

PHYSICS 130/130A - ELECTRICITY AND  
MAGNETISM

Laboratory Manual

Spring 2022

PHYSICS & ASTRONOMY DEPARTMENT  
KNOX COLLEGE  
Galesburg, Illinois



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# PREFACE

The goals of physics are to understand nature and to enable making accurate predictions about nature. Physicists often set about pursuing these goals by reasoning mathematically from a small set of fundamental laws which look much like mathematical axioms. Because of this emphasis on mathematical reasoning and logical deduction, it is easy to lose sight of the crucial fact that physics, like the other sciences, is **experimental**. This means that experiments are the basis for the laws of physics and all the predictions we derive from them – the “laws” are in essence just concise summaries of experimental results – and in this way, they are quite different from mathematical axioms. When a theoretical prediction conflicts with an experimental finding, it is always the theory which must be discarded – so *experiments constrain theory*. It is experiment which sorts out which theories are possible and which are not. Naturally, the real story is often more complicated than this simple picture: there are examples of great theorists who refused to believe in experiments that seemed to contradict their views and whose intuitions about nature were ultimately vindicated by more careful later experiments. There have also been some great theorists who tried this dangerous game and lost. Notwithstanding these interesting complexities of physics research as a human endeavor plagued with fascinating individual cases that challenge any generality we state, the fundamental principle remains that experiments are the ultimate basis of our physical knowledge.

Real experiments are also a messy business. It is almost never easy to disentangle a single phenomenon or principle to be tested from all the other interactions and phenomena that are always present. Right away we are forced to make approximations, to try to neglect interactions that are hopefully small (like air resistance), and to model others that may not be small (like sliding friction) in ways that we know are imperfect. There is always the issue of choosing an appropriate model (i.e. a mathematical description of the experiment that inevitably leaves some things out). Of course, one wants to be sure that what is left out is in fact negligible, or, more precisely, one wants to have some estimate of the size of the errors made. So good experiment design involves error analysis, which can be surprisingly intricate. In this course you will encounter some of these issues of experiment design and uncertainty analysis, but our focus will be primarily on the using the physics you learn in the classroom to understand real phenomena in the lab. **Applying the tools and techniques you learn in the classroom to analyzing your experiments will give you good practice in using the physics you are learning.**

This manual begins with information about the course policies and instructions for preparing your lab reports. This is a good place to check if you have questions about what is expected in your reports. The introductory section also includes some general information about reporting measured numbers properly and analyzing experimental uncertainties. Make sure to also look over this information while preparing your reports! This useful information is followed by descriptions of the weekly laboratory experiments.



# LABORATORY COURSE INFORMATION

Knox College Physics 130/130A - Spring 2022

**LAB MEETINGS:** Wednesdays in room SMC D105

**LAB INSTRUCTOR:** Tom Moses

**office:** SMC D116

**email:** tmoses@knox.edu

**office phone:** 341-7341

**LAB REPORT HONOR CODE POLICY:** You are encouraged to work together on lab reports; you may consult other students as well as tutors, other physics faculty, etc. , in addition to your textbook, as well as other reference materials. However, your final write-up must be your own unique product. Duplicate reports, even from lab partners, are not acceptable and likewise, sharing any exact text or plots from your report is not acceptable.

**LAB REPORT SUBMISSION:** Lab Reports are due on the following Friday at 4PM (or later, depending on when I leave for the afternoon.) In other words, you will perform your lab on Wednesday and have about 2 days to make your lab report. Reports should be dropped in the box in the hallway across from the lab room. See the next section for instructions on preparing your lab reports.

**LATE POLICY:** Late labs get a 10% deduction per (business) day (must be in by about 4PM to be considered in for **that day**). Special arrangements can be made (in advance, whenever possible) for illness, emergencies, unavoidable absences, sports competitions, etc.

**LABORATORY COMPUTERS:** Use the login name

.\Physics\_Lab

and the password

Knox1837

Alternatively, you may use your ordinary Knox network username and password to log onto the lab computers - in that case, **be sure to log off before leaving the lab.**





# PREPARING LABORATORY REPORTS

## I. Report Format

Laboratory reports for this course will be streamlined, since we want you to focus on understanding the physical ideas rather than on crafting scientific reports.

Lab reports may be typed or neatly handwritten.

The report you hand in should consist of the following parts:

### 1. Identifying information:

- Your name
- "Lab partners:" followed by the names of your lab partner(s)
- Your lab time (Period 2, 3, 5, or 6)

2. **Answers to the questions** including any necessary data analysis, calculations, and plots. Answer lab questions in complete sentences, and clearly define any mathematical symbols used. Clearly label/title all material such as plots and tables and reference them by this label in your answers/explanations.

3. **Raw data** as an appendix, attached to the end. You also should title your appendices (e.g. Appendix A) so they can be referenced in your answers if necessary.

No introduction, methods, procedure, or conclusions sections are required in your lab reports this term.

## II. Answers to Questions

Most questions will require answers that include a numerical answer as well as an explanation or some sort of response. Provide this explanation as a concise, clearly worded statement. You should spellcheck, make sure you use good grammar, write in complete sentences, etc.

However, don't forget that the mathematics is also a key part to your method, so whenever calculations are required, show them in full detail. If you type your report, you may either write the equations **neatly by hand** or **format them properly** using a computer text-setting tool (e.g. in Word using the Equation Editor, Mathematica, or some other math-typing tool). If a number of very similar repetitive calculations are necessary, you need only show one example calculation.

**When showing your calculations make sure you always:**

- **define all symbols** used, e.g.  $m$  = mass of ball;  $v_o$  = initial speed of glider, etc.,
- **specify the units** of all measured quantities, including the slopes and intercept of plotted lines, unless they are unitless,

- take care to use a reasonable number of **significant digits**.

### III. Raw Data

Present data cleanly and clearly. Whenever appropriate, present data in chart or tabular form. If you have handwritten raw data records, staple them to the back of your report as an appendix.

- **Give your data tables a title** so it is clear what the data refer to.
- **Specify the units** of measured quantities and take care to **use a reasonable number of significant digits**.
- Whenever possible, **estimate the uncertainty** in a measured quantity. For example, if you are recording a length measurement of 0.500 m that you believe is accurate to within 2 mm, write:  
length of track =  $L = 0.500 \pm 0.002$  m.

### IV. Working Together

You are encouraged to work together on lab reports and may consult with anyone or any book that you may find helpful. **Your final write-up must be your own unique product - typed by yourself without any other draft report to help you.** In particular, duplicate reports, even from lab partners, are not acceptable and will be viewed as a violation of the Honor Code.

**Please feel free to consult me if you have questions whenever I am in my office or by email for help with any aspect of your laboratory experiment or report.**

### V. Experimental Accuracy

The experiments in this course generally give results that are accurate to better than  $\pm 10\%$  of the accepted values. If your experimental results differ from the expected values by significantly more, say 40%, then you likely have made an error in your calculations or a significant mistake in the lab procedure. In such a case, you should recheck your calculations or return to the laboratory and repeat the required measurements. The laboratory will be open every weekday from about 9AM until 5PM or so.

### VI. Preparing plots

All plots must be prepared using computer software such as Excel, Mathematica, or something similar. Plots must have a title and labels for the  $x$ - and  $y$ -axes, including the units of the plotted quantities. **Do not connect the data points with line segments** and do not attempt to draw a best fit line by eye. If the data set is linear, you should use a computer application (hopefully whatever you used to plot the data) to fit a straight line to your data

similar to the process explained below for how to do so in Excel.

#### **INSTRUCTIONS FOR PREPARING PLOTS USING EXCEL**

1. Type or copy-and-paste data into columns in Excel.
2. Click-and-drag to select the data, then choose **Insert**, then click the **Scatter Plot** icon on the menu bar, then select the scatter plot with only markers from the drop-down menu.
3. With the plot selected, click the **Layout** tab under **Chart Tools**. You can then click appropriate icons to add a chart title and axis labels. Click **Gridlines** and select **none** to eliminate gridlines.
4. To add a linear regression or fit line to your plot, click **Trendline**, then **More trendline options**. In the popup dialog box, choose type **Linear** and check the boxes to **Display equation on chart** and **Display R-squared value on chart**. The R-squared value gives an indication of the linearity of your data;  $R\text{-squared} = 1$  for perfectly linear data. Be sure to show sufficient digits so that the deviation of your value from 1 can be ascertained. Be sure to show a reasonable number of significant digits in the slope and  $y$ -intercept given on the plot. You can format the number of digits displayed by right-clicking on the trendline equation displayed on your graph and selecting the **Format** option.

Not all data is appropriate for applying a linear fit. Make sure you are plotting data that you *expect* a linear relationship for before going through this procedure.

## CALCULATIONS IN EXCEL

Often in this course you will want to create a new data column containing values calculated using the values contained in other columns. You can, and should, do this in an automated way. When you click on a cell in Excel in the new column a formula bar should appear somewhere near the top of the window. In that formula bar is where you will want to enter the formula for whatever calculation you would like perform. Details on creating formulas can be found in the **Help** documentation in Excel, but a couple of simple examples are given below:

= A1\*2+1                      (Doubles the value in cell A1 and adds one)  
=(A1^2+B1^2)^0.5            (Adds the squared values in cells A1 and B1 and takes the square root.)

Note that **formulas always start with the equals sign =**. After having typed a formula for one cell, you can copy-and-paste it into all similar cells (Excel automatically understands that it should use cells in the appropriate row for each calculation) by just clicking and dragging a box over all the appropriate cells.

# REPORTING MEASURED NUMBERS (SIGNIFICANT DIGITS)

Reporting a measured number with an appropriate number of digits is important since any number published in a scientific report implicitly implies a certain experimental resolution. In other words, if you report a length of 1.045 mm, you are not just asserting the length, but also that your measuring device had a resolution of thousandths of a millimeter. So, if you display too many digits, you are making a misleading claim about the precision of your measurement.

Deciding how many digits are appropriate to report is not always simple - the Physics and Astronomy departments covers the proper mathematical theory on this topic in later courses PHYS 241 and PHYS 245. However, there is a very simple *approximate* way to do it that works quite well: the method of “significant digits.” Keeping track of the number of significant digits is quite easy to do and gets the number of digits about right ( $\pm 1$  digit), which keeps the experimental uncertainty to within about an order of magnitude (i.e. a factor of ten) of the correct value. Because it is simple and approximately right, the method is very worthwhile and all serious science students should get in the habit of keeping track of the number of significant digits in every reported number. Significant digits turns out to be both a useful and easy way to approximate our uncertainty.

