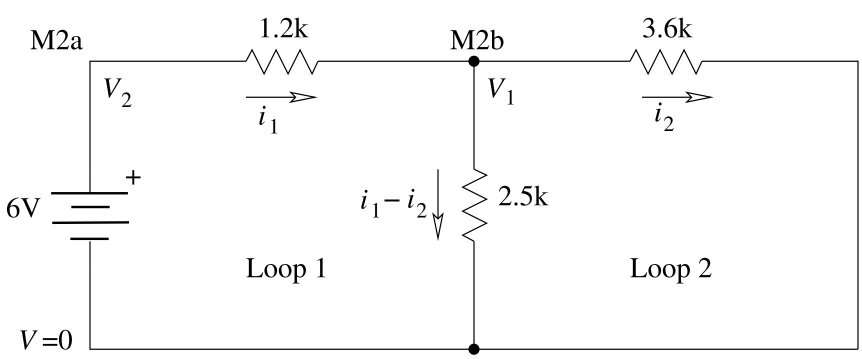
The objective for this experiment is the analysis of resistive circuits. In the last experiment, methods were given to simplify circuits by the series and parallel rules. More complicated circuits involving several loops or more than one power source require a more comprehensive method of analysis to determine the current flowing through (and the voltage drop across) each device in the circuit. We will develop and use the Maxwell loop method, which is an analysis which combines the two laws of Kirchhoff. These are:

1. The sum of the voltage drops around any loop is zero.
2. The sum of the currents flowing into any node is zero.

Kirchhoff's laws are based on the conservation of energy and charge in electrical circuits.

## 3.1 A two-loop circuit

We will illustrate the Maxwell loop method using a simple circuit which we analyzed last time using series-parallel rules:




The circuit has two loops, "Loop 1" and "Loop 2." Let us define $i_1$ to be the current flowing through the 1.2 k resistor in the direction shown.. Similarly, current $i_2$ is the current flowing through the 3.6 k resistor. For the component shared between the two loops, 2.5 k, a current $i_1 - i_2$ is assigned. Note that this satisfies Kirchhoff's current law: the current flowing into the node "M2b" is equal to the sum of the two currents flowing out of that node: $i_1 = i_2 + (i_1 - i_2)$.

Next, Kirchhoff's voltage law is used to write equations for each of the loops by summing the voltage drops observed as one moves around the loop. Moving around each loop in a counterclockwise direction, we obtain:

$$\begin{aligned}(i_1 - i_2)\cdot 2.5\,\mathrm{k} + i_1 \cdot 1.2\,\mathrm{k} - 6\,\mathrm{V} &= 0\\ i_2 \cdot 3.6\,\mathrm{k} - (i_1 - i_2)\cdot 2.5\,\mathrm{k} &= 0\,,\end{aligned}$$

You should note the following:

1. The number of currents defined is equal to the number of loops.
2. There is one equation for each loop.
3. The voltage across a resistor is positive if the current is oriented in the opposite direction as our motion around the loop.
4. The constant term in an equation represents any voltage source that appears in that loop. It is positive if the battery is oriented in the same direction as our motion around the loop.

These properties will be useful for analyzing the more complicated cases we do later.

Finally, let us find the currents $i_1$ and $i_2$. First, we group coefficients of the currents and move the constant terms to the right hand side:

$$\begin{aligned}(2500 + 1200)\cdot i_1 - 2500 \cdot i_2 &= 6\,\mathrm{V}\\ -2500 \cdot i_1 + (3600 + 2500)\cdot i_2 &= 0\,.\end{aligned}$$

Here, we have used the relation amperès=volts/ohms, A = V/Ω. Then we drop the units and write the two equations in matrix form:

$$\begin{pmatrix} 3700 & -2500 \\ -2500 & 6100 \end{pmatrix} \cdot \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} 6 \\ 0 \end{pmatrix}$$

The equations can now be solved using the program `xlinear` on the lab computers.

### 3.1.1 Procedure

Before connecting any components together, measure the values for the resistors with the Tenma Digital Multimeter (DMM) in the Ω mode:

| | |
|---|---|
| 1.2 k | M2a and M2b |
| 3.6 k | M2b and M2c |
| 2.5 k | M2b and M2d |

Next, connect:

- M2c to M2d,
- the power supply − lead to M2d and + lead to M2a, and

- the DMM − lead to M2c.

Select the V mode for the DMM. Select 6 V for the power supply and turn it on. Use the red (+) lead of the DMM to read the voltage at two points in the circuit:

M2b $V_1 =$
M2a $V_2 =$

### 3.1.2 Analysis

Repeat the analysis in Section 3.1 with your measured values in place of the nominal values. Each of the resistances must be replaced with resistance as measured with the meter. The voltage in the first loop equation, given above as 6 V, needs to be replaced with the measured voltage of the power supply.

For our circuit there is only one unknown voltage $V_1$. However, there are several ways to calculate it, and these should all give the same result and agree with the measured value:

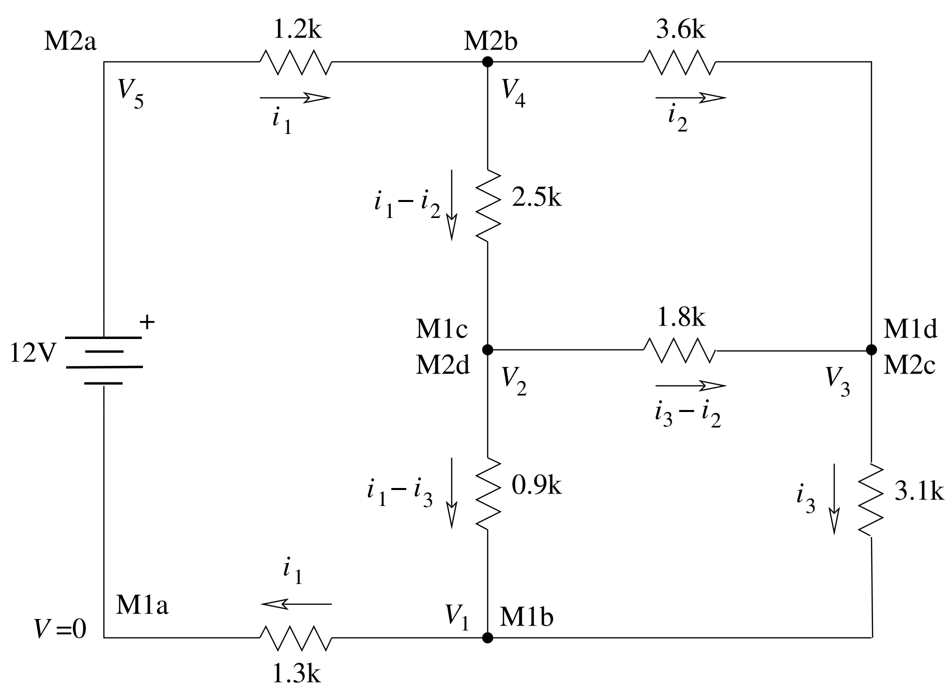
$$V_1 = 6\,\mathrm{V} - i_1 \cdot 1.2\,\mathrm{k} = i_2 \cdot 3.6\,\mathrm{k} = (i_1 - i_2) \cdot 2.5\,\mathrm{k}\ .$$

Notice that you need to use your measured values instead of the nominal values: 6 V, 1.2 k, *et cetera.*

As a check on Kirchhoff's voltage law, we can check for the conservation of energy. The power input, from the power supply, is $i_1 V_2$; this should be the same as the sum of all the resistor power outputs, found by $i^2 R$, where $R$ is the true resistance and $i$ is current flowing through that resistor.

## 3.2 A three-loop circuit

In this circuit we will try to generalize the methods introduced above.



### 3.2.1 Procedure

Before you connect any components to make the circuit, use the DMM ($\Omega$) to measure and tabulate the resistances that will be used:

| | | |
|---|---|---|
| 1.2 k | M2a to M2b | $R =$ |
| 3.6 k | M2b to M2c | $R =$ |
| 2.5 k | M2b to M2d | $R =$ |
| 1.3 k | M1a to M1b | $R =$ |
| 0.9 k | M1b to M1c | $R =$ |
| 1.8 k | M1c to M1d | $R =$ |
| 3.1 k | M1d to M1e | $R =$ |

Select the V mode for the meter, and construct the circuit:

- connect with alligator clip leads:
  - M1b to M1e
  - M1c to M2d
  - M1d to M2c
- connect the power supply: positive (red) to M2a, negative (black) to M1a.
- connect the DMM negative lead to M1a.

Measure and tabulate the voltages observed at the points:

| | |
|---|---|
| M1b | $V_1 =$ |
| M1c | $V_2 =$ |
| M1d | $V_3 =$ |
| M2b | $V_4 =$ |
| M2a | $V_5 =$ |

### 3.2.2 Analysis

Set up the simultaneous equations for the three loops. The constant term for the first loop is the measured value $V_5$ for the power supply. The constant terms for the other loops are zero because they have no voltage sources in them. Identify the some of the resistances in each loop and the resistance values shared between loops; used the measured resistance values rather than the nominal values.

Use the `xlinear` program to solve for the three loop currents. Then use these currents along with Ohm's law to predict what the voltages should be. Use your measured values for $V_5$ and the resistances, rather than the nominal values. Start by finding $V_1$, then find $V_2$, $V_3$, and $V_4$. In each case, how well do your predicted voltages agree with the measured values?

# Experiment 4

# Diodes and Capacitors

The objectives of this experiment are:

1. to study the non-linear behavior of the diode, and
2. to stud the capacitor as a charge storing device.

## 4.1 The Zener diode

Semiconductor diodes are used as rectifiers: the application of a small voltage in the forward conduction direction causes current to flow freely, while voltage applied in the reverse direction causes no current to flow. The rectifier is analogous to a hydraulic check-valve: current can flow in one direction but not the other. A diode has the property that when a very large reverse voltage is applied, current flows in the reverse direction when the voltage exceeds the reverse breakdown voltage. The Zener diode is specially doped with impurities to make its reverse breakdown voltage smaller and more stable; the result is a stable device which has a predictable voltage under a range of current conditions; see Figure 4.1. The Zener diode can be used as a voltage reference for controlling the output of regulated power supplies, such as those used in computers. We will study the current-voltage characteristics for a Zener diode in both the forward and reverse bias modes.

The forward bias characteristics are predicted by theory to follow the equation

$$i = i_0 \left( \mathrm{e}^{\frac{qV}{\eta k_B T}} - 1 \right), \tag{4.1}$$

where

$q$ is the charge of the electron (absolute value),

$V$ is the applied voltage,

$k_B$ is the Boltzmann constant,

$T$ is the temperature (in kelvin),

$\eta$ is a material constant, 1 for germanium, 2 for silicon, and

$i$ is the current in the diode.

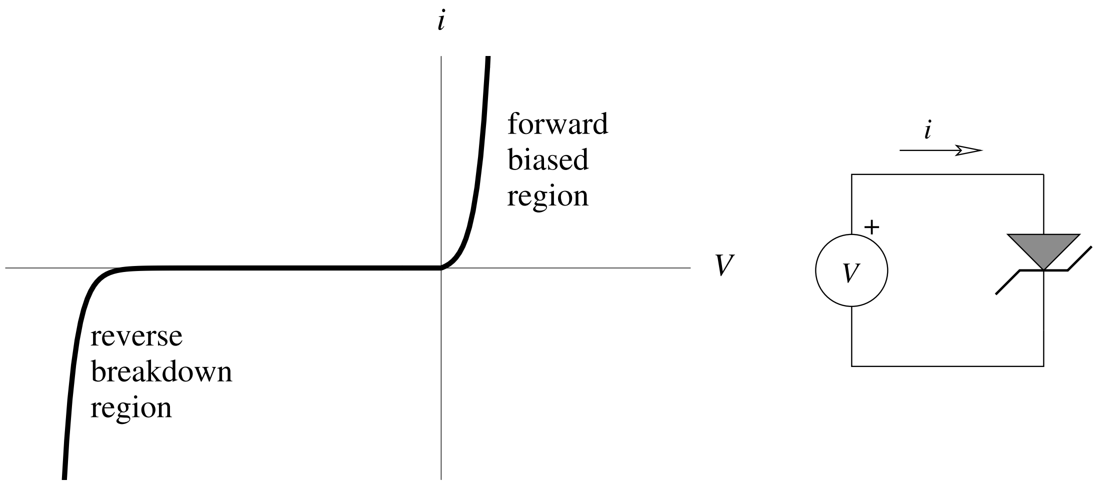
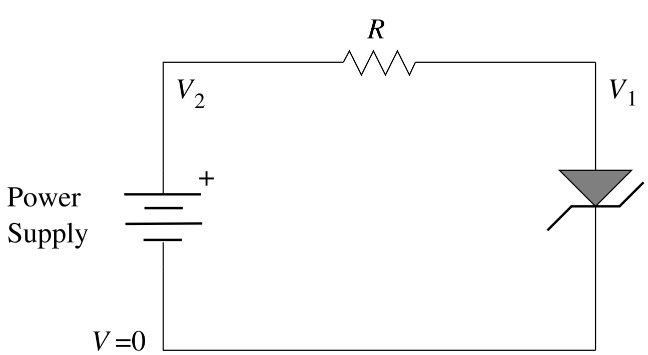



Figure 4.1: Voltage vs. current for a Zener diode.

The ratio $\frac{q}{k_B T}$ is equal to $39\,\frac{1}{\mathrm{V}}$ at room temperature. For any value of $V$ larger than a tenth of a volt, the constant term $-1$ is negligible, and a plot of the logarithm of the current vs. voltage should be a straight line. The slope of this line can be used to find the material constant $\eta$. In the reverse bias case, the current-voltage characteristic is probably also logarithmic, but theory is less clear about this. A typical $i$ vs. $V$ curve is illustrated in Figure 4.1; note that—in contrast to the resistor—the diode is quite nonlinear.

## Procedure

It will be necessary to generate a wide range of currents, for which the diode voltage must be measured with maximum precision. We will take advantage of the large range of resistance values available to generate these currents.



*Forward bias* occurs when the black band end of the diode is connected to the negative side of the power supply. Construct the following data table in your lab notebook:

| nominal $V_2$ (V) | nominal $R$ (k$\Omega$) | $R$ | $V_2$ | $V_1$ | $i = \frac{V_2 - V_1}{R}$ |
|---|---|---|---|---|---|
| forward bias: | | | | | |
| 20 | 470 | | | | |
| 10 | 470 | | | | |
| 5 | 470 | | | | |
| 20 | 14 | | | | |
| 10 | 14 | | | | |
| 5 | 14 | | | | |
| 20 | 2.2 | | | | |
| 10 | 2.2 | | | | |
| 5 | 2.2 | | | | |
| reverse bias: | | | | | |
| 20 | 50 | | | | |
| 5 | 50 | | | | |
| 1 | 50 | | | | |
| 20 | 5 | | | | |
| 10 | 5 | | | | |
| 5 | 5 | | | | |
| 20 | 0.5 | | | | |
| 10 | 0.5 | | | | |
| 5 | 0.5 | | | | |

Use the $\Omega$ function of the DMM to measure, to two or three significant figures, the resistance for each of the resistors used. Record the measured values in your table in the $R$ column.

Construct the circuit for the listed values of $R$ and $V_2$, and fill in the forward bias portion of the table.

For the reverse bias, the same circuit is used, but the diode is turned around so that the non-black-band end connects to the negative lead of the power supply.

## Analysis

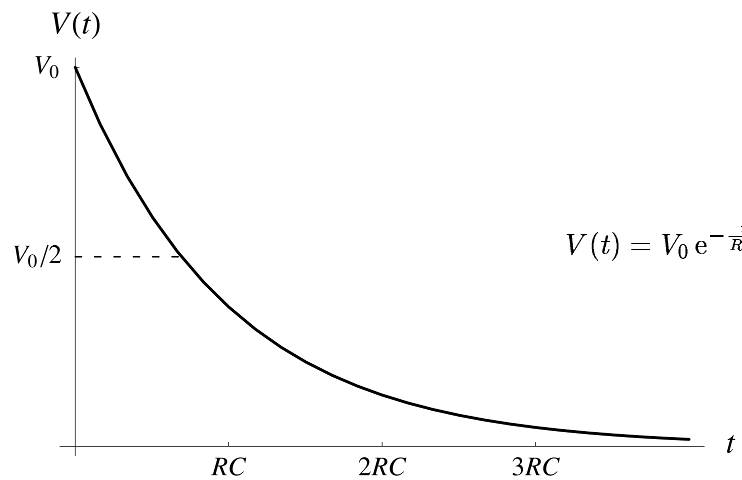
Complete the last column of the table. Use the **`physics`** program, menu **`Math`** and **`Linear Regression`** to plot $\log(i)$ vs. $V_1$. This means that $V_1$ should be the horizontal axis and $\log(i)$ is the vertical axis. As always, $\log(x)$ is the natural logarithm of $x$. You should make two plots: one for the forward current and one for the reverse current. Record the slope of the line for the forward-bias graph. Take the log of Equation (4.1) and compare with the slope you obtained to obtain a value for $\eta$. How well do the data follow the straight line predicted? What does your value for $\eta$ imply about your diode?

If you look at the reverse-bias graph, you should see a sudden and dramatic increase in current as the voltage goes above a certain value. This is called an "avalanche effect." What is the voltage where this occurs? Since there is no straight line, there is no point in performing a linear regression on this data.

## 4.2 Resistor-capacitor discharge

The second part of the experiment explores the capacitor as a charge and energy storage device. When a capcitor, capacitance $C$, is charged to a voltage $V$, the charge stored is $Q = CV$.

When a charged capacitor $C$ is shorted through a resistor $R$, the charge flows out of the capacitor and through the resister. As the charge remaining in the capacitor decreases, the voltage decreases, and, consequently, the current flowing out of the capacitor decreases. This leads to an exponential decay of the voltage:



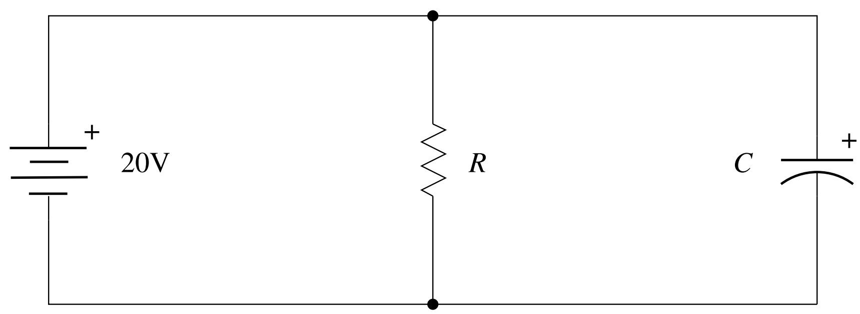

$$V(t) = V_0\, e^{-\frac{t}{RC}} .$$

For example, the time required for the initial voltage to decay to one-half of its value is $RC \log(2)$ or $0.693RC$. This result is independent of the initial charge of the capacitor. We will study this decay to determine whether it is indeed exponential and, if so, what values are obtained for the capacitance of different capacitors.

### Procedure

Locate the 470 k resistor used in the first part of the experiment. One of the capacitors to be used is mounted on the same board; it is blue, has a + polarity marking, and carries a nominal 50 $\mu$F label, which is misleading. This type of capacitor is guaranteed by the manufacturer to have a minimum capacitance given on the label; the true capacitance can be considerably larger. We will use a larger capacitor for the second part of the experiment.

Use alligator clip leads to construct the following circuit:




Do the following:

1. charge the capacitor: connect the red lead from the power supply to the + end of the capacitor;
2. discharge the capacitor: disconnect the the red lead from the power supply and measure the voltage on the capacitor while it discharges through the resistor, using a stopwatch to measure time.

For the first series of measurements, set up the circuit with $C = 50\,\mu$F and $R = 470\,$k. Measure the time it takes for the voltage to fall from its original value to

1. half of this voltage,
2. 1/4 of this voltage,
3. 1/8 of this voltage, and
4. 1/16 of this voltage.

If this discharge is truly exponential, the ratio of the times should be 1/1, 1/2, 1/3, and 1/4. Is this what you observe?

For the second series of measurements, we will find $t_{1/2}$, the time for the capacitor to fall to one half of the original voltage. For the large capacitor, you will have to choose an appropriate resistor; find one such that $RC$ is somewhere around 10 to 20 seconds. Try the following combinations:

1. $50\,\mu$F and 100 k;
2. $50\,\mu$F and 470 k;
3. the large capacitor and your choice of resistor.

In each case use $t_{1/2} = 0.693RC$ to solve for the value of $C$. How do your values for $C$ compare with the value printed on the capacitor?

# Experiment 5

# Diamagnetism and Paramagentism

The objective for this experiment is to see how different materials behave in the presence of a magnetic field.

## 5.1 Introduction

When a substance is placed in a magnetic field, there are two possible things that happen:

**diamagnetism** When a material is placed in a magnetic field, small magnetic moments are induced in the material which oppose the external magnetic field. Thus, the material favors being in a region with lower external magnetic field. This is a relatively weak effect which occurs in all materials.

**paramagnetism** Some materials have intrinsic magnetic dipoles in them. When an external magnetic field is applied, these magnetic dipoles line up in the same direction as the external magnetic field. The material favors being in a region with larger external magnetic field (since the magnets attract each other). This effect can be relatively large.

What about permanent magnets? These are materials have intrinsic magnetic dipoles (like paramagnetism), but these dipoles line up on their own, with no external field applied. This is called **ferromagnetism**.

Since magnets are always dipoles, a constant external field produces no net force on a magnet. However, if the field changes with position, then a net force is produced. Let us see how this works for a magnetic dipole with dipole moment $\boldsymbol{\mu}$. The energy of a magnetic dipole in a uniform magnetic field $\mathbf{B}$ is

$$U = -\,\boldsymbol{\mu}\cdot\mathbf{B}\,.$$

The force due to a change in potential energy in the $x$-direction is

$$F = -\frac{dU}{dx}\,,$$

so the force on a dipole due to a changing electric field is

$$F = \mu\frac{dB}{dx}\,.$$

In conclusion, a dipole in a non-homogeneous magnetic field will feel a net force acting on it. The direction of this force will depend on the direction of $\boldsymbol{\mu}$.