## DETERMINATION OF THE NUMBER OF SIGNIFICANT DIGITS IN A MEASURED QUANTITY:

The number of significant digits in a measured number is determined by the resolution of the measuring equipment and by the magnitude of the quantity measured.

### Examples:

A ruler with  $\pm 0.1$  mm precision is used to measure a one millimeter long sample.  
The result is: 1.0 mm  $\pm$  0.1 mm. (The quantity 1.0 mm has 2 significant digits).

The same ruler is used to measure a ten-centimeter long sample.  
The result is: 100.0 mm  $\pm$  0.1 mm (The quantity 100.0 mm has 4 significant digits).

Vernier calipers with  $\pm 0.05$  mm precision are used to measure the one millimeter sample.  
The result is: 1.00 mm  $\pm$  0.05 mm (The quantity 1.00 mm has 3 significant digits).

(Note that the uncertainty has only one significant digit – uncertainties are not accurately known quantities. Note also that the measured number has as many digits after the decimal point as the uncertainty so that they can be added.)

## PROPAGATION OF SIGNIFICANT DIGITS IN A CALCULATION:

### 1. Adding/Subtracting

The number of significant digits in the result is determined by the operand with the least number of significant digits after the decimal point.

**Examples:**

$$\begin{array}{r}
 2.005 \\
 0.04 \\
 + 13.2415 \\
 \hline
 15.29
 \end{array}$$

$$\begin{array}{r}
 1.954 \\
 - 0.43 \\
 \hline
 1.52
 \end{array}$$

## 2. Multiplying/Dividing or Other Operations (exponentiating, etc.)

The number of significant digits in the result is the same as the smallest number of significant digits in any of the operands.

**Examples:**

$$2.005 \times 1.04 \times (3.2 \times 10^2) = 6.7 \times 10^2$$

*(Note: Writing the above result as 670 is ok, but it is somewhat ambiguous whether or not the zero is supposed to be significant. The use of scientific notation avoids this ambiguity).*

$$\sin(1.2\pi) = -0.59$$

## 3. Using extra digits in intermediate steps of a calculation to avoid round-off error

You should generally use extra digits in intermediate steps to avoid error due to repeated round-offs. (Note that one or at most two extra digits is plenty; using all eight digits displayed by the calculator is always a waste of time).

If you use extra digits, this should be done in a part of your report designated for calculations. **In the section of your report where you provide answers to the questions, the reported numerical values must have an appropriate number of significant digits.**

# A BRIEF INTRODUCTION TO ERROR ANALYSIS

## ERRORS AND UNCERTAINTIES

Suppose the theory you are testing predicts a value of 2.0 for a particular quantity, but your experimental value is 1.5. Is your experimental value consistent with the theory or not?

This sort of situation arises all the time with experiments: the measured number is not exactly identical with the predicted theoretical value. To draw any conclusion from the experiment, it's necessary to know what the precision of the measured number is. For example, if the measured number and its uncertainty are  $1.5 \pm 0.5$ , the measurement is consistent with the theoretical prediction of 2.0; however, if the measured number were  $1.5 \pm 0.1$ , it is not. Knowing the uncertainty in your measured number is an essential part of the experiment. The uncertainty number (the  $\pm 0.1$ ) is customarily called the “experimental error” although the term is somewhat misleading - no sort of error has necessarily been made by anyone - uncertainties are inherent in the measuring process due to the limitations of the instruments used and sometimes due to the statistical uncertainty inherent in the natural phenomenon itself.

## TYPES OF ERRORS

It is important to realize that uncertainties can get into an experiment in a surprising number of different ways, and often just identifying the major source of uncertainty can be a challenge. The most obvious way uncertainties enter is through the limitations of the measuring instruments; for example, the smallest markings on the ruler are millimeters, so the uncertainty of a ruler measurement must be at least a millimeter. However, the uncertainty of a ruler measurement could easily be much more than a millimeter. Suppose you are measuring the focal length of a lens by focusing light from a distant source on a screen and measuring the lens-to-screen distance with a ruler. Different distances (maybe differing by a few mm) might look equally in focus to you, so the uncertainty in this case is a few mm. This is a *problem of definition* – the visual determination of “in focus” has uncertainty.

As another example, you might try measuring the length of a tabletop and find that you get slightly different measurements depending on what part of the table you measure – because its sides are not quite smooth or perhaps imperfectly parallel. Here again the uncertainty could be larger than the uncertainty coming from the ruler's markings. This uncertainty is due to *model error*: the model of the tabletop as rectangle is not exact.

Sometimes the way a measuring device is read contributes an error: if you are constrained to view the ruler from an angle rather than perpendicularly, the geometry of the viewing can result in *parallax error*.

Another possibility is that the ruler was manufactured poorly, with the markings 1% too close together – then all measurements made with this ruler will be low by 1%. This non-random error due to miscalibrated equipment, which is always present to some degree, is called *systematic*

**error.** It can be difficult to estimate the size of systematic errors: sometimes the equipment manufacturer specifies a probable or guaranteed maximum degree of systematic uncertainty in an equipment manual, sometimes an experimenter must undertake a separate *calibration experiment* to test the measuring instrument against a known standard (which itself has a specified maximum uncertainty, hopefully small).

Some uncertainties are actually **random**, and then the degree of uncertainty can be measured accurately by repeating the experiment many times – the degree of scatter among the measured values (i.e. standard deviation) can usually be taken as the measure of the uncertainty. In practice, however, uncertainties usually result from many sources – systematics, random uncertainties, and various model errors – and it is not always easy to figure out what source of uncertainty is dominant and which can be safely ignored.

As a last word on experimental error, it is important to understand that “human error” is **not** a legitimate type of experimental error. In other words, if you did a procedure wrong or wrote down a wrong number, **this does not count as “experimental error”** – it is simply a mistake. Note that *the lab can be made available day and night, so if you should discover a mistake, you are encouraged to return and redo a procedure or an experiment.*

## ESTIMATING UNCERTAINTIES

As the above discussion indicates, figuring out the size of an experimental uncertainty can be tricky. Fortunately, we usually only require an estimate, and this is usually not too difficult. For ruler and other scale reading measurements,  $\pm$  half the smallest scale division is a reasonable estimate for the uncertainty (but be alert for situations where the actual uncertainty is larger, as in the examples above). This rough estimate will handle ruler and balance measurements. For timing measurements (including velocity), it is often convenient to repeat the measurement a few times - the maximum deviation from average gives a rough, order-of-magnitude measure of the uncertainty.

## PROPAGATING UNCERTAINTIES

Once you know the uncertainties in the raw measured quantities in an experiment, you may still need to know the uncertainty in some other value calculated from the raw quantities. For example, after you measure the mass  $m \pm \Delta m$  and the volume  $V \pm \Delta V$  of an object, you might want to know the mass density and its uncertainty. Of course, the mass density  $\rho$  is given by  $\rho = \frac{m}{V}$  – but what is its uncertainty? This is the problem of *propagation of uncertainties* – figuring how uncertainties are affected when they propagate through a calculation or a series of calculations. There are well-established statistical rules for how to figure this out – but the rules are a little complicated and actually only rigorously valid for random uncertainties following the normal, or bell-curve, frequency distribution (although the method is *approximately* valid generally, and in practice used almost universally). We present instead a simpler approach for estimating the uncertainties in this course (which are usually dominated by systematic rather than random uncertainties): the uncertainty  $\Delta\rho$  in the density is given by  $\Delta\rho = \frac{1}{2}(\rho_{\max} - \rho_{\min})$ , where  $\rho_{\max}$  is the maximum density consistent with the data and  $\rho_{\min}$  is the minimum density. Hence we have  $\rho_{\max} = \frac{m+\Delta m}{V-\Delta V}$  and  $\rho_{\min} = \frac{m-\Delta m}{V+\Delta V}$ . Take a close look at the plus and minus signs in these relations



and note that  $\rho_{\max}$  is *not* the maximum mass over the maximum volume, but rather the maximum mass over the *minimum* volume.

The above approach to propagating uncertainties gives a *worst-case estimate*: the density reaches its limiting value  $\rho \pm \Delta\rho$  only when *both* mass and volume are at the (appropriate) ends of their respective ranges. If the uncertainties in mass and volume were random and uncorrelated, one might expect this event (both mass and volume simultaneously at the limit of their allowed ranges) to be rather unlikely, and the above procedure would then give an *overestimate* of the uncertainty. On the other hand, if the uncertainties in mass and volume are not random but due to systematic errors, we may in fact be most interested in this worst-case bound on the uncertainty. And as a practical matter, this estimate of the uncertainty will in most cases be not too much larger (say, within a factor of 2) than that calculated by a statistically rigorous approach. And in most cases, this degree of accuracy in the estimate of uncertainties is quite adequate – the calculation of uncertainties is sometimes not a very exact science! Thus, it is always important to document **how** you calculated your uncertainties.

## Uncertainty in the Slope and $y$ -intercept of a Linear Fit

(Reference: J. Higbie, Am. J. Phys., Vol. 59, No. 2, February 1991)

Though the derivation goes beyond the scope of this class, one can calculate the uncertainty in the slope and  $y$ -intercept from the correlation parameters given to you in your linear fit.

- The uncertainty in the slope ( $\delta m$ ) is given by:

$$\delta m = \frac{|m| \tan(\arccos(R))}{\sqrt{N-2}} \quad (1)$$

where  $m$  is the slope,  $R$  is the square root of the  $R^2$  value from the linear fit, and  $N$  is the number of data points in the data set. Note that there cannot be any uncertainty in the fit of your data if there are no more than 2 data points!

- The uncertainty in the  $y$ -intercept ( $\delta b$ ) is given by:

$$\delta b = \delta m \cdot x_{\text{rms}} \quad (2)$$

where  $x_{\text{rms}}$  is the root mean square value of the  $x$  values.

- The root mean square value of a set of  $x$  values can be found as

$$x_{\text{rms}} = \sqrt{\frac{1}{N} \left( \sum_{i=1}^N x_i^2 \right)} \quad (3)$$

As you can see, it is the “root” of the “mean” of the “squares”. Note that, the further the values are from the  $y$ -axis the larger the  $x_{\text{rms}}$  value and consequently the larger the uncertainty in the  $y$ -intercept for a given slope uncertainty.

### Further Reading

Students interested in further reading on the subject of error analysis are directed to John Taylor’s excellent and highly accessible text *An Introduction to Error Analysis*.



# PHYSICS 130/130A - EXPERIMENT 1

## MEASURING VOLTAGE AND CURRENT

### 1 Introduction

Two important quantities used in studying electric circuits are *voltage* and *current*. As you will learn in class, the voltage difference between two points measures how much work is needed to move a unit of charge between those points. The current in a circuit is the quantity of charge flowing through a wire each second.

To help you visualize these quantities, we can make use of an analogy to water flowing in a pipe. The current in a wire is analogous to the rate at which water is flowing through a pipe (gallons/sec), while the voltage is roughly analogous to the pressure difference forcing the water to flow in the pipe. The units of voltage are Volts (1 Volt = 1 Joule/Coulomb). The units of current are Amperes (1 Amp = 1 Coulomb/sec). The most common sources of voltage are the battery and the power supply, both of which provide a constant voltage difference between their output terminals. When a voltage is applied to some components in an electric circuit, current will flow, just as when pressure differences are applied to a network of water pipes, water will flow through the pipes.

The purpose of today's exercise is to familiarize you with devices used in the measurement of voltage and current: the voltmeter (voltage), the ammeter (current), and the oscilloscope (time-varying voltage). A digital multimeter (DMM) can be used as either a voltmeter or an ammeter.

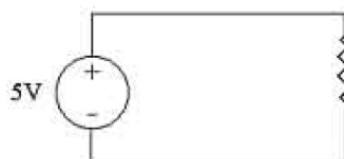


Figure 1: A very simple electric circuit.

In the simple circuit diagram shown in Figure 1, the circle corresponds to a voltage source (power supply), the straight lines correspond to wires, and the jagged line is the symbol for a resistor, which we will study at a greater length next week. You can think of a resistor as an obstacle in the current path that limits or resists the flow of charge, just as an obstacle in a water pipe limits the flow of water past it.

A voltmeter is a device with two input probes, which measures the voltage difference between those probes. It's used by simply touching or connecting the probes between the pair of points on the circuit for which you want to measure the voltage difference. An ammeter also has two measurement probes, and the meter will tell you how many amps of current are flowing in one probe, through the meter, and out the other probe. An ammeter must be **in line** with the current being measured. To insert an ammeter in a circuit, you must temporarily open or break the circuit to allow the ammeter to be inserted in line with the current path. If you attempt to use an ammeter

like a voltmeter and just touch the probes between two points having a voltage difference, you will have to incur the expense of buying a new fuse. See the Figure 2 below.

## 2 Procedure

### 1. DC Measurements

The power supply will produce a voltage that is constant over time; this is a DC voltage. Hook up your DMM in voltmeter (DC) mode as shown in Figure 2 above and adjust your power supply voltage to 5 Volts (which you need to measure using your voltmeter). Next, attach your resistor across the power supply's output as shown in Figure 2 (but don't put the ammeter in yet). Does the voltage change? If so, adjust it back to 5 Volts.

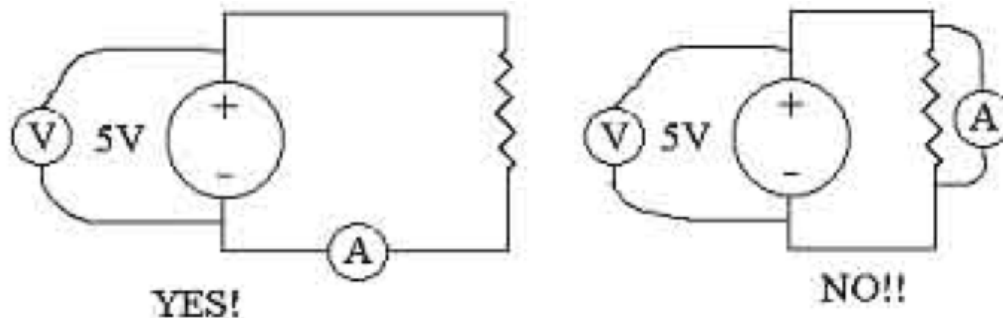


Figure 2: Diagram showing how to properly connect a voltmeter (V) and ammeter (A).

Now put your second DMM into ammeter mode, and connect it properly into the circuit and measure the current ( $I$ ). **Be careful and read over how to properly connect the ammeter to measure current before doing this, you can easily blow fuses which costs money! Please don't do this!**

- Record the value of the current. Make sure you include correct units.

$$I = \underline{\hspace{2cm}}$$

When we discuss resistors in class, we will say that the resistance is given by voltage divided by current ( $R = V/I$ ).

- Using the above formulation, what resistance do you calculate from your data?

$$R = \underline{\hspace{2cm}}$$

INSTRUCTIONS FOR USING THE DIGITAL MULTIMETER (DMM):

- To measure DC **voltage**, connect one lead wire to the input labeled V (it might also be labeled with other symbols like  $\Omega$ ); connect the other lead to the COM. Then turn the dial to one of the positions marked  $\overline{V}$  (the overbar indicates a DC voltage). The numbers in the different positions represent the maximum voltage for that measuring range; for example, the 2 position will measure voltages up to 2.00 V and the 200m

position will measure voltages up to 200 mV (millivolts). which is 0.200 V. Generally, you should use the smallest range that works, as it will display the most digits and provide the most precise reading.

- (b) To measure DC **current**, be sure the ammeter is connected properly in the circuit and the power is off. Connect one lead wire to the input labeled mA (milliamps) and the other lead to COM. Turn the dial to one of the positions marked  $\bar{A}$ . As before, the different numbers represent the maximum current for that particular range; for example,  $200\mu$  means  $200 \mu\text{A}$  (microamps) = 0.2 milliamps = 0.0002 Amps.

## 2. AC Measurements

The previous measurement used DC (constant in time) voltages that resulted in constant currents. However, many useful circuits have time-varying voltages and currents. Taking a measure of rapidly changing voltages is often done with an oscilloscope. We will be using a computer interface and digital oscilloscope. This same computer interface will be used as a waveform generator to produce a time varying voltage. One of the purposes of this part of the lab is to get introduced to the various controls and measurement techniques for the digital oscilloscope and waveform generator.

A set of INSTRUCTIONS FOR USING THE PICO SCOPE DIGITAL OSCILLOSCOPE AND WAVEFORM GENERATOR will be available as needed, but you will be shown in lab the basics of using the Picoscope, which is fairly intuitive.

- (i) Set up the PicoScope waveform generator (also called a function generator) to produce a sine-wave signal at a frequency of 2 kHz (2000 Hertz, or 2000 complete cycles/sec) at an amplitude of 2 V. You may have to try several things with the controls to figure out how to do this. Feel free to look at all the different options available in the waveform generator menu - you will see that there are many different output waveforms such as sine wave, triangle wave, or square wave as well as controls to adjust the amplitude and frequency of the wave produced. These are all controls you will want to become familiar with.
- (ii) Now we want to measure the time-varying voltage that the waveform generator is producing using the digital oscilloscope function of the PicoScope. Connect the waveform generator output (labeled AWG) to the oscilloscope input channel A (labeled A). Set your display screen to show the show the input in channel A. Press Go button and you should get a graph showing voltage ( $y$ -axis) vs. time ( $x$ -axis). There many controls that allow you to affect how the graph is displayed, doing simple operations like rescale the axes, freeze the measurement, display measurements of various useful parameters (like frequency), etc. Spend some time learning to use the program and understanding how it works. Feel free to change the waveform generator output parameters to explore its features as well.
- (iii) Once you have explored the program a bit, set the waveform back to the initially requested setting, that is a sine-wave with frequency of 2 kHz and amplitude of 2 V, and find a good display setting for this wave. Measure and record the peak to peak voltage.

- Peak to Peak Voltage: \_\_\_\_\_

(iv) Measure and record the period (repeat time) of the sine wave. Pay careful attention to units.

- Period:\_\_\_\_\_

(v) The frequency (cycles per unit time) of a wave is the reciprocal of the wave's period. Using your measured period, calculate the wave's frequency.

- Frequency:\_\_\_\_\_

- Is this frequency consistent with the frequency set by the waveform generator?:\_\_\_\_\_

(vi) If you have time, explore the other measurements you can take and try to understand them a bit. This interface will be used for many of the labs this term.

### 3 Data Analysis & Presentation:

*This portion of the lab can be done on your own.*

Graphical presentation of data is a powerful tool, aiding in conceptualization, interpretation and error analysis. In the lab component of this course, you will use a computer plotting software such as Excel, KaleidaGraph, or Mathematica (all available on KnoxAnyWare) for generating graphs. Excel, though the most limited of the programs mentioned, is most widely available and will meet the needs of this course. **I do not recommend using Google Sheets** as many students have experienced problems with it and it is generally difficult to get to produce plots in the style required. This manual (page xi) contains detailed instructions for plotting in Excel, but feel free to explore the more powerful graphing/data analysis programs available.

Imagine the data below represents measurements of the current  $I$  flowing through a circuit as the voltage  $V$  is varied at regular increments. If we want to visualize this data we need to plot it. In this case,  $I$  is the dependent variable (to be plotted on the  $y$ -axis) and  $V$  is the independent variable (to be plotted on the  $x$ -axis).

$V$ (V)	$I$ (mA)
5	7.85
6	9.62
7	10.40
8	13.31
9	13.83
10	16.39
11	17.55
12	18.56

Plot this data in the table, label the axes and give the plot a title. Adjust the range of the axes so that the data nicely fills the space. All plots you submit should have axes with labels and units and should be adjusted so there is not a large amount of blank space. Make sure your data is plotted as points (not connected dots), and remove any gridlines from your plot. These are also general style settings you should always use.

Now, perform a linear fit to your data. Click **Trendline**, then **More trendline options**, and select **Linear**, **Display Equation on Chart**, and **Display R-squared Value on Chart** in the dialog box.