## 5.2 Torsion balance

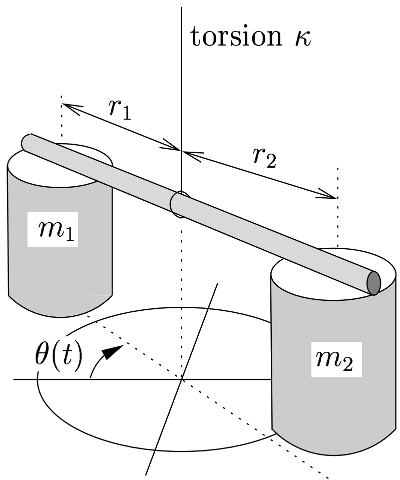
To measure the force on a magnet, we will use a torsion balance. As the horizontal beam is rotated, the wire exerts a torque $\tau$ on the beam. Using Hooke's law, the torque is proportional to the angle:

$$\tau = -\kappa\,\theta\ , \tag{5.1}$$

where $\kappa$ is the torsion constant of the wire. The resulting motion of the beam is that of a simple harmonic oscillator:

$$\theta(t) = A\sin(\omega t)\ .$$

Since this is a rotational system, instead of mass, we use the moment of inertia




$$I = m_1 r_1^2 + m_2 r_2^2$$

and, instead of $F = ma$, we use its rotational analog $\tau = I\alpha$, where $\alpha$ is the rotational acceleration. Thus, we get:

$$\begin{aligned} \tau &= I\alpha = I\frac{d^2\theta}{dt^2} \\ -\kappa\,\theta(t) &= -I\omega^2\theta(t) \end{aligned}$$

so

$$\omega = \sqrt{\frac{\kappa}{I}}\ .$$

If you measure the period of rotation $T = 2\pi/\omega$ and find the moment of inertia $I$, you can calculate the torsion constant of the wire $\kappa$.

## 5.3 Procedure

First, we need to find the torsion constant of the wire.

1. Set up the torsion balance with two matching samples. Find the moment moment of inertia $I$ for your setup.

2. Measure the period $T$ using several oscillations and dividing. You should repeat your measurement so that you are sure the errors are under control.

3. Calculate $\kappa$.

Next, you will measure the force of the magnet on several samples. Use water and two other substances as your samples.

1. Mount matching (in weight) samples on each end of the horizontal beam.
2. Find the equilibrium angle of the torsion pendulum. This is perhaps the most difficult part of the experiment.
3. Place the magnet near the sample and observe how much the beam rotates before the force of the wire equals the force of the magnet. The change in angle is $\Delta\theta$.
4. Is the force attractive or repulsive?
5. Measure the equilibrium angle again.

## 5.4 Analysis

First, you need to convert your deflection angle $\Delta\theta$ to radians. If the force $F$ of the magnet on $m_1$ is equal to torque provided by the torsion wire, then the torque is

$$\tau = r_1 F = -\kappa\,\Delta\theta\ .$$

You can use this equation to find the force exerted by the magnet.

In your conclusion, you should discuss which samples were diamagnetic and which were paramagnetic. Also, compare the relative size of the force for different samples. Make a quantitative estimate of the error associated with your measurements of the force.

# Experiment 6

# Magnetic Fields

The objective for this experiment is study three properties of the magnetic field:

1. an electrical current (in a wire) produces a magnetic field,
2. the direction of this field is given by the right hand rule, and
3. a *change* in the magnetic field going through a closed loop (of wire) induces a voltage in that loop.

The experiment consists of five parts; lab groups will rotate to use each of the seven available stations.

The magnetic field **B** has units of tesla (T) if you are using SI units. In terms of more familiar units, the tesla is equal to

$$\mathrm{T} = \frac{\mathrm{N \cdot s}}{\mathrm{C \cdot m}}$$

Be sure to use the appropriate SI units—meters, seconds, ampères, volts—in the formulas so that **B** will have units of tesla.

In this lab, we will introduce the "permeability of the vacuum," $\mu_0$. It plays a similar role as the permittivity of the vacuum, $\epsilon_0$, that we encountered while studying the electric field. The constant $\mu_0$ tells us how big of a magnetic field is produced by a given current. SI units are cleverly set up so that $\mu_0$ has an exact value:

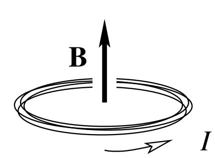
$$\mu_0 = 4\pi \times 10^{-7}\,\frac{\mathrm{T \cdot m}}{\mathrm{A}}$$

where "A" is ampères.

## 6.1 Terrestrial magnetism

Figure 6.1 shows the experimental apparatus for this part of the lab. It consists of a wire wrapped $N$ times around a ring-shaped support with radius $a$. If a current $I$ is passed through the wire, the magnetic field produced at the center of the ring is given by the expression

$$\mathbf{B} = \frac{N\mu_0 I}{2a}\hat{n}$$



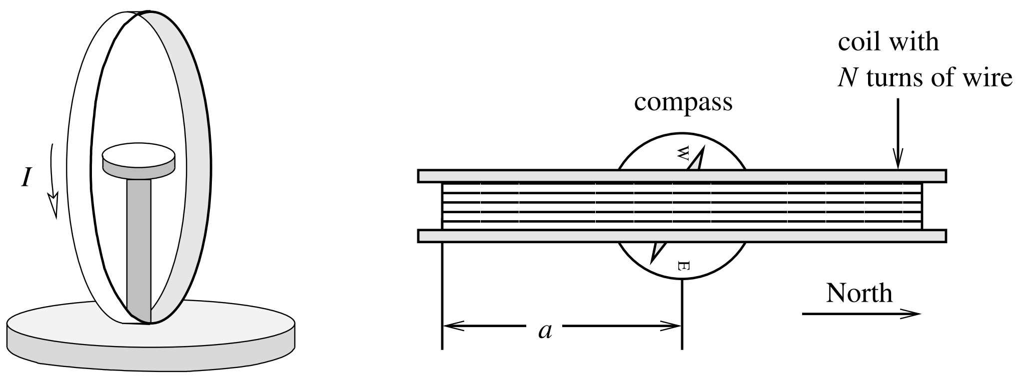



Figure 6.1: A loop-shaped coil used to produce magnetic fields.

and is perpendicular to the plane of the coil as shown. Rotate the coil so that its magnetic field is pointing east or west, perpendicular to earth's magnetic field. Note that the ammeter and the power supply meter also produce magnetic fields; keep them as far away from the compass as possible.

The total magnetic field detected by the compass is the vector sum of the coil's magnetic field plus the earth's magnetic field. Deflections of the compass of 27° and 45° from the position with no current occur when the coil's magnetic field is $0.5\times$ and $1\times$ the earth's field. Measure the current required to obtain these deflections and calculate the earth's magnetic field. Do the two deflections give consistent results? In your lab report, draw a vector diagram showing why deflections of 27° and 45° are expected for these fields. You can compare your result for the horizontal component,[1] of the earth's magnetic field with values in your textbook.

## 6.2 Field near a straight wire

The experimental set-up is shown in Figure 6.2. Start by counting $N$, the number of turns of wire in the loop. Adjust the Variac control on the lab power supply to obtain a meter current of $I = 1\,\mathrm{A}$. Use the small compass to determine the direction of the field near the vertical wire with descending current. Does the field change direction when the compass is held at different positions about the wire? Repeat with the vertical wire with ascending current. Do your observations confirm the right hand rule as explained in your textbook?

With the meter current set at $I = 2\,\mathrm{A}$, use the larger compass to find the location on the board north from the wire at which the compass deflects 45° from the north-south direction: here the wire field is equal to the earth's field. Measure the distance from the center of the wire to the center of the compass. Next find the distance at which the deflection from north is 63°; here the field is twice the earth's field. Compare the distances at which the fields of the wire are in the 1:2 ratio. Now decrease the meter current to 1 A; does the compass deflection relax from the 63° value to 45°? Compare these observations with the following equation from your textbook:

$$B = \frac{\mu_0 I N}{2\pi a}$$

[1]The earth's magnetic field also has a vertical component but this experiment is not sensitive to it.

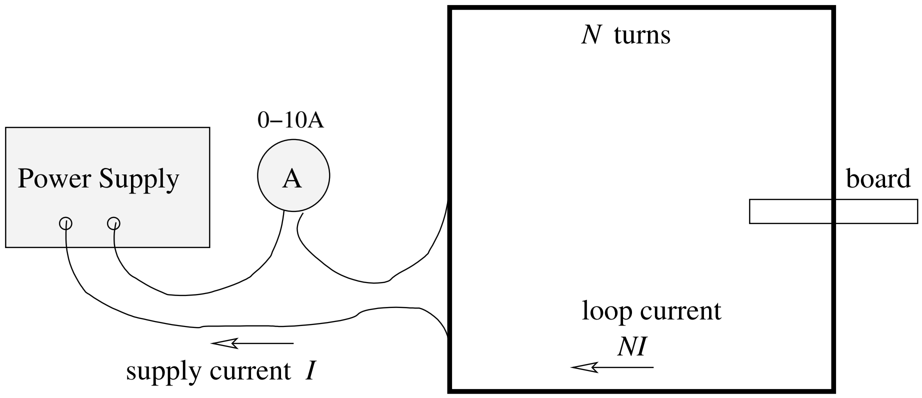
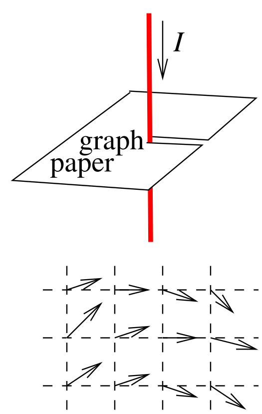



Figure 6.2: Apparatus for studying field near a straight wire.

where $a$ is the distance from the wire. Use the data for one of your 45° deflections to estimate the horizontal intensity of the earth's field; compare your answer with the field you find in Section 6.1.

## 6.3 Magnetic field lines




Place a sheet of graph paper on the surface so that the wire goes through the center of the sheet. Adjust the power supply so that it is producing about 0.5 ampères of current; the current passing through the wires produces a magnetic field around the wires. Use a compass to find the direction of the magnetic field at various points on the sheet and mark the direction of the magnetic field with an arrow. The marks should be around 1/2 to 1 inch apart. There are two things you should look for:

1. Note the behavior of the **B** field near the wire.
2. There is a point where the earth's magnetic field and field from the wire add up to zero. Note how the **B** field behaves in the vicinity of this point.

## 6.4 Measuring the field of a permanent magnet

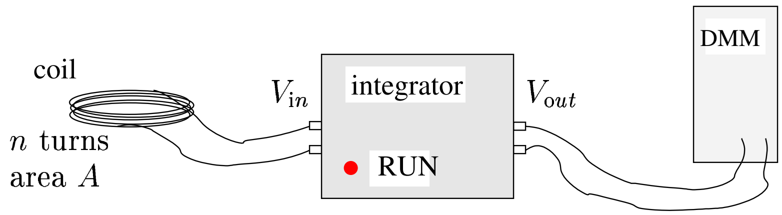
Consider a coil of $n$ turns and area $A$. If this coil is placed in a magnetic field $B$, a voltage $V$ is generated in the coil. In fact, any change of the magnetic field induces a voltage in the coil:

$$V(t) = nA\,\frac{d}{dt}B(t)\ .$$

Thus, if we define $\Delta B$ to be change in the magnetic field,

$$\int V(t)\,dt = nA\,\Delta B\ . \tag{6.1}$$

We can use this effect to measure the magnetic field in a permanent magnet. In this experiment, we have a coil of wire connected to a "voltage integrator."




This electronic device integrates the input voltage $V_{\text{in}}$ over time,

$$V_{\text{out}} = \frac{1}{\zeta} \int V_{\text{in}}\, dt \;, \tag{6.2}$$

where the value of $\zeta$ is written on the integrator box. Combining Equations (6.1) and (6.2), we have

$$\Delta B = \frac{1}{nA} \int V_{\text{in}}\, dt = \frac{\zeta}{nA} V_{\text{out}} \;.$$

Here are some general instructions for using the voltage integrator:

1. Turn on the power switch on the side of the box.
2. Connect the digital multimeter (DMM) to the output voltage $V_{\text{out}}$.
3. Place the coil of wire in the magnetic field.
4. Press and hold down the RUN button.
5. Remove the coil of wire from the magnetic field.
6. Record the voltage on the DMM.
7. If the output voltage $V_{\text{out}}$ seems to drift a lot, call your instructor and complain bitterly.

## Procedure

This is what you have to do for this part of the lab:

1. Use the larger value for $\zeta$.
2. Place the voltage integrator between the poles of the large magnet so that the magnetic field is perpendicular to the coil. Use the voltage integrator to find the magnetic field produced by the magnet (use the smaller value of $\zeta$). Remember, the voltage integrator measures *changes* in the magnetic field.
3. What happens if you flip the coil over by 180°?
4. See what happens when you rotate the coil to be parallel to the magnetic field. Remember, the integrator measures the magnetic flux going *through* the coil.

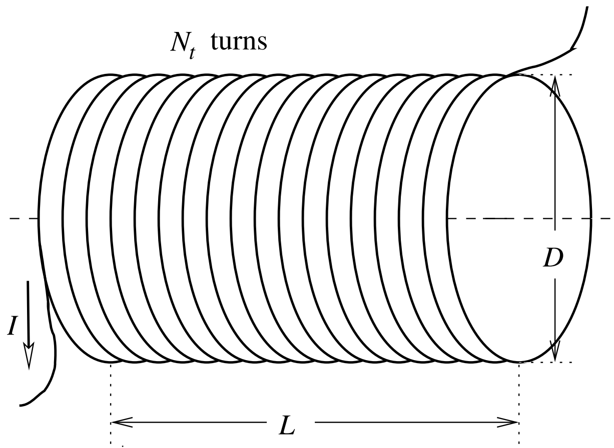



Figure 6.3: Solenoid. $N_t = 418$, $D = 4.7\,\text{cm}$, and $L = 9.2\,\text{cm}$.

5. See what happens if you start with the coil away from the magnet and then place it in the magnetic field.

6. Now for something completely different:

   (a) start with the coil away from the magnet and press the RUN button;

   (b) insert the coil between the magnets, and observe $V_{\text{out}}$;

   (c) still holding the RUN button, remove the coil from the magnet and observe $V_{\text{out}}$ again.

   Explain what you observed.

## 6.5 Field in a solenoid

In this section of the lab, we will measure the magnetic field produced by a solenoid; see Figure 6.3. Measure the magnitude of **B** at the center of the solenoid for a current $I$ of about 400 mA. (See the beginning of Section 6.4 for instructions on using the voltage integrator.) Compare your result with the formula for the magnetic field at the center of a solenoid of finite length:

$$B_{\text{center}} = \frac{\mu_0 I N_t}{\sqrt{L^2 + D^2}}$$

Note that $N_t$ is the *total* number of turns on the solenoid. In the same manner, measure the magnetic field at the end of the solenoid. Compare your result with the formula for the magnetic field at the end of a long solenoid:

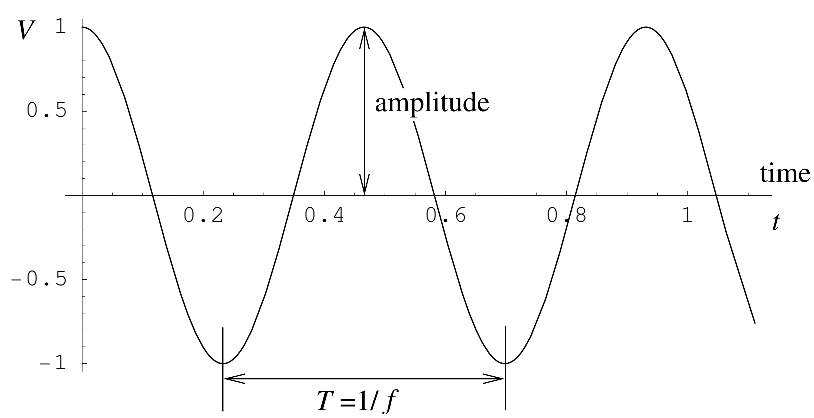
$$B_{\text{end}} = \frac{\mu_0 I N_t}{2L}$$

# Experiment 7

# Alternating Current Measurements

The objective for this experiment is to become familiar with equipment used in studying AC circuits.[1]

In previous experiments, we dealt with circuits where the voltages did not change very much with time. In the case of AC circuits, the voltages change with time. Usually, we are interested in systems where are voltages and currents are periodic functions of time.




Thus, $T$ is the time for one period of oscillation and the maximum voltage during one period is called the amplitude. The frequency $f$ is the reciprocal of the period, with units of Hertz (Hz), and the angular frequency $\omega$ is $2\pi f$.

## 7.1 AC Equipment

In this lab, we will introduce the two most important tools for studying AC circuits: the function generator and the oscilloscope.

### 7.1.1 Function Generator

The function generator supplies various waveforms—a sine wave, a square wave, or a triangle wave—at the frequency that you specify. The sinusoidal waveform will be used most frequently.

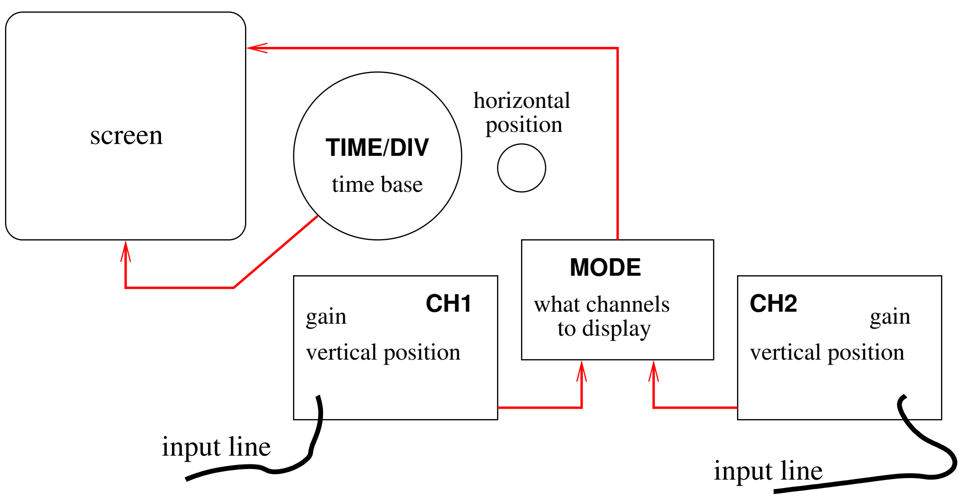
[1] AC is short for "alternating current."

The frequency is set by two controls: a course adjustment to set the overall frequency scale and a fine adjustment knob to set the exact frequency. The frequency is accurate to ±1 digit of the display. Locate the amplitude control knob. You can use this to adjust the amplitude of the output from 0 to about 15 V; a setting between 25% and 50% of full scale should work for most of our experiments.

### 7.1.2 Oscilloscope

The oscilloscope is one of the most useful instruments in the electronics lab. The large number of knobs on the front panel can be a bit intimidating, but don't let all those knobs scare you! Once you have a signal on your screen, you can (and should) play around with the knobs and see what they do. In practice, you will find that the hardest part is getting a signal on the screen in the first place.

The oscilloscope makes a plot of voltage versus time. Typically, an oscilloscope will have two channels, CH1 and CH2, which means that it can plot two different voltages simultaneously. The most important controls are: the vertical gain control VOLTS/DIV and the vertical POSITION control for each channel, the MODE knob which selects the channel(s) that are displayed, and the time base control TIME/DIV which selects the scale on the horizontal (time) axis.




How does the oscilloscope know when to start plotting? This is controlled by the "trigger" mechanism. The oscilloscope monitors an input signal and when that signal gets above some specified voltage LEVEL, it starts plotting voltage as a function of time. Generally, we will use one of our input signals, CH1 or CH2, as the trigger. Thus, you should set the MODE to AUTO, the trigger SOURCE switch to internal INT, and choose the trigger control INT TRIG to be the appropriate channel. If the scope is not being triggered in some way, then nothing will show up on the screen.

## 7.2 Checking out the equipment

For the first part of today's experiment, we will simply observe the voltage coming from the function generator.

1. Turn on the function generator and choose the sinusoidal output.
2. Adjust the frequency to be about 2000 Hz.
3. Set the amplitude control to about 1/3 of full scale.
4. Find the POWER switch and turn on the oscilloscope.
5. Connect the generator output to the CH1 scope input. (Connect the red signal leads together and connect the black ground leads together.)
6. Since you are looking at CH1, set the MODE and INT TRIG controls accordingly.
7. Fiddle with the knobs until you get a nice sine wave on your screen. Ask your instructor for help if you get stuck; if your instructor ignores you, keep playing with the knobs.

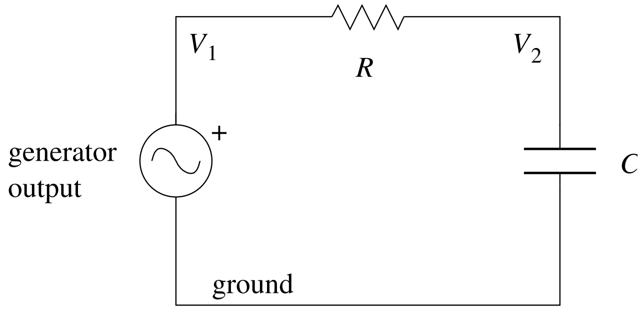
Now that you have a signal, you can try the following:

1. Adjust the time base TIME/DIV so that at least one period of the sine wave is displayed on the screen.
2. Adjust the horizontal POSITION so that you can see the beginning of the graph on the left side of the screen.
3. Observe what happens to to the phase of the sine wave as you adjust the trigger LEVEL. What happens if you adjust it too far?
4. Measure the period $T$ of one cycle of oscillation. Note that the time base TIME/DIV controls the number seconds per division in the horizontal direction. How does the associated frequency $f = 1/T$ agree with the display of your function generator?
5. Measure the amplitude of the wave. The trick here is to adjust the vertical POSITION control so that the wave is centered on the horizontal axis (so the negative amplitudes are equal to the positive ones). Note that the gain VOLTS/DIV controls the number of volts per division in the vertical direction.
6. Experiment with different frequency ranges. Can you set the time base TIME/DIV so that one or two periods are shown on the screen?

## 7.3 RC circuit

### Procedure

Locate a 10 k resistor and a 0.01 $\mu$F capacitor on the component board and construct the following circuit:




Since we want to look at both $V_1$ and $V_2$ as a function of time, connect the CH1 input of the scope to $V_1$ and connect CH2 to $V_2$. In each case, the ground lead should be connected to the $V = 0$ part of the circuit. Set the oscilloscope to display both channels and to trigger from CH1.

Set the function generator to about 1000 Hz with a sine wave output and record the exact frequency $f$. Adjust the vertical POSITION of each sine wave so that it is symmetric about the horizontal axis. Measure the amplitude of of each wave. Be sure that the vertical gain VOLTS/DIV for each channel is the same. Notice that the phases of the two waves are different. Measure the phase difference $\Delta t$, in seconds, you can decrease the time base TIME/DIV to get a more accurate measurement. Next, repeat these measurements for a frequency of 3000 Hz.