## 4 Questions

1. What is the measured current ( $I$ ) and calculated resistance ( $R$ ) from procedure 1? Make sure you include units.
2. What is the measured peak-to-peak voltage and period from procedure 2? What frequency did you calculate from this period? Was this frequency consistent with the frequency set from the waveform generator? Be quantitative about how consistent they are.
3. Attach the plot produced in section 3 with the linear fit and equation of the fit and  $R^2$  displayed. What is the slope and  $y$ -intercept of your fit (make sure you give units)? What is the  $R^2$  of your fit and what does this value indicate?
4. The slope you identified in the previous question has a particular physical relevance. Given that you are plotting current ( $I$ ) versus voltage ( $V$ ), what physical quantity should the slope represent? Explain your reasoning. Using your data what is the resistance of the circuit being measured in the hypothetical experiment in section 3?

# PHYSICS 130/130A - EXPERIMENT 2

## RESISTANCE AND OHM'S LAW

### 1 Introduction

Ohm's Law expresses the proportionality between the voltage applied across a resistor and the resulting current through the resistor. The proportionality is expressed in the equation  $V = IR$  (voltage = current  $\times$  resistance), which is fundamental to any study of electric circuits or electronics. We will attempt to verify Ohm's Law experimentally, and in the process will become better acquainted with the common diagnostic tools of the electronics laboratory, the digital multimeter, the waveform generator, and the oscilloscope. *See Giancoli 25-1 to 25-4 for more information about Ohm's Law.*

From the point of view of the physicist, there are some interesting questions about electrical conduction in materials: (1) Why should the current be proportional to applied voltage, rather than depending on applied voltage in a more complicated way? (2) And what properties of a material are important in determining the value of the constant  $R$ , and how can we calculate  $R$  from knowledge of the material properties? These questions are actually rather difficult to answer, and require some understanding of the transport properties of electrons (carriers of the current) in the crystal lattice of a metal. The problem is inherently quantum mechanical and requires techniques from the field of solid state physics to address. A thorough understanding of conduction in materials is far from complete; a good example is the problem of high temperature superconductivity, still mysterious after years of intense research.

### 2 Procedure

#### I. TESTING OHM'S LAW IN A DC CIRCUIT

1. The digital multimeter, or DMM, is a versatile laboratory test instrument that can measure AC or DC voltage, current, and resistance. Use the DMM to measure the resistance of the nominally 2 k $\Omega$  resistor.
  - Record the measured resistance of the resistor.

The nominal resistance of a resistor is indicated by a three stripe color code. If the stripes denote the numbers  $n$ ,  $m$ ,  $p$ , then the resistance  $R$  in ohms is given by  $R = nm \times 10^p$ . The correspondence between colors and digits is given by:

Black	= 0
Brown	= 1
Red	= 2
Orange	= 3
Yellow	= 4
Green	= 5
Blue	= 6
Violet	= 7
Gray	= 8
White	= 9

A sort-of mnemonic for the color code is "ROY G. BIV" (except that the color indigo is not used, and it doesn't include black, brown, gray, or white). For example, if the color code of a resistor is brown-black-red, it is a nominally 1.0 k $\Omega$  resistor. Study that example carefully - the relation  $R = nm \times 10^p$  looks a bit like scientific notation, but is not exactly, and  $n$  and  $m$  are not multiplied. A fourth stripe is sometimes used to indicate the tolerance, or "allowable" deviation of the resistance from its nominal value. Gold indicates 5% tolerance and silver indicates 10% tolerance. If there is no fourth stripe, the resistor has a 20% tolerance.

2. A DC, or direct current, circuit is one for which all voltage generators are constant in time. Laboratory voltage generators are called power supplies, or simply supplies. The voltage output of the LabVolt power supply can be DC or AC, with corresponding constant or sinusoidal voltage out.

Set up the circuit shown below in Fig. 1. Be sure the supply is off when making any connections. Be careful to connect the ammeter leads to the DMM properly. Set the supply on range B (if your supply has this option), turn the amplitude control dial to zero, and switch on the supply.

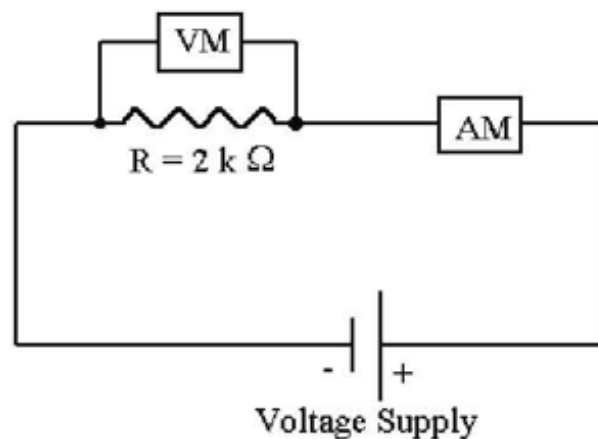


Figure 1.

3. Adjust the LabVolt amplitude dial until the current reads 1 mA.
  - Record the current and voltage (make sure you include units).

- Repeat the measurement at 1 mA increments up to a maximum current of 8 mA.

Current									
Voltage									

## II. TESTING OHM'S LAW IN AN AC CIRCUIT

An AC, or alternating current, circuit is one containing time-varying voltage sources. Time-varying voltages can be displayed on an oscilloscope as we explored last week where we get a graph of the voltage ( $V$ ) on the  $y$ -axis (vertical) and time ( $t$ ) on  $x$ -axis (horizontal).

1. First connect the wave generator output of your PicoScope to channel A input of the PicoScope digital oscilloscope. Turn on the signal generator and set to generate a sine-wave with amplitude of 2 V and frequency of 400 Hz. Confirm that the wave displayed is the wave you expect to see just to make sure that your function generator is working properly. Record the peak-to-peak voltage and period of your sine-wave.
2. A potentiometer, or pot, is a variable resistor. By rotating the knob, a small wire (called the wiper) is dragged across a resistive film. The length of the resistive medium between the wiper and a contact at one end of the film can be varied by moving the wiper. The resistance varies with the length so that the device acts as an adjustable resistor.

Connect the DMM, set to measure resistance in Ohms ( $\Omega$ ), across the wiper and one fixed terminal of the pot.

- Measure and record the value of  $R$  when the pot's dial indicator reads 0.00, 1.00, ..., 10.00. This procedure is called "calibrating the pot."

Pot Setting										
Resistance										

3. Now set up the circuit shown below in Fig. 2. Use the DMM, set on AC 1 mA scale, as the AC ammeter. The PicoScope is functioning as an AC voltmeter. Be sure that the "Ground" (black) terminal connections to the PicoScope are attached to the same point in the circuit - it is vital that all parts of the circuit share a common ground (otherwise you will likely get a lot of unwanted noise in your signal).

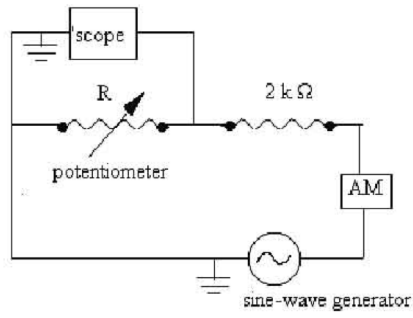


Figure 2.

- Measure peak-to-peak voltage ( $V_{p-p}$ ) and RMS current ( $I_{RMS}$ ) for pot indicator dial settings from 1.00 to 10.00. Convert the current readings  $I_{RMS}$  to “peak-to-peak”  $I_{p-p}$  readings by multiplying  $I_{RMS}$  by  $2\sqrt{2}$  and record the  $I_{p-p}$  readings in the table below.

Pot Setting											
$V_{p-p}$											
$I_{RMS}$											
$I_{p-p}$											

### 3 Questions

1. What are the measured period and frequency of the sine-wave? Your measurement should involve the uncertainty in the period and frequency. Take care with significant digits and units. Calculate the percent difference between the measured and expected frequencies. Are your measurements consistent with the expected values?
2. Plot  $V$  vs.  $I$  from Procedure I. (Note on usage: "V vs. I" means  $V$  is on the  $y$ -axis,  $I$  on the  $x$ -axis.)
  - (a) What should the plot look like if Ohm's Law accurately describes the behavior of the resistor? (Be as precise as possible).
  - (b) Do your data support Ohm's Law? Explain.
  - (c) Determine  $R$  from the plot. Compare the value of resistance determined from the plot to that measured by the DMM and find the percent difference in the two values. (If the values disagree substantially, you should track down your mistake.)
  - (d) What is the tolerance of your resistor? Do your two measured values of the resistance (using the DMM and using your plot) fall within the tolerance of the stated resistance of your resistor? Explain.
3. Plot  $V/I$  vs.  $R$  in Procedure II. Use the values of  $R$  measured with the DMM during your calibration.
  - (a) What should the plot look like if Ohm's law accurately describes the behavior of the resistor? (Be as precise as possible.)
  - (b) Do your data support Ohm's Law? Explain. (*Hint: Ohm's Law predicts a straight line plot with a certain slope and intercept.*) If your deviations from Ohm's Law are large, again you'll want to track down any possible mistake.
4. If you were to find a resistor with stripes blue-gray-green-silver, what would be the maximum and minimum values of its possible resistance within the acceptable tolerance?
5. In the AC circuit, the ammeter measured the current  $I_{total}$  through both the  $2\text{k}\Omega$  fixed resistor and the pot. How is  $I_{total}$  related to  $I_{pot}$ , the current through the pot? Justify your answer. (Assume the 'scope has infinite resistance.)



# PHYSICS 130/130A - EXPERIMENT 3

## SERIES AND PARALLEL RESISTANCE

### 1 Introduction

In our last two labs, we were introduced to ammeters, voltmeters, and resistance. We found that resistors obey Ohm's Law,  $V = IR$  (voltage = current  $\times$  resistance).

In this lab we will gain more experience with circuits and circuit measurements. In particular, we will explore how multi-resistor circuits can be understood and how we can predict what the effective resistance of a resistor network will be.

We will also learn how to use a soldering iron and solder. A soldering iron is basically a heater. The tip of the iron gets hot enough to melt an alloy of lead and tin, called solder. To connect two resistors, heat up the soldering iron by plugging it in, then place the resistors where you want them and melt a little bit of solder onto the wires where they cross. Be sure to heat up the wires a little bit too, hot enough so that the solder forms a good bond.