Finally, switch the function generator to produce square waves. Decrease the frequency to less than 1000 Hz for a better view of what is going on. Do you see an exponential decay for $V_2$? Sketch a graph of the voltages as a function of time. What is the $t_{1/2}$ for this exponential? Recall, that we discussed $t_{1/2}$ a few weeks ago in Section 4.2.

### Analysis

When working with AC circuits, it is helpful to generalize the concept of resistance. One finds that—for AC signals—current can flow through a capacitor. The higher the frequency, the more current will flow through. Thus, we can think of a capacitor as having some sort of "resistance" at non-zero frequencies. This is called the "impedance" of the capacitor.[2] In keeping with the resistor analogy, impedance has units of ohms. The impedance of the capacitor is

$$Z = \frac{1}{2\pi f C} \,.$$

The ratio of the amplitudes of $V_1$ and $V_2$ is predicted to be

$$\sqrt{\frac{Z^2 + R^2}{Z^2}} \;;$$

[2] Actually, impedance $Z$ is a complex number. We will treat it as real in this lab.

how does this compare with your measurements? The phase difference, in degrees, of the two waveforms is

$$360^\circ f\,\Delta t\,.$$

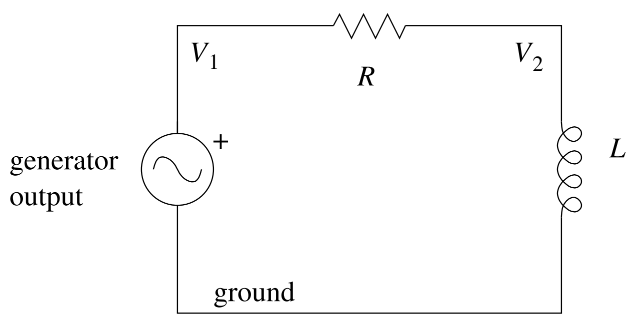
Theory predicts that $V_2$ will lag behind $V_1$ by an angle of

$$\arctan\left(\frac{R}{Z}\right)\;;$$

how does this compare with the measured phase difference? You should analyze both the $f = 1000\,\mathrm{Hz}$ and $f = 3000\,\mathrm{Hz}$ data. Finally, compare your value of $t_{1/2}$ with the value predicted by the formula in Section 4.2.

## 7.4 RL Circuit

Next, we will study a resistor-inductor circuit. An inductor is basically a coil of wire wrapped around a ferrite core. The strength of an inductor is measured in henries (H). Locate the $L = 1.0\,\mathrm{H}$ inductor on your circuit board. Use this inductor and the 10 k resistor to construct the following circuit:




Select a sine wave with frequency of about 1000 Hz and measure the amplitudes and phase difference of $V_1$ and $V_2$.

Now, you should repeat the analysis of Section 7.3 for the RL circuit. Compared to the RC circuit, the phase difference has the opposite sign, and the impedance formula becomes

$$Z = -2\pi f L\,.$$

Note that, in contrast with the capacitor, the impedance of the inductor *increases* with frequency. Other than the two differences noted here, the analysis of the RL circuit is identical to that of the RC circuit. In your conclusion, discuss the phase shift of the RL circuit versus the phase shift of the RC circuit.

Finally, let us see what happens to the RL circuit when the signal generator produces a square wave. Sketch a graph of what you see on the oscilloscope. How does it differ from the graph of the RC circuit?

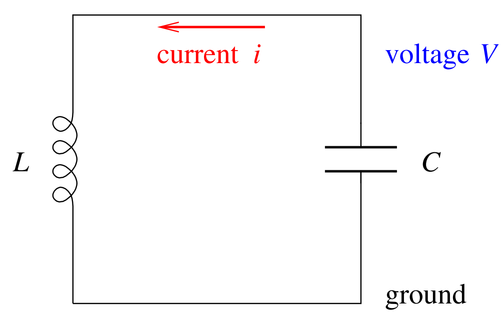
# Experiment 8

## AC Circuits: Resonance

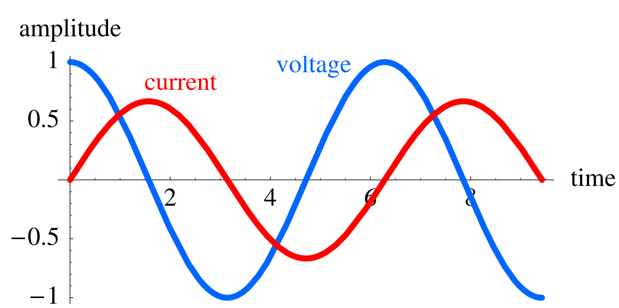
The objective for this experiment is to study resonance phenomena in circuits containing both capacitance and inductance.

## 8.1 Introduction

In today's lab, we will study circuits consisting of an inductor and capacitor connected in a loop.




For an electrostatic charge, the capacitor stores energy $\frac{1}{2}CV^2$ while, for an electric current $i$, the inductor stores energy $\frac{1}{2}Li^2$. If we start with the capacitor full of charge, current flows out of the capacitor and through the inductor. Thus, as the capacitor is discharged, energy is transferred to the inductor. Once the capacitor is completely discharged, all of the energy is stored in the inductor. However, the current flowing through the inductor causes the capacitor to recharge, and so on. Thus, we obtain sinusoidal motion for both the voltage and the current.




Note that the voltage and current, as a function of time, are 90° out of phase.

If we solve the equations describing this circuit, we would find that the frequency is given by the formula

$$f = \frac{1}{2\pi}\frac{1}{\sqrt{LC}} . \tag{8.1}$$

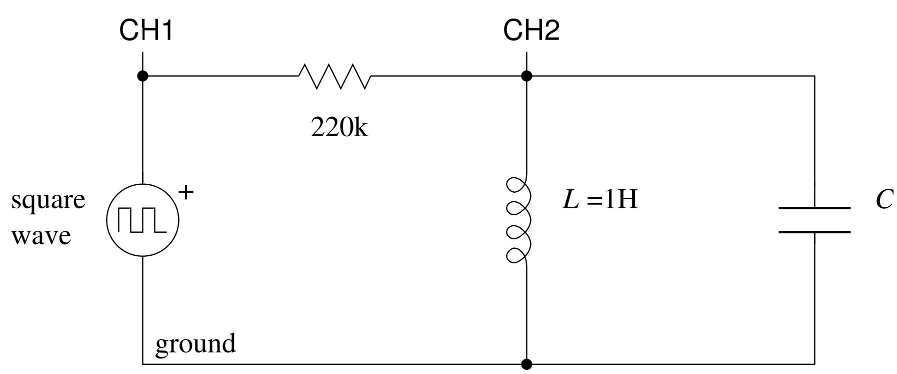
The equations for this circuit are exactly the same as those of the harmonic oscillator. If we replace $L$ with $m$ and $1/C$ with $k$, we obtain the familiar simple harmonic oscillator formula,

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} . \tag{8.2}$$

In this experiment we will examine the response of the inductor-capacitor (LC) circuit to a perturbation which sets it into oscillation. Then we shall study the LC resonator as an element in an AC circuit.

## 8.2 Resonator ringing

Construct the following circuit with a $C = 10\,\text{nF}$ capacitor and a 100 Hz square wave on the signal generator:




The 220 k resistor is coded red-red-yellow. Connect the oscilloscope leads to monitor the output of the signal generator on CH1 and to monitor the voltage across the capacitor on CH2. You should set the trigger INT TRIG to CH1 and the MODE to display both channels. Adjust the time base TIME/DIV and the vertical gain VOLTS/DIV to get a nice graph of both channels on the screen (you should see at least one period of the square wave).

Observe what happens when the voltage output of the square wave changes: there is a burst of sine oscillations in the LC circuit which slowly decay. Now, let us measure the "ringing frequency" of these oscillations. Adjust the time base so that you see just a few periods of these oscillations. Measure the time for one cycle and calculate the frequency. You can get a more accurate answer by measuring the total time for several oscillations and dividing by the number of oscillations. Compare your result with Equation (8.1). How many oscillations are there before the amplitude decreases to one half of its maximum size?

Repeat these measurements for the 1 nF capacitor. Also, how many oscillations are there before the amplitude decreases to one half of its original size? How your results differ from the case of the 10 nF capacitor?

## 8.3 Resonance for a sinusiodal signal

Next, we will investigate the resonant behavior of the LC circuit for sine waves. We will use the circuit in Section 8.2, except that you should set the signal generator to generate sine waves.

1. Set up the circuit with the 1 nF capacitor.

2. The resonant frequency of the LC circuit is given by Equation (8.1). If the signal generator is set to a frequency below this resonance, the amplitude of the oscillations will be small. As the frequency of the signal generator is increased, the amplitude of the oscillations increase. Above the resonant frequency, the amplitudes will decrease again.[1] Find the frequency where the amplitude at a maximum.

3. At the resonant frequency, find the ratio

$$\frac{\text{LC circuit amplitude}}{\text{signal generator amplitude}}.$$

4. Below the resonant frequency, the phase of the circuit will be ahead of the signal generator. At resonance, the phase difference will go to zero. Above the resonance, the phase will lag behind that of the signal generator. Record the frequency where the phase difference goes to zero.

5. Calculate the resonant frequency using Equation (8.1).

Repeat the above procedure with the 10 nF and 0.1 $\mu$F capacitors. In your conclusion, discuss how well your results agree with each other and with Equation (8.1). Do you note any trends in your results as you change the capacitance?

[1] The LC circuit acts as a sort of filter: only input signals with frequencies near the resonance frequency produce a large output.

# Experiment 9

# The speed of light

The objective of this lab is to study the propagation of electromagnetic waves.

## 9.1 Introduction

In this class, we have been studying the properties of electric and magnetic fields, **E** and **B**. Most of these properties were first discovered in the early nineteenth century by men like Örsted, Ampère, and Michael Faraday. In 1864, James Clerk Maxwell took the various equations describing electricity and magnetism known at that time and combined them into four equations,

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \quad \text{(Gauß law)} \tag{9.1}$$

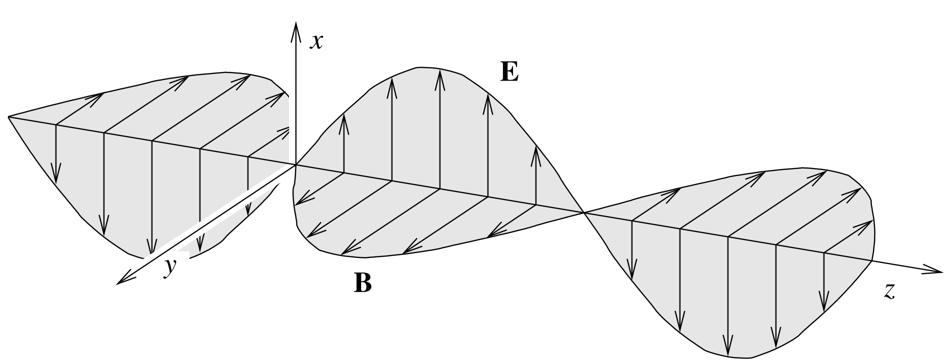
$$-\mu_0\epsilon_0 \frac{d}{dt}\mathbf{E} + \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad \text{(Ampère's law, extended by Maxwell)} \tag{9.2}$$

$$\nabla \cdot \mathbf{B} = 0 \quad \text{(Gauß law for magnetic fields)} \tag{9.3}$$

$$\frac{d}{dt}\mathbf{B} + \nabla \times \mathbf{E} = 0 \quad \text{(Faraday's law)}\ , \tag{9.4}$$

where $\rho$ is the charge density and **J** is current density. These four equations are known collectively as "Maxwell's equations." Since these equations are written in derivative form, they probably don't look familiar to you. In fact, Equation (9.1) is just Coulomb's law! The discovery of Equations (9.1)–(9.4) was perhaps the greatest scientific achievement of the nineteenth century.

One important prediction of Maxwell's equations is the fact that **E** and **B** fields can oscillate as waves and that these "electromagnetic waves" can travel through space.



Electromagnetic waves take many forms, depending on the frequency (and wavelength) involved:

| wavelength (m) | frequency (Hz) | type |
|---|---|---|
| $10^4$ to 1 | $10^4$ to $10^{10}$ | radio waves |
| $10^{-3}$ to $7 \times 10^{-7}$ | $10^{11}$ to $5 \times 10^{14}$ | infrared |
| $7 \times 10^{-7}$ to $4 \times 10^{-7}$ | $5 \times 10^{14}$ to $8 \times 10^{14}$ | visible light, red to violet |
| $4 \times 10^{-7}$ to $10^{-10}$ | $8 \times 10^{14}$ to $10^{18}$ | ultraviolet |

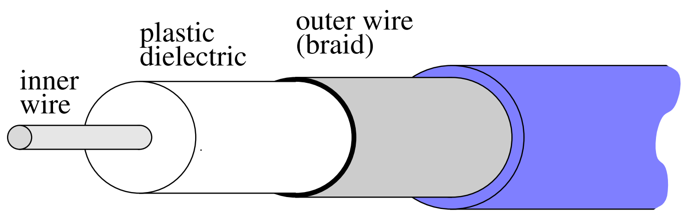
Note that the most familiar form, visible light, only takes up a small fraction of the total spectrum of frequencies. Maxwell's equations predict that all of these waves—no matter what frequency—travel at the same speed,

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 2.99792458 \times 10^8 \, \frac{\text{m}}{\text{s}} \, . \tag{9.5}$$

In SI units, $c$ is *defined* to have exactly this value. Also, in SI units, the second is defined in terms of a Cesium clock and is known very accurately. Since the value of $c$ and the second are fixed, when we measure the speed of light, we are actually measuring how long a meter is.

## 9.2 Coax Cable

In this section, we will study the propagation of an electrical signal through a coax cable. A coax cable consists of two cylinders of wire separated by an insulating material.




For a cable of length $\ell$, the capacitance $C$ and self-inductance $L$ are given by the formulas:

$$C = \frac{\ell \kappa \epsilon_0}{2\pi \log\left(\frac{r_o}{r_i}\right)} \quad \text{and} \quad L = 2\pi \ell \mu_0 \log\left(\frac{r_o}{r_i}\right) \, ,$$

where $r_o$ and $r_i$ are the radii of the outer and inner conductors[1] and the dimensionless constant $\kappa > 1$ is the dielectric constant of the insulator. For most insulators, $\kappa$ is less than five.

If one puts an electrical signal on one end of the coax, the signal travels down the inner wire at a speed dictated by the self-inductance per unit length $L/\ell$ and capacitance per unit length $C/\ell$ of the coax cable. The velocity of the signal is given by

$$v_{\text{coax}} = \frac{\ell}{\sqrt{LC}} = \frac{1}{\sqrt{\mu_0 \epsilon_0 \kappa}} \, . \tag{9.6}$$

Comparing with Equation (9.5), we see that the signals propagate through the coax at a velocity somewhat less than $c$ since $\kappa > 1$.

[1] As always, $\log(x)$ is the natural logarithm of $x$.

### Measuring the velocity

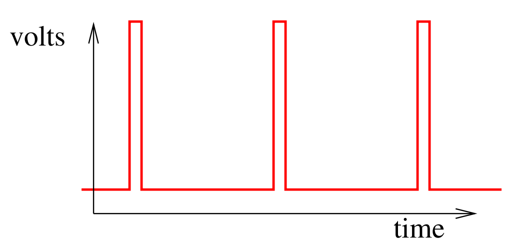
1. Record the length of the coax cable.
2. Take one end of the coax cable and connect the inner wire to the function generator output and to the CH1 input of the oscilloscope. Connect the outer wire of the coax to the ground leads.
3. Adjust the function generator to produce a square wave at a frequency of 50–100 kHz.
4. Set the oscilloscope to trigger, INT TRIG, from CH1. Adjust the time base TIME/DIV so that you see one period of the wave on the screen. Adjust the trigger LEVEL so that you can see the very beginning of the input waveform. Does your square wave look very square?
5. Connect the other end of the coax to CH2 of the oscilloscope. (Don't forget to connect the ground lead to the outer wire of the coax.)
6. Now, we want to focus our attention on the beginning of the input waveform. Adjust the time base TIME/DIV to be as small as possible. Measure the time delay of the *beginning* of the output signal relative to the *beginning* of the input signal. You may have to further adjust the trigger LEVEL to get a good measurement.

Now, you can find $v_{\text{coax}}$, the velocity of a waveform moving through the coax. In addition, you should estimate the error[2] associated with your measurement of $v_{\text{coax}}$.

In your conclusion, compare your answer for $v_{\text{coax}}$ with $c$. Is the difference larger than your estimate of error? Finally, use your result for $v_{\text{coax}}$, along with Equations (9.5) and (9.6), to find the dielectric constant $\kappa$ of the insulator.

### Reflections

It is pretty obvious that the nice square wave output of the function generator has been badly mangled by the coax cable. To better see what is going on, we will adjust the function generator so that it produces a train of pulses.




1. Adjust the function generator to output narrow pulses. On the newer function generators, select the pulse setting. For the older generators:
   (a) Find the DUTY knob on the function generator and pull it to invert the signal.
   (b) Turn the DUTY knob all the way up.

[2]This is similar to error estimations in the first two labs last semester.

2. Increase the frequency to the maximum allowed rate. The frequency should now read something like 250 kHz.

3. Adjust the time base TIME/DIV on the oscilloscope so that you can see several of the pulses.

4. For this part of the experiment, you only need to look at the CH1 signal. You can disconnect CH2 from the other end of the coax cable.

On the screen of the oscilloscope, you should see the pulses produced by the function generator as well as several smaller pulses. Now, we are ready to begin our investigation.

Measure the time delay between the beginning of a large pulse and the beginning of the following small pulse. (You might want to temporarily decrease your time base to do this more accurately.) How does this compare with the time delay that you measured previously? What do you conclude about the smaller pulses? (This is an important question! If you are confused, ask your instructor for help.)

1. Draw a sketch of the waveform that you see on the screen of the oscilloscope.

2. Now, take the other end of the coax and touch the inner wire to the outer wire. Draw a sketch of the waveform that you see.

3. A potentiometer is a resistor whose resistance can be varied by turning the knob. Take your potentiometer and attach it to the other end of the coax, one clip on the inner wire and the other clip on the outer wire.

4. Adjust the potentiometer so that the small pulses are as small as possible.

5. Disconnect the potentiometer and measure its resistance.

When this resistance is equal to the "impedance" of the coax cable, the waves are not reflected from the end of the cable. We introduced the concept of impedance in Section 7.3 as a generalization of resistance for non-zero frequencies. We can also talk about the impedance of a coax cable. In this case, the impedance $Z$ is independent of frequency and is determined by the self-inductance $L$ and the capacitance $C$,

$$Z = \sqrt{\frac{L}{C}} = \frac{1}{2\pi} \log\left(\frac{r_o}{r_i}\right) \sqrt{\frac{\mu_0}{\kappa \epsilon_0}} \,. \tag{9.7}$$

Here, $r_o$ and $r_i$ are the radii of the outer and inner conductors.[3] (The ratio $\sqrt{\mu_0/\epsilon_0} \approx 377\,\Omega$ is the impedance associated with electromagnetic waves traveling through free space.) Use Equation (9.7) to find the ratio of the radii, $r_0/r_i$. Do you obtain something reasonable? As part of the conclusion in your lab report, you should relate what you saw in the demonstration and what you observed in this experiment.

[3]As always $\log(x)$ is the natural logarithm of $x$.

# Experiment 10

# Properties of Lenses

The objectives for this experiment are to verify the lens formula, to study the focusing properties of simple lenses, and to use the lensmaker's formula to find the refractive index of the glass in the lens.

Consider a simple, thin, convex lens shown in Figure 10.1. The distances to the object and the image are related to the focal length $f$ of the lens, by

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \,. \tag{10.1}$$

As a first estimate of $f$, hold the lens and a piece of paper so as to focus the image of some distant object on the paper; a house on College Avenue, viewed through the window, serves nicely as a distant object. Have a lab partner measure the distance from the paper to the center of the lens as you maintain the best focus. Because $d_o \gg d_i$, $d_i \approx f$.

On the optical bench, for series of eight values for $d_o$, ranging from $f$ to about $5f$, determine the corresponding value of $d_i$. At the correct value of $d_i$ the image should focus sharply on the image screen. Note that, if I take $1/d_i$ as my horizontal axis and $1/d_o$ as my vertical axis, Equation (10.1) is just an equation for a straight line. With this in mind, use the `physics` program, menu `Linear Regression`, to perform a linear regression of your data, plotting $1/d_o$ vs. $1/d_i$. If the lens formula applies, the slope should be -1 and the two intercepts should both be equal to $1/f$. Use both intercepts to determine $f$ for your lens. If they are not the same, use their average to determine $f$.

Does the result from the optical bench give about the same value for $f$ as your first estimate? Estimate the error associated with each method of determining $f$. Are your two values for $f$ significantly different? The value obtained with the optical bench is probably the more reliable measurement.

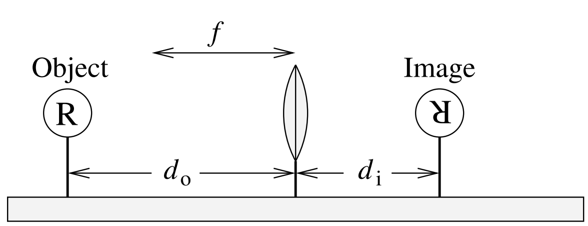



Figure 10.1: Simple lens

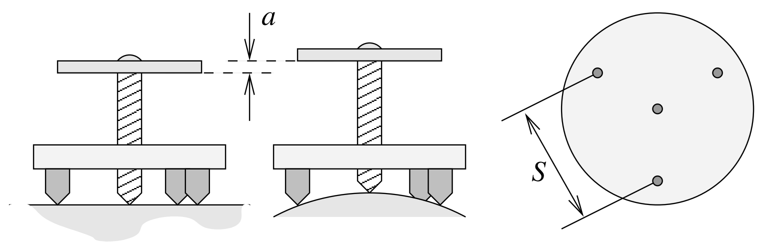



Figure 10.2: Spherometer

Next, let us study the curvature of your lens using the spherometer. Two complete sets of measurements are required to find the curvature for both surfaces of the lens. Place a small piece of tape on one side of the lens to be sure that you do not accidentally measure the same side twice. Choosing a spherometer small enough to fit your lens, place it on a sheet of flat glass and adjust the central micrometer screw until all four feet are touching the glass. Then, counting complete turns and fraction of a turn, adjust the central foot until all four feet touch the surface of the first side of your lens. The central foot moves a distance $a$ of one centimeter for every 20 turns of the screw. Measure also the average distance in cm between the feet of the triangular base using the calipers; this distance is $S$. The radius of curvature for the surface you have examined is given by

$$R = \frac{S^2}{6a} + \frac{a}{2}\,.$$

Record this radius of curvature, then repeat the procedure to find the radius of curvature of the other side of your lens. The two radii will be called $R_1$ and $R_2$. If one side of your lens is flat, its radius is taken as infinity.