**BEWARE: The iron stays hot, as does the solder connection. The lead-based solder is not dangerous to handle. However, you should wash your hand at the end of the lab especially before eating anything.**

### 2 Procedure

#### A. RESISTORS IN SERIES

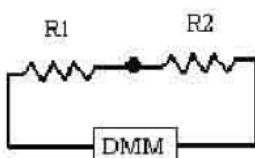
1. Record the resistance of the two resistors and their tolerances based on their color code.

$$R_1 = \text{_____} \pm \text{_____} \qquad R_2 = \text{_____} \pm \text{_____}$$

2. Measure the resistances of two resistors using the DMM.

$$R_1 = \text{_____} \pm \text{_____} \qquad R_2 = \text{_____} \pm \text{_____}$$

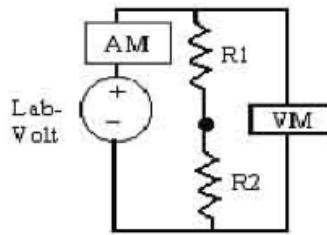
3. Solder one end of one resistor to one end of the other resistor. Resistors connected this way are said to be connected in series. Using the DMM as an ohmmeter, measure the total resistance of the resistors, as shown below





$$R_{tot} = \text{_____} \pm \text{_____}$$

4. Connect the resistors to the LabVolt power supply as shown below. Connect a voltmeter (VM) and an ammeter (AM) as shown. With the dial set to 0, turn on the power supply and then set the dial of the power supply up to 6. Record the voltage  $V_{tot}$  (across both resistors) and the current  $I$ . Without changing the LabVolt dial setting, rearrange the voltmeter connections to measure the voltage  $V_1$  across  $R_1$  only, and then the voltage  $V_2$  across  $R_2$  only.



$$V_{tot} = \text{_____} \pm \text{_____}$$

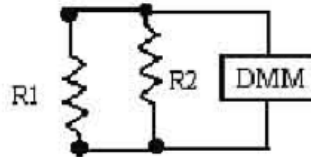
$$I = \text{_____} \pm \text{_____}$$

$$V_1 = \text{_____} \pm \text{_____}$$

$$V_2 = \text{_____} \pm \text{_____}$$

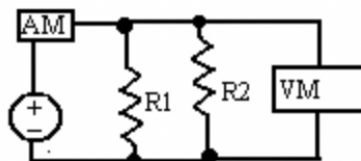
## B. RESISTORS IN PARALLEL

1. Solder the free ends of the resistors together. Resistors connected this way are said to be connected in parallel. Using the DMM as an ohmmeter, measure the total resistance  $R_{tot}$  of the parallel resistors, as shown below:



$$R_{tot} = \text{_____} \pm \text{_____}$$

2. Connect the resistors to the Lab Volt power supply and connect a voltmeter (VM) and ammeter (AM) as shown below.

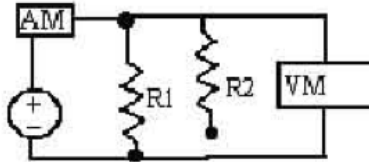


3. With the dial set to 0, turn on the power supply and then set the dial of the power supply to 6. Record the voltage  $V_{tot}$  the current  $I_{tot}$ . Then move the voltmeter connections to measure the voltage across  $R_1$  (position the clips on either side of  $R_1$  as close to the resistor as possible) and the voltage across  $R_2$ .

$$V_{tot} = \text{_____} \pm \text{_____} \qquad I_{tot} = \text{_____} \pm \text{_____}$$

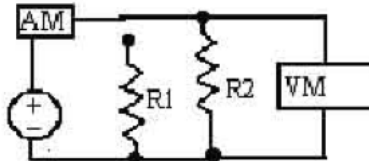
$$V_1 = \text{_____} \pm \text{_____} \qquad V_2 = \text{_____} \pm \text{_____}$$

4. Cut one connection between the two resistors and set up the circuit as shown below. With the same LabVolt dial setting as in Procedure 3, measure the current passing through  $R_1$ .



$$I_1 = \text{_____} \pm \text{_____}$$

5. Modify the previous circuit to one which measures the current of  $R_2$  as shown.



$$I_2 = \text{_____} \pm \text{_____}$$

### 3 Theory: Circuit Basics (Survival Guide)

Current is the rate of flow of charge through a circuit element. It is measured in Amps (amperes, abbreviated A).  $1 \text{ A} = 1 \text{ Coulomb of charge per second}$ . For the DMM (digital multi-meter) to measure current, it must be placed into the current path, since the current must flow through the meter.

Voltage is related to potential energy, and is measured in volts (V). Only voltage *differences* are relevant. The voltage difference between two places is the potential energy difference for a test charge  $q$  placed at those locations, divided by the charge  $q$ . Positive currents flow from higher voltage to lower voltage. (The negatively charged electrons actually flow from low to high voltage.) For the DMM (or oscilloscope) to measure voltage, it must be attached to the two places between which you are measuring. The voltmeter does not conduct current (in the ideal case), so it is not part of the circuit. **It is usually easiest to hook up the voltmeter last when you construct a circuit.**

Resistance of a device (resistor, wire, your body, etc.) is a measure of how difficult it is for a charge to pass through it. The units of resistance are ohms ( $\Omega$ ). Resistance controls the current that flows when a voltage is placed across the device. To measure the resistance between two points, connect the DMM between those points. It is generally a bad idea to measure the resistance of objects when they are hooked up in a circuit - disconnect the object from the circuit first.

Ohm's Law,  $V = IR$ , relates the voltage  $V$  across a resistive device to the current  $I$  that flows through the device. Depending on the problem at hand, it may be useful to think of the current as being caused by the voltage you apply, or the voltage as being a result of the fact that current is flowing. Keep in mind that **not all materials obey Ohm's Law** but many of the ones we will be working with do.

#### • Resistors in Series

When resistors are hooked together one after the other, they are said to be in series.

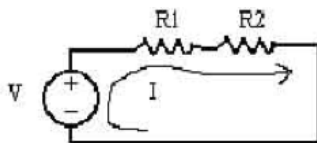


Figure 1: Resistors in series attached to a power supply.

In this configuration, the resistors are guaranteed to have the same current flowing through each of them. Since charge is conserved (neither created nor destroyed), all the charge that flows through one resistor must also pass through the other resistor. The circuit above has a certain current  $I$  that flows when the DC voltage supply is set to  $V$ . As far as the voltage supply is concerned, this is just like having ONE resistor ( $R_{eq}$ ) hooked up where  $R_{eq} = V/I$ :

We can calculate the value of the equivalent resistance  $R_{eq}$  from the values  $R_1$  and  $R_2$ :

The voltage drops across  $R_1$  and  $R_2$  are:  $V_1 = IR_1$  and  $V_2 = IR_2$ . The total voltage drop  $V$

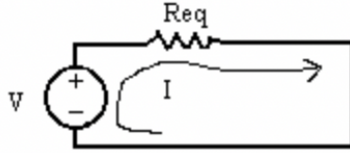


Figure 2: An equivalent circuit to that in Fig. 1 with one resistor with “equivalent resistance”.

must be  $V_1 + V_2$  (since the potential energy differences add) and this must be the same as the DC supply voltage  $V$ . Thus:

$$V = V_1 + V_2$$

$$\text{or, } IR_{eq} = IR_1 + IR_2$$

Hence,  $R_{eq} = R_1 + R_2$  (for resistors in series).

### • Resistors in Parallel

The other way to combine two resistors is to connect them side by side, or in parallel.



Figure 3: Resistors in parallel attached to a power supply.

In this configuration, the resistors will share the same voltage drop, but the currents through them are not necessarily the same. However, since charge is conserved, the amount of current leaving the DC supply must equal the sum of the two currents flowing through the resistors. If this were not true, then charge would pile up at a junction.

Say the current flowing from the DC supply is  $I$ , and the current through resistor  $R_1$  is  $I_1$  and through  $R_2$  is  $I_2$ . The voltage of the DC supply is  $V$  and the voltages across the resistors are  $V_1$  and  $V_2$ . We have:

$$V_1 = V_2 = V \quad \text{and} \quad I = I_1 + I_2.$$

Let’s look for the equivalent circuit:

This circuit is equivalent in the sense that with the right choice of  $R_{eq}$ , the same voltage  $V$  as in Fig. 3 will produce the same current  $I$  as in Fig. 3:  $V = IR_{eq}$ .

Combining these equations, we arrive at:

$$\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2}$$

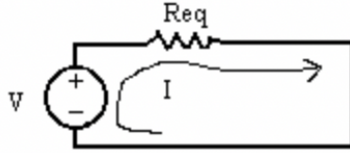


Figure 4: Equivalent circuit to Figure 3.

or, dividing by  $V$  gives us

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} \text{ (for resistors in parallel)}$$

## 4 Analysis and Questions

1. Discuss *briefly but clearly* how your measurements in Procedure A support the equation derived for the equivalent resistance of two resistors in series. Be sure to discuss your measurements of resistance and also your measurements of voltage and current.
2. Discuss how your measurements in Procedure B support the derivation of the equation for the equivalent resistance for two resistors in parallel. Be sure to discuss your measurements of resistance and also your measurements of voltage and current.
3. (a) If you hooked three resistors, 100, 200, and 300  $\Omega$ , in series, what would be the resistance across the whole group of resistors? Show your work.  
 (b) If you hooked up these same three resistors in parallel, what would be their equivalent resistance? Show your work.  
 (c) BONUS (optional): Suppose a mad scientist hooked up a parallel circuit with a large number of resistors (say, more than a hundred), with resistances 100, 200, 400, 800, 1600  $\Omega$ ... and so on. Give a numerical estimate of the net resistance to 2% accuracy. Show your calculation.
4. When you hook up a voltmeter to a circuit, you are providing another possible pathway for current - that is, *through the voltmeter*. Usually this is not a problem, provided that the resistance of the voltmeter is much larger than the resistance of elements of the circuit. Suppose you have a circuit containing a DC supply (voltage  $V$ ) and a resistor  $R$ , and you want to use a voltmeter (with resistance 10 M $\Omega$  or  $10^7\Omega$ ) to measure the voltage drop across a resistance  $R$ . What is the largest value of  $R$  for which the current drawn from the DC supply will change by no more than 1% when the voltmeter is attached?  
 (*Hint:* The current through  $R$  alone is  $I = \frac{V}{R}$ , where  $V$  is the DC supply voltage. What is the current through the parallel combination of  $R$  and the voltmeter?)