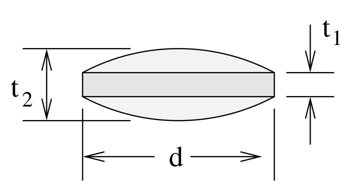
The lensmaker's formula relates the focal length of a thin lens to these radii and to the refractive index of the glass,

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where $n$ is the refractive index. This form of the equation takes both radii of curvature as positive, assuming that your lens is convex on both sides. Use the best value for $f$ from your analysis of the optical bench measurements, along with your two radii of curvature, to determine the refractive index of the glass in your lens.

While this method is capable of great precision, errors are likely to be made by people not used to working with spherometers. For this reason, a rough check of results is provided. Measure with the calipers the diameter of your lens, along with the thickness at two points: at the edge and at the center:

$$f \approx \frac{1}{8(n-1)}\left(\frac{d^2}{t} + t\right) \qquad n \approx 1 + \frac{1}{8f}\left(\frac{d^2}{t} + t\right)$$




$$t = t_2 - t_1$$

These equations can be used to solve for the refractive index. While this system is not as accurate, it should give results similar to the spherometer method. If the refractive index is more than 0.05 different from that of the spherometer system, it is likely that an error has been made in using the spherometer and you should repeat those measurements.

There are two commonly used glass formulations for lenses. Crown glass usually has a refractive index of about 1.50, while flint glass, containing heavier elements, is closer to 1.65; which type of glass do you conclude you have in your lens?

Suppose your lens were made of a substance with the refractive index of water $n = 1.33$. What would be its focal length under these conditions?

# Experiment 11

# Interference and the Hydrogen atom

The objectives for the experiment are:

1. To study the wave properties of light using several interference experiments and
2. to calibrate a diffraction grating and to use this to measure the spectrum of atomic Hydrogen.

## 11.1 Introduction

Without a doubt, quantum mechanics was the greatest physical discovery of the twentieth century. Quantum mechanics tells us something very important: how atoms and molecules work. Thus, it provides the foundation for many branches of science: chemistry, electronics, optics, *et cetera*.

The basic idea in quantum mechanics is that all matter has both particle- and wave-like properties. In some situations an electron sometimes behave like a particle; in other situations it behaves more like a wave (orbitals in an atom, for example). The same is true for light: in some of today's experiments, we use the wave properties of light to perform interference experiments. However, in Section 11.3, we will treat light as a particle, called the "photon."

## 11.2 Procedure

In this lab, we will carry out four separate measurements; they can be performed in any order. However, you must use the same laser for Sections 11.2.2 and 11.2.3. The teams will move from one station to another until they have the data for all four parts. The two devices used here are the two-slit pattern, which is a pair of transparent parallel lines on an opaque photographic film, and the diffraction grating which is equivalent to several thousand parallel, equidistant slits.

### 11.2.1 Distance between slits for the double-slit

The slits are far enough apart to be resolved by the eye or with a magnifying glass, but a microscope must be used to determine their distance of separation accurately. The traveling microscope has a sample stage which is moved from side to side with a micrometer screw. Choose a pair of slits on the film, turn the micrometer screw and find the distance between the two slits. The distance is measured from the *center* of one slit to the *center* of the other slit. One turn of the micrometer screw = 0.5 mm.

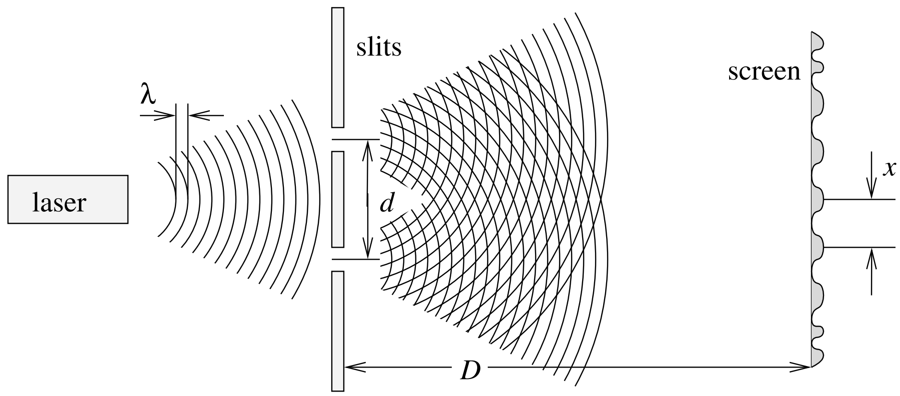



Figure 11.1: Two slit interference of light.

### 11.2.2 Two-slit interference of laser light

The laser is ideal for interference measurements because it produces light that is well collimated, and monochromatic (one wavelength). Care must be taken that the you do not look directly into the laser beam. In this experiment, we will use either a diode laser or a He-Ne gas laser.

Passing the light through the slits in the direction perpendicular to their plane, observe the row of spots on a piece of paper that is a distance $D$ (about 2 meters) away from the slits; see Figure 11.1. Find $x$, the distance between two adjacent spots. You will get more accurate results if you find the total distance between several spots (as many as possible) and dividing.

$$\lambda_l = \frac{xd}{D} \,. \tag{11.1}$$

Calculate the wavelength of the laser light $\lambda_l$. Depending on the laser, you should find a wavelength somewhere between 600 and 700 nm.

### 11.2.3 Diffraction grating calibration

Pass the laser light through the diffraction grating perpendicular to its plane and observe the diffraction pattern on a screen that is a meter or two away; see Figure 11.2. Althought you can observe higher order spots, the screen should be placed so that the first order spots $n = 1$ and $n = -1$ appear near the outer edges of the screen. Measure the distance from the grating to the

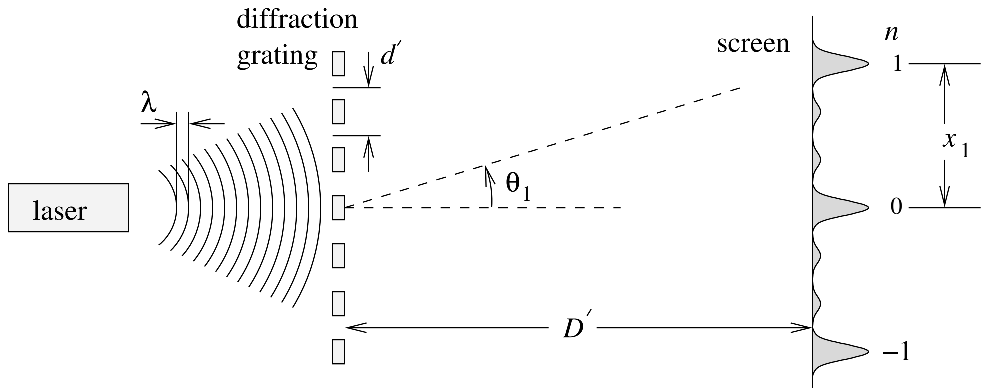



Figure 11.2: Interference pattern from a diffraction grating.

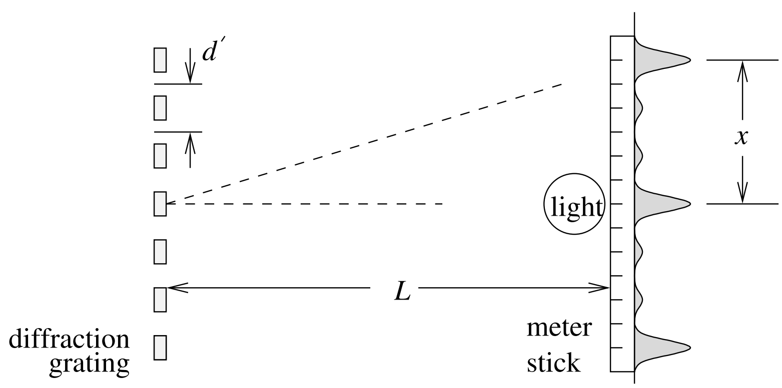



Figure 11.3: Viewing the Hydrogen spectrum by looking through a diffraction grating.

screen $D'$, and divide the distance between the $n = 1, -1$ spots by 2 to obtain $x_1$. We have

$$d' = \frac{\lambda_l}{\sin\theta_1} = \frac{\lambda_l}{\sin\left(\arctan\left(\frac{x_1}{D'}\right)\right)} . \tag{11.2}$$

Use the wavelength $\lambda_l$ (obtained in Section 11.2.2) to find $d'$, the distance between adjacent lines on the grating.

### 11.2.4 Spectrum of the hydrogen atom

A simple spectrometer is formed by holding the grating directly in front of the eye while the grating is a distance $L$ of about 1.00 m from the meter stick; see Figure 11.3. A meter stick near the tube can be viewed to estimate the position of each of the colored lines presented to the eye. The tube should be at the 50 cm mark; for each of the colored lines, determine how far the line is from the tube. For example, a line at 80 cm is $x = 0.30$ m from the tube. Solve for the wavelength of each of the lines:

$$\lambda = d' \sin\left(\arctan\left(\frac{x}{L}\right)\right) , \tag{11.3}$$

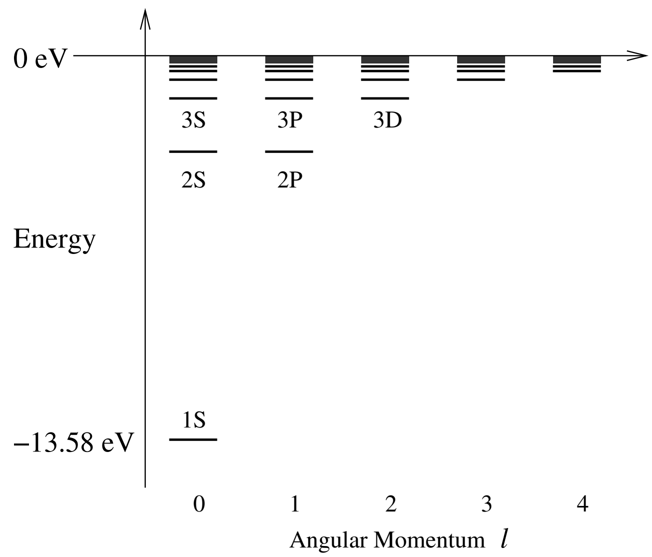



Figure 11.4: The spectrum of the Hydrogen atom. The various orbitals, 1S, 2S, 2P, 3P, *et cetera* are labelled by their principle quantum number $n$ and their angular momentum $l$. For example, 3P corresponds to $n = 3$ and $l = 1$.

where $d'$ was found in Section 11.2.3. Note that some of the spectral lines appear to be red. You will also note that the laser output is also red. What can you conclude about the wavelength of theses lines? Do your numerical answers agree with this?