# PHYSICS 130/130A - EXPERIMENT 4

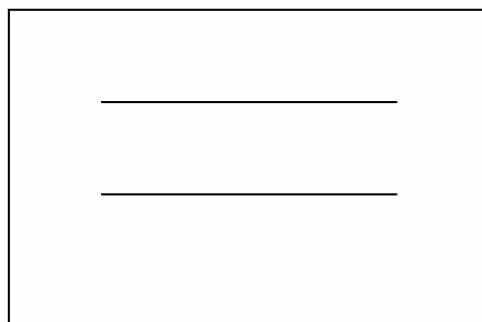
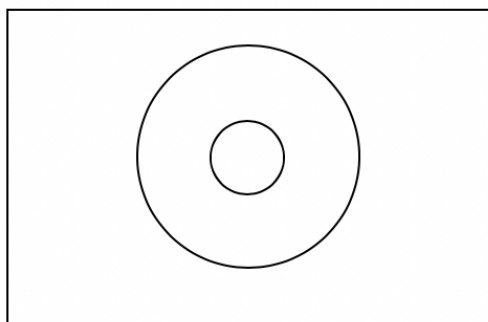
## POTENTIAL MAPPING

### 1 Introduction

The voltage that we have been measuring in the last few weeks of lab is exactly the same thing as the electrostatic potential: the potential at a point measures how much work per Coulomb of charge is necessary to move charge to that point from a place at which the potential is zero. In this week's lab you will be measuring and mapping the potential as a function of position in a thin layer of water.

### 2 Procedure

You will be applying a known voltage to a pair of aluminum electrodes. You will study electrodes having circular symmetry (concentric circles) and straight-line electrodes like those shown below:



First, apply a voltage of 6 V between the circular electrodes by attaching them to the outputs of your LabVolt (Ground to the outer circle, (+) voltage at the inner electrode) and adjust the voltage to 6 V.

Measure and record the current flowing out of the LabVolt with the +6 V applied between the circular electrodes.

$$I_{circle} = \text{_____} \pm \text{_____}$$

Then attach the common lead of your voltmeter to ground. You will use the other lead of your voltmeter to probe the potential (i.e. voltage) as a function of position.

Check that the inner electrode is at 6 V. Now measure the voltage at four angles for a diameter of 1.5". That is, take measurements of potential at angles of  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ . Record those voltages in the data table in Question 2. Repeat for diameters of 2", 2.5", ... 5.5".

For the linear electrodes, adjust the potential difference to 6.0 volts, and along a central line from the grounded plate to the 6V plate, measure the potential at distances of (0.25", 0.5", 0.75", 1.0", 1.25", 1.5", and 1.75") from the grounded plate.

Then, find the positions of a series of points with a potential of 1.5V. Record the location of each of those positions on your handout sheet with a dot, and connect those dots with a smooth curve. Plot all points along the equipotential curve, both in the region between the plates and outside the plates, until the equipotential curve closes or leaves the paper.

**Each lab partner should do this on their own sheet while in lab!**

Repeat this process for equipotentials at 2.5V, 3.5V, and 4.5V.

Measure and record the current flowing out of the LabVolt with the +6 V applied between the circular electrodes.

$$I_{line} = \text{_____} \pm \text{_____}$$

### 3 Lab Questions

1. Calculate the resistance  $R$  (in Ohms) of each of the electrode pairs. Be sure to include uncertainty.
2. For the circular electrode map, you are measuring the potential at diameters between 1.5" and 5.5". Write the voltages in the following data table.

Voltage	0°	90°	180°	270°	Average
1.5"					
2"					
2.5"					
3"					
3.5"					
4"					
4.5"					
5"					
5.5"					

We are interested in a formula that describes how this potential varies with radius. Two possible formulae are:

$$V = A \ln(r) + B$$

$$V = \frac{A}{r} + B$$

in which  $A$  and  $B$  are constants to be determined from your linear fits. Note that the first possible formula matches the potential of an infinite line charge in 3 dimensions, while the second matches that of a point charge.

- (a) Make two graphs, one of  $V$  ( $y$ -axis) vs.  $\ln(r)$  ( $x$ -axis) and the other of  $V$  vs.  $1/r$ . For each plot, perform a linear fit of the data.



- (b) Explain why a straight-line behavior on one of these graphs and not the other will allow us to distinguish the correctness of one of these formulae (and the incorrectness of the other).
  - (c) From the results of your graphs and fits, which of these formulae seems to be a better representation of the potential in the circular electrodes? You may wish to consider the respective  $R^2$  values as well as your eye.
  - (d) From your best fit, what values of  $A$  and  $B$  do you determine? Be sure to include uncertainty in these two values.
  - (e) *Challenge to think about:* Note that the first possible formula matches the potential between two concentric cylindrical electrodes in 3 dimensions, while the second matches the potential between two concentric spherical electrodes. Try to rationalize why the formula you got should be the correct one.
3. For the linear electrodes:
- (a) Make a graph of the potential as a function of distance  $y$  up from the  $V = 0$  electrode, as measured along the center between the two electrodes.
  - (b) What dependence on  $y$  should one expect? Explain why. Do you observe that dependence?
4. (a) On your potential map for the linear electrodes, sketch (using a different color from your equipotential lines) plausible electric field lines. Be sure the electric field lines extend to the edge of the chart, if appropriate.
- (b) Explain the rationale for the way you drew the electric field lines.
5. (a) Under what circumstances should equipotential lines be equally-spaced?
- (b) How well is your answer to (a) consistent with your observations on each of the electrode pairs?

**6. Extra Credit: Optional**

The resistivity of a 2-dimensional medium is measured in Ohms, and the total resistance of a rectangular 2-D resistor (with length  $L$  in the direction of current flow and width  $W$  transverse to the current direction) will be given by  $R = \frac{\rho L}{W}$ , where  $\rho$  is the resistivity of the medium. From your data in this experiment, find two estimates for the resistivity of the thin layer of water. Note that the 2-dimensional resistivity has the same units as resistance (Ohms).

# PHYSICS 130/130A - EXPERIMENT 5

## CAPACITANCE

### 1 Introduction

When charge is placed on a conductor, charges redistribute on other nearby conductors, since opposite charges attract. Let us consider two separate conductors, one having charge  $+Q$  and the other having charge  $-Q$ , with potential difference  $V$  between the conductors. The ratio  $Q/V$  turns out to be constant. That is, if  $Q$  is doubled,  $V$  will be found to double also. The constant ratio is denoted  $C$  and called capacitance:  $C = Q/V$ . The value of the capacitance depends on the geometry of the charge distribution, or in other words, on the shapes of the conductor's surfaces and their relative separation and orientation in space. For only a few configurations is it easy to calculate the capacitance explicitly; the parallel plate capacitor, made of two parallel conducting planes, is an important solvable configuration. Besides their theoretical significance in our study of electromagnetism, capacitors have a practical utility due to their ability to store electric energy - along with resistors and transistors, capacitors are found in nearly every electronic device.

We will investigate the effect of a capacitor in a simple AC circuit, the resistor-capacitor, or RC, circuit (see Fig. 1). Suppose the capacitor plates initially differ by electric potential  $V_o$ , and the switch is closed at time  $t = 0$ . From the definitions of capacitance and current plus some calculus, it is straightforward to derive an expression predicting that the current  $I(t)$  in the circuit decreases exponentially according to

$$I(t) = \frac{V_o}{R} e^{-t/RC} = \frac{Q_o}{RC} e^{-t/RC},$$

where  $Q_o$  is the charge on the capacitor at time  $t = 0$  (so the second equality follows directly from the first using the definition  $C = Q/V$ ). The quantity  $RC$ , with dimensions of time, is important since it determines the decay rate of the exponential function. The quantity  $RC$  is called the characteristic time constant of the circuit. You will construct an RC circuit and measure its time constant in order to determine the capacitance  $C$  of an unknown capacitor. The notion of identifying combinations of parameters in a problem with appropriate dimensions (length, time, mass) in order to estimate the characteristic scales of length, time, or mass is a useful idea in many areas of physics.

In a second part of the experiment, you will replace the capacitor by a series or parallel combination of capacitors. By measuring the capacitances separately and in combination (by measuring the time constant  $\tau = RC$ ), you will check the rules derived in class for adding capacitances in series and in parallel.

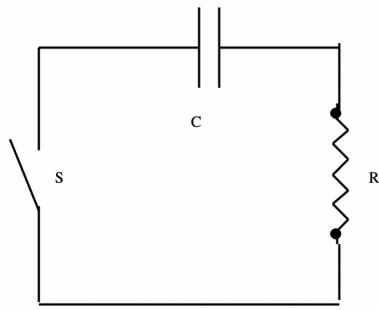


Figure 1: An RC circuit. The switch  $S$  is closed at time  $t = 0$

## 2 Procedure

### I. Determination of Unknown Capacitance:

1. Record the identification number of your unknown capacitor: \_\_\_\_\_
2. Using your multimeter as an ohmmeter, measure and record the resistance of the potentiometer at dial settings 0.00, 1.00, 2.00, ... 10.00.

Pot Setting											
Resistance											

3. Set up the circuit shown below in Fig. 2. Be sure that the (black) ground lead from the oscilloscope is connected to the same side of the potentiometer as the (black) ground lead from the signal generator.

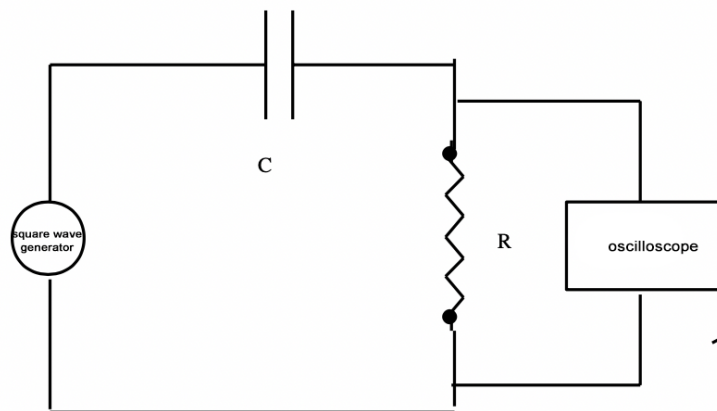


Figure 2: An RC circuit driven by a square-wave generator.  $R$  = potentiometer,  $C$  = capacitor.

- Set the potentiometer dial to 1.00. Set the function generator to produce a square-wave with a period several times longer than the characteristic RC decay time of your circuit. This may take some trial-and-error, as you adjust the frequency of the signal generator. When you have selected a good frequency for the square-wave, you will be able to see a reasonable portion of the exponential decay curve.
- Using the oscilloscope to make the measurement, find the time  $\tau$  required for the voltage to decay to  $1/e = 37\%$  of its maximum value. This time  $\tau$  is  $RC$ , the characteristic decay time of the RC circuit. Then repeat the measurement for potentiometer dial settings of 1.00, 2.00, ..., 10.00 and record your results in a table. Be sure to note uncertainty.

Pot Setting											
Time (w/unc.)											

## II. Series and Parallel Combination of Capacitances:

- Put the blue and green capacitors, one at a time, in the circuit shown in Fig. 2, measure and record their capacitance by the time-constant method described above. You need only make one measurement of the time constant for each capacitor (set the potentiometer for 10 k $\Omega$ ). (Both capacitors are in  $\mu\text{F}$  range, so if your measurements differ wildly from this you will want to re-check them.)
- Connect the capacitors in series, and measure and record the time constant of the series combination. Then connect the capacitors in parallel and repeat the measurement.

### 3 Lab Questions

1. Consider an RC circuit, as shown in Fig. 1. If the switch is closed at  $t = 0$ , the current in the circuit is given by

$$I(t) = \frac{V_o}{R} e^{-t/RC},$$

where  $V_o$  is the initial voltage on the capacitor.

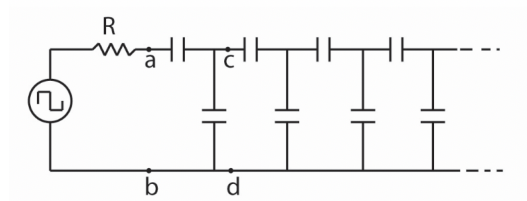
- (a) Find an expression for the voltage  $V(t)$  across the resistor, in terms  $R$ ,  $C$ ,  $V_o$ , and  $t$ .  
*Hint:* How is the voltage across a resistor related to the current through it?
  - (b) How long must one wait until  $V(t)$  has decreased by a factor of  $e$ ? (that is, for what  $t$  will  $V(t) = V_o/e$ ?)
  - (c) How long must one wait until  $V(t)$  has decreased to 10% of its original value?
2. Plot your results from Procedure I with the time constant  $\tau$  on the  $y$ -axis and potentiometer resistance  $R$  on the  $x$ -axis.
    - (a) What is the identification number of your unknown capacitor?
    - (b) Use your plot to determine the value of the unknown capacitance  $C$ . Determine the uncertainty in your result.
    - (c) While the equation relating the time constant to resistance would lead you to expect a  $y$ -intercept of zero, you will note that is not the case for your data. The explanation is that the Arbitrary Waveform Generator (AWG) of the PicoScope has added its own internal resistance to that of the pot in the circuit. Use the information from your graph to determine the output resistance of the AWG.
  3.
    - (a) For your investigation of the parallel combination of capacitors, what value of effective capacitance did you measure? Be sure to include the AWG's resistance in this calculation and all of the following ones! Also calculate the uncertainty of the capacitance in this question and those that follow.
    - (b) What are the individual values of capacitance of the  $C_{green}$  and  $C_{blue}$  capacitors you measured?
    - (c) Find the sum  $C_{green} + C_{blue}$  of the capacitance values you used.
    - (d) Are your results consistent with theory when uncertainty is considered? Explain.
  4.
    - (a) For your investigation of the series combination of capacitors, what value of effective capacitance did you measure?
    - (b) What is the inverse of the sum of the inverse capacitance values you used?  
(*i.e.* evaluate  $(\frac{1}{C_1} + \frac{1}{C_2})^{-1}$ , where  $C_1$  and  $C_2$  are the individual values of the capacitors

you used.) Determine the uncertainty here as well.

- (c) Are your results consistent with theory for series capacitors when uncertainty is considered? Explain.

5. The circuit shown below continues to the right indefinitely. The resistor has resistance  $R$  and each capacitor has capacitance  $C$ . Find the effective capacitance between points **a** and **b**, and the time constant of the circuit.

(*Hint:* The capacitance seen looking in between terminals **a** and **b** is identical to the capacitance seen looking in between terminals **c** and **d**. Denote it by  $C_{eq}$  and redraw the capacitance network with the part between terminals **c** and **d** replaced by  $C_{eq}$ .)





# PHYSICS 130/130A - EXPERIMENT 6

## DIGITAL ELECTRONICS

**NOTE: This week, no lab report is required – this lab grade is based solely on the success or failure of your circuit.**

### 1 Introduction

Experimental physicists (and other scientists) often build their own apparatus, sometimes because it is cheaper or faster than buying premade equipment, sometimes because equipment with the required characteristics just does not exist or is not easily found. Familiarity with electronics is thus a highly desirable skill for the working scientist.

In previous labs, we built and investigated circuits for measuring an unknown resistance and capacitance. Those circuits were examples of *analog* circuits. Analog circuits are circuits in which the voltage and current vary *continuously* over a range of values. This week, we will investigate *digital* circuits, in which only two *discrete* values of voltage occur. As we will see, two different voltages are sufficient to perform any kind of logical operations, and accordingly, digital circuits are the basis of computers. The two voltages used in a common class of digital electronic circuits are  $\approx 5\text{ V}$  and  $\approx 0\text{ V}$ , and go by the names HIGH and LOW respectively, or TRUE and FALSE (logic), or 1 and 0 (binary).

Electronic devices called *logic gates* are used to perform basic logical operations on HIGH and LOW voltages. The logic gates are composed of many transistors and the resulting package, called an *integrated circuit*, IC, or chip, is about 1 cm long and available from electronics retailers for about 50 cents. Input voltages are applied to metal leads, called pins, connected to the IC. The output voltage appears on another pin, a few nanoseconds later.

Logic gates are available which perform all the basic logical operations familiar from elementary math, such as AND, OR, NOT, etc. These logical functions can be described completely by their truth table, which gives the value of the function for each possible set of values of its arguments. For example, let us suppose we have two digital voltages A and B, so A and B must be either 0 (FALSE) or 1 (TRUE). Then we define AND(A,B) by  $\text{AND}(A,B) = 1$  if  $A=1$  and  $B=1$  and  $\text{AND}(A,B)=0$  otherwise. More intuitively, AND(A,B) is true if both A and B are true, but AND(A,B) is false if either A or B are false. This corresponds to the usual meaning of *and*; for instance, the statement *I am solving a differential equation and I am very happy* is true only if both clauses are true, but false if either clause is false.

This information can be summarized in a truth table for the AND function, shown below:



A	B	AND(A,B)
FALSE	FALSE	FALSE
FALSE	TRUE	FALSE
TRUE	FALSE	FALSE
TRUE	TRUE	TRUE

Table 1: **Truth Table** for the AND function

A	B	AND(A,B)
0	0	0
0	1	0
1	0	0
1	1	1

Table 2: The same as Table 1, in a simpler format

In the tables, the values of the arguments A and B are shown in the left columns, and the resulting values of AND(A,B) is shown in the right column. **The symbols HIGH, TRUE, and 1 are synonymous in digital electronics, as are the symbols LOW, FALSE, and 0.**

Truth tables for some other logical functions are shown below. OR(A,B) is true if either or both arguments are true. The NOT(A) function just changes TRUE to FALSE and vice versa. The exclusive OR function XOR(A,B) function is true if one and only one of the arguments (A,B) is true. XOR corresponds to our usual usage of the word *or*; for instance, in the statement *I will marry Bill or I will marry Eric* we are usually interpreted to intend to marry Bill and not Eric, or Eric and not Bill. A mathematician or electrical engineer would perhaps say *I will marry Bill xor I will marry Eric*.

A	B	OR(A,B)
0	0	0
0	1	1
1	0	1
1	1	1

Table 3: Truth Table for the OR function

A	NOT(A)
0	1
1	0

Table 4: Truth Table for the NOT function

Longer logical expressions can be made by combining the simple logical functions AND, OR, and NOT. For example, the function NOT(AND(A,B)) is a combination of NOT and AND. The combination of NOT and AND functions is so useful that a special IC logic gate for NAND (a contraction of NOT-AND) is available. Likewise, one can get an IC that performs a NOR (NOT OR) operation. The XOR function can be built up using AND, OR, and NOT functions. The truth table for the NAND function is shown below.

A	B	AND(A,B)	NAND(A,B) = NOT(AND(A,B))
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

Table 5: Truth Table for the NAND function

Digital logic gates are represented in circuit diagrams by special symbols shown below. All the input permutations to the gate for inputs A and B are shown on the left, and the respective outputs, AND(A,B) (for example), is shown on the right.

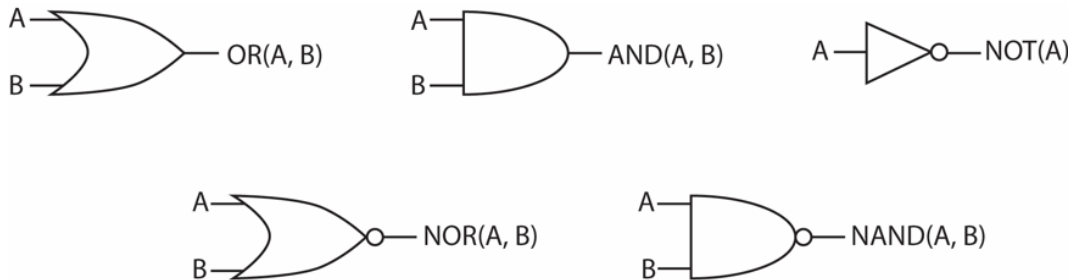


Figure 1. Symbols representing logic gates.

Sometimes the outputs of one gate are used as the inputs of another gate, as in the NAND gate made from an AND gate and a NOT gate shown below.

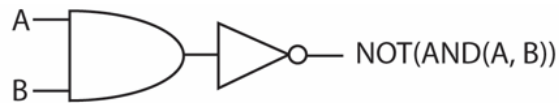


Figure 2. A NAND gate built using an AND gate followed by a NOT gate.

## 2 Procedure

1. Build 3 copies of the LED (light-emitting diode) indicator circuit shown in Figure 3. Put two (using red LEDs) on the left side of the breadboard, and put one (using a green LED) on the

lower right. Be sure that the diode lead marked + (or the longer of the two diode leads) is toward the positive voltage as shown. Use a wire connection that can be made (connected to +5 V) or broken (connected to the ground) as the switch shown in the diagram. Verify the operation of all LED circuits - the LED should light up when the positive side is connected to 5 V and the lower side of the 2 k $\Omega$  resistor is connected to ground.