## 11.3 Analysis

The Hydrogen atom is the simplest possible atom: one electron orbits around one proton. It is simple enough that one can calculate the atomic orbitals and their energies analytically; see Figure 11.4. This is done by solving Schrödinger's equation (if you take quantum mechanics, you will learn how to do this). The energy of an orbital—principle quantum number $n$—is

$$E_n = -\frac{m_e e^4}{8\epsilon_0^2 h^2 n^2} , \tag{11.4}$$

where $m_e$ and $e$ are the mass and charge of the electron and $h$ is Planck's constant. Note that the energy depends on $n$ but not on the angular momentum $l$. An electron, as it orbits around a proton, *must* occupy one of these orbitals. It can only have certain energies: those allowed by Equation (11.4).

What happens when light is emitted from a Hydrogen atom? It takes energy for the atom to do this. If the electron is already in the 1S orbital, no light is emitted since the electron is already at the lowest possible energy. If the electron is at another orbital, say the 2P, then it can lose energy by jumping down to the 1S orbital. Using (11.4), the energy lost would be $E_2 - E_1$.

What would the wavelength of the light be? To answer this question, we will need to use some quantum mechanics. According to quantum mechanics, the light will come off as a "photon" with frequency $f$ and energy

$$E_\gamma = hf \ ,$$

Relating wavelength $\lambda$ to frequency, $\lambda f = c$, the photon's energy is

$$E_\gamma = \frac{hc}{\lambda} \ .$$

Calculate the wavelengths predicted for several transitions $n \to n'$:

$$2 \to 1 \quad 3 \to 1 \quad 4 \to 1 \quad 3 \to 2 \quad 4 \to 2 \quad 5 \to 2 \quad 4 \to 3 \quad 5 \to 3 \quad \textit{et cetera}$$

and determine which three transitions are in the visible region 400 nm to 700 nm. Compare these with the wavelengths you observed in Section 11.2.4.

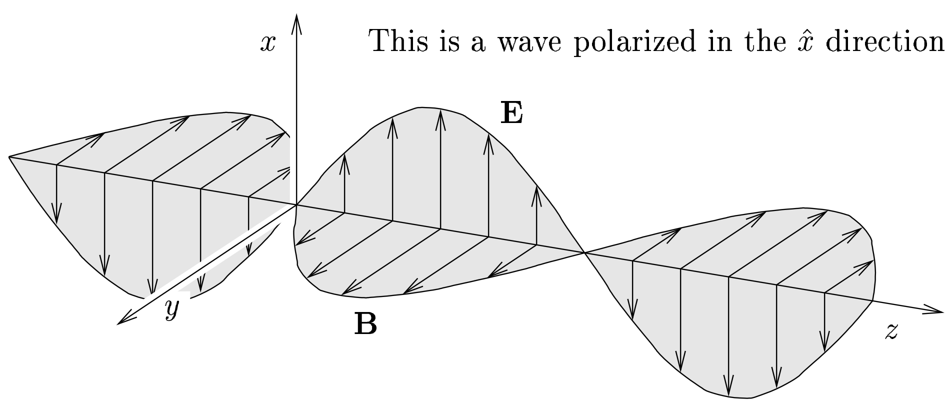
# Experiment 12

## Polarization and Nuclear Decay

In today's lab, we will conduct two unrelated experiments. First, we will finish our study of optics with some simple polarization experiments. Then we will study the decay of radioactive nuclei.

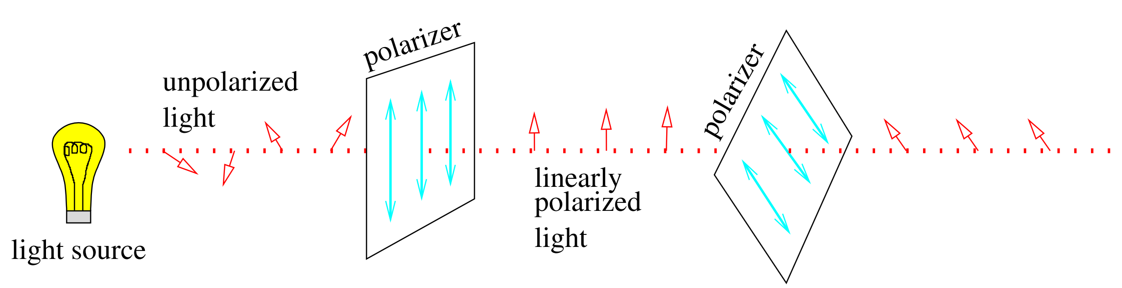
### 12.1 Polarization of Light

One important property of light is that it can be polarized. If light is traveling, say, in the $\hat{z}$-direction, the polarization is defined to be the direction of the associated electric field. It can either be in the $\hat{x}$ or $\hat{y}$ directions, or some linear combination thereof.



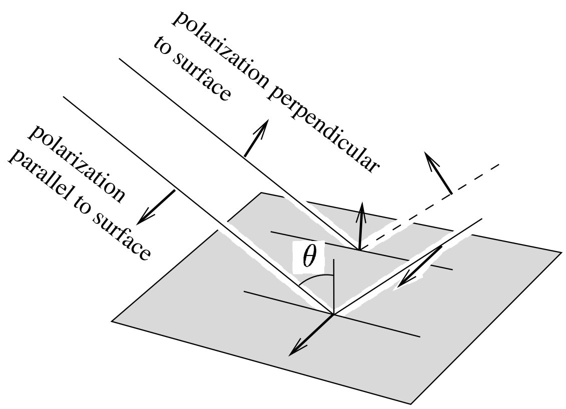

This is a wave polarized in the $\hat{x}$ direction.

There are some materials, consisting of long polymer chains all lined up in one direction, that only transmit light that is linearly polarized in a certain direction. This is called a "polarizer."



If light passes through a polarizer, light that is polarized in the wrong direction is absorbed and the light that emerges is linearly polarized. If this light passes through a second polarizer, the amount of light that emerges is dependent on the angle of the second polarizer relative to the first. If both polarizers are oriented in the same direction, then light passes through; if they are perpendicular, then no light passes through.

When light is reflected off some surfaces, such as water or glass, the light polarized parallel to the surface is reflected much better than the light polarized "perpendicular" to the surface.




In fact, at a special angle $\theta$ called the Brewster angle, *none* of the light polarized "perpendicular" to the surface is reflected. The formula for the Brewster angle is

$$\tan(\theta) = n \tag{12.1}$$

where $n$ is the index of refraction of the material.

Some molecules are either "left handed" or "right handed." A familiar kind of sugar, Dextrose, is a good example. This "handedness" or "chirality" can have an interesting effect. If one shines a linearly polarized light through the material, the direction of the polarization will rotate as the light passes through the material.

## Procedure

- Look at a light source (the window, for instance) through *two* polarizers. Observe what happens as you rotate the second polarizer relative to the first. For how many angles (out of 360°) does the light not go through the second polarizer?

- Using the pan of water, determine the direction of polarization of your polarizers. Also, use a protractor or rulers to measure the value of the Brewster angle.

- Calculate the Brewster angle using Equation (12.1) and compare the angle with your experimental result.

- Find the polarization of the laser you are using. Is it polarized? If so, in what direction? (Be sure to describe which laser you are using.)

- If the output of your laser is unpolarized, you can make a polarized beam simply by putting a polarizer in the path of the beam.
- Shine some polarized light through the sugar sample. Observe what direction and how many degrees the polarization is rotated.
- Draw a picture explaining the direction of the rotation. Make sure your picture is unambiguous.
- What does the word “Dextrose” mean? What language is it from?

## 12.2 Decay of Radioactive Nuclei

The objective for this experiment is to measure the half-life for the short-lived isotope $\mathrm{Ba}^{137\mathrm{m}}$ using a Geiger detector and counter. The radioactive isotope $\mathrm{Ca}^{137}$ emits a $\beta$-particle (an electron) and decays into $\mathrm{Ba}^{137\mathrm{m}}$. The $\mathrm{Ba}^{137\mathrm{m}}$ nucleus then decays into $\mathrm{Ba}^{137}$, emitting a $\gamma$-ray (“gamma-ray,” a high-energy photon).

$$\begin{array}{rl} \mathrm{Cs}^{137} \rightarrow \beta^- + & \mathrm{Ba}^{137\mathrm{m}} \\ & \downarrow \\ & \mathrm{Ba}^{137} + \gamma \end{array}$$

The first decay takes place in the ion-exchange column generator. The $\mathrm{Ba}^{137\mathrm{m}}$ that is produced can be washed out of the generator with a solution that does not remove the Cesium. This yields a sample containing only $\mathrm{Ba}^{137\mathrm{m}}$, and one can observe the emission of $\gamma$-rays as the nuclei decay into normal $\mathrm{Ba}^{137}$.

The probability for a given nucleus to decay is independent of time. However, once it decays, it is gone. For a sample containing many nuclei, number of decays per unit time is proportional to the number of nuclei remaining in the sample. Thus, if there are $N(t)$ nuclei at time $t$, the decay rate is

$$\frac{d}{dt} N(t) = -\lambda N(t) \tag{12.2}$$

where $\lambda$ is the “decay constant” of the substance. The solution of this equation is:

$$N(t) = N_0 \, \mathrm{e}^{-\lambda t} \tag{12.3}$$

where $N_0$ is the number of nuclei at time $t = 0$. The “half-life” $T_{1/2}$ is defined to be the time where one half of the nuclei have decayed. In terms of the half-life,

$$N(t) = N_0 \, 2^{-t/T_{1/2}} \; . \tag{12.4}$$

### Procedure

This experiment must be performed under the supervision of your lab instructor. A Geiger Counter is used to detect the gamma rays from the decay of $\mathrm{Ba}^{137\mathrm{m}}$. Even without a sample, the Geiger Counter detects some amount of “background radiation.” When determining the number of counts from the sample of $\mathrm{Ba}^{137\mathrm{m}}$, the counts due to background radiation must be subtracted.

1. We will start by measuring the number of background counts over a three minute interval.
2. Place the sample below the Geiger Counter and record the number of counts that occur each minute for a total of about 15 minutes.
3. Finally, we will measure the background rate a second time over a three minute interval.

We will use the average of both measurements of the background — divided by the number of minutes — as our background rate.

### Analysis

Let $C(t)$ be the number of counts recorded by the Geiger counter in one minute minus the background. The number of decays should be proportional to the number of nuclei still present in the sample, $C(t) \propto N(t)$. Using Equation (12.4),

$$C(t) = \text{const} \cdot 2^{-t/T_{1/2}}$$

If we take the logarithm of this equation, we obtain

$$\log\left(C(t)\right) = \log(\text{const}) - \frac{t}{T_{1/2}} \log(2) \tag{12.5}$$

where $\log(x)$ is the natural logarithm of $x$. Use the `physics` program, menu `Math` and `Linear Regression` to plot $\log(C(t))$ as a function of $t$. Compare your linear regression with Equation (12.5) and find $T_{1/2}$. Compare the value for the half-life with that found in the literature. What half-life would be observed if we had started with a sample with twice as much starting material? Why? Calculate the decay constant $\lambda$.

Experiments like this are known as "counting experiments." Errors in counting experiments are particularly easy to analyze: if you count $N$ objects, then the associated error is simply $\sqrt{N}$. Use this to estimate the *relative* error in your measurement of the background rate. (Recall that you measured the background for a total of six minutes.)

Another source of error in this measurement is that the detector requires about 0.3 ms to reset itself after detecting a gamma ray. Any particle arriving during this "dead time" goes undetected. This error can be avoided by using samples with low activity, but this introduces the errors from the fluctuations of the background radiation. What effect do you anticipate that the "dead time" has on the number of counts measured at various times in the experiment?