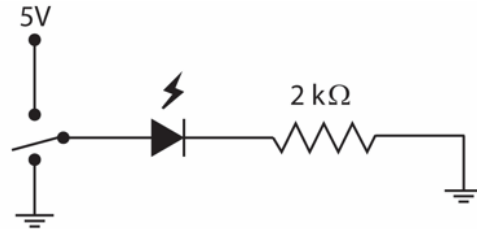


Figure 3. Light emitting diode (LED) circuit.

- The ICs use the 5 V as their power source. **Be careful *never* to exceed this voltage** - 6 V or more will destroy the IC. Connect +5 V to one top rail of the breadboard, and ground (black terminal) to a bottom rail.
- Turn the power off.** Always be sure power is off when plugging in ICs or making power and ground connections to them. Input and output connections can be made with the power on. Connect power (+5 V rail) to pin 14 of the NAND IC (this chip is marked 7400) as shown in the circuit diagram in Figure 4. Connect ground to pin 7. (See the pinout diagrams on the following pages. These diagrams indicate what gets connected to which pins of the IC). Turn the power on. Now, using the red LED indicator circuits as inputs A and B (connected to pins 1 and 2), and using the green indicator circuits as the output NAND(A,B) (pin 3), verify circuit you have wired does, in fact, reproduce the truth table of the NAND gate.

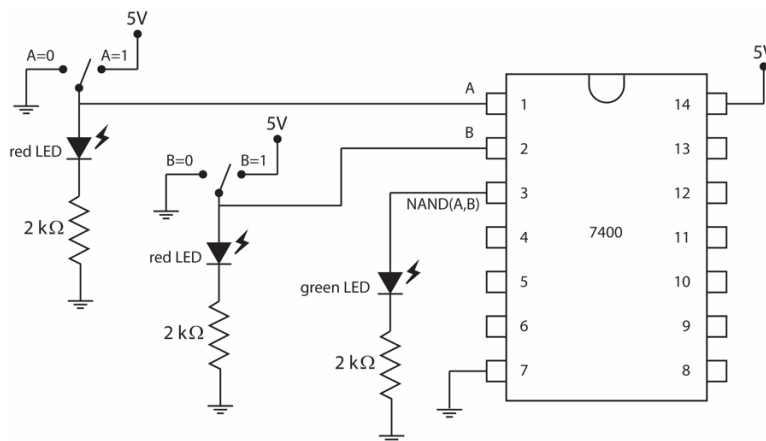


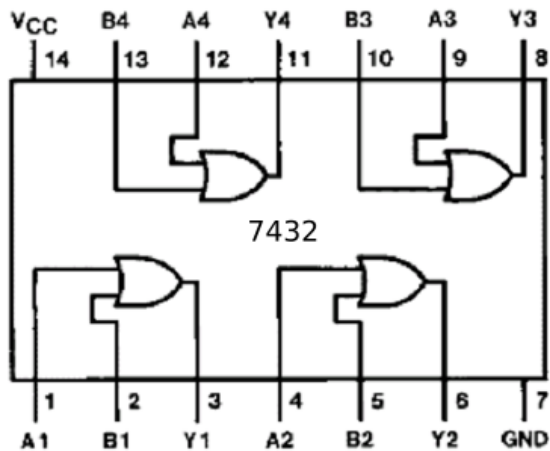
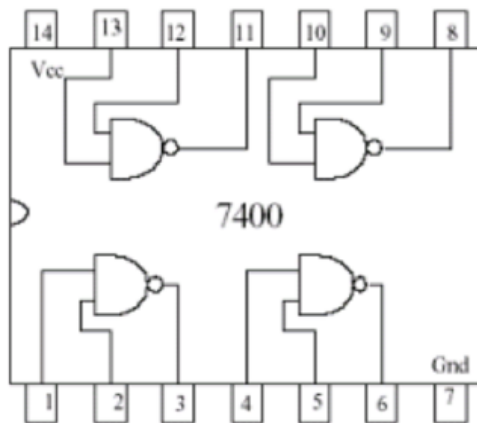
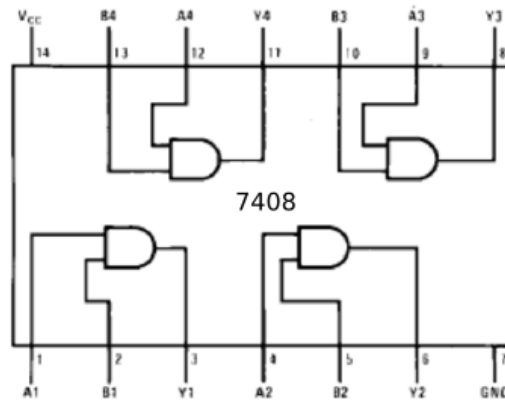
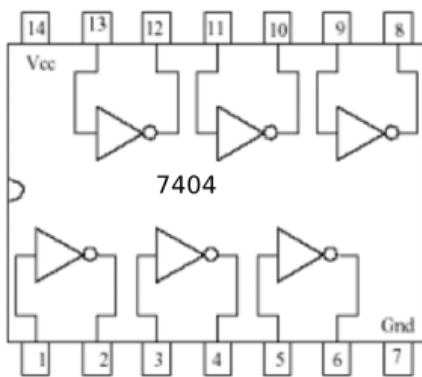
Figure 4. NAND gate circuit with LEDs for displaying inputs A and B and out put NAND(A, B).

- Now build an AND gate using the 7400 NAND and the 7404 Inverter (NOT gate). Use the red LEDs as inputs A,B and display the output with the green LED. **Demonstrate successful operation of this circuit to the Professor for credit in this lab.**

NOTE: No lab report is required – this lab grade is based solely on the success or failure of your circuit. If you are not able to complete this in the allotted lab time you will have

to set-up your circuit on your own time and make an appointment to demonstrate it to the professor. You will need to do so before the end of the day on Friday to receive credit. You may ask questions and receive help, but honor code rules still apply and you need to figure out how to get the circuit working yourself.

- EXTRA CREDIT: (2 pts) Build an XOR gate using the 7408 AND gate, the 7432 OR gate, and the 7404 inverter. Use the display LEDs as before. Note, these IC chips have three gates on each chip. Again, demonstrate successful operation of your circuit to the professor to get approved. If you read the lab carefully, you may be able to design this circuit before coming to class.





# PHYSICS 130/130A - EXPERIMENT 7

## MAGNETIC FORCE AND THE CURRENT BALANCE

### 1 Introduction

You have seen (or will very soon see) in class that currents create magnetic fields, and that current-carrying wires experience a force due to magnetic fields. The result of these two phenomena is that two parallel current-carrying wires should attract each other if the currents are flowing in the same direction, and repel if the currents are flowing in opposite directions.

Your textbook claims the following experimental result for the magnetic field created by a long, straight wire:

$$|B| = \frac{\mu_0 I}{2\pi R}$$

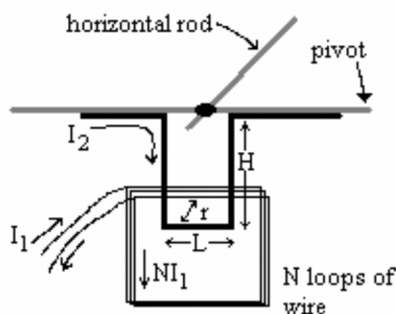
where  $\mu_0$  is the permeability of free space;  $\mu_0 = 4\pi \times 10^{-7} \text{ T m/A}$ .

The force on a wire of length  $L$  in a magnetic field  $B$  is given by:

$$|F| = BIL \sin \theta$$

where  $\theta$  is the angle between the current  $I$  and the magnetic field.

Our goal in this lab is to do a series of experiments to check the correctness (or incorrectness) of these predictions. The apparatus we will use to observe forces on current-carrying wires is the Current Balance. Schematically the balance looks something like this:



The horizontal rod attached to the pivot is adjusted so that the loop carrying  $I_2$  is vertical and a desired distance away from the loops carrying  $I_1$ , with both currents off. The  $I_1$  loop has  $N$  turns and the two loops are connected in series so that  $I_1 = I_2 = I$ . In this case, putting together the above two equations, theory predicts the total force per length to be

$$\frac{F}{L} = \frac{\mu_0 N I^2}{2\pi r}$$

## 2 Procedure

### Experiment 1

**Goal:** Verify that the force per unit length (for fixed distance  $r$ ) varies as current squared  $I^2$ .

1. Calibrate the electronic balance: With no weight on the balance, push the power ON button. Then push and hold down the CAL button until the flashing 100.00 appears. Release the CAL button and move the 100g standard mass onto the balance pan. When the stationary 100.00 appears, the balance is calibrated.
  2. Choose the hanging loop that has the longest length  $L$ . (Measure that length).
  3. Adjust it so it is hanging **vertically**, with length  $L$  in the **same horizontal plane** as the horizontal bundle of wires of the fixed coil.
  4. There is a string hanging down from the horizontal rod. Put a 50g weight on the balance so it covers the string. Adjust the system so the bottom of the balanced wire is **2.0 cm** from the bundled wire coil. Push the TARE button on the balance so that it reads 0.000g.
  5. Now adjust the current so that the current  $I = 1.0$  A. There should be a force on the hanging loop that will cause an upward force on the string, thus reducing the mass reading on the balance. The torque which causes this pivoting motion will be given by  $|\tau_1| = HF$ , where  $H$  is the distance from the horizontal hanging loop to the pivot axis, (as shown in the diagram above) and  $F$  is the magnetic force created by the currents.
  6. Turn the current off and check that the balance reads 0.000g. If not, push the TARE button and turn the current on again.
  7. This torque is balanced by a torque  $|\tau_2| = mgx$ , where  $x$  is the string's horizontal distance from the pivot axis and  $m$  is the (negative of) the mass reading on the balance. If the hanging loop remains in equilibrium, then the net torque must be zero meaning the two torques are balancing each other. Thus measuring  $m$ ,  $x$ , and  $H$  will allow us to calculate  $F$ .
- Repeat the above measurements for  $I = 2, 3, 4,$  and  $5$  amps, filling in the data table below (also make sure to record  $L$  and  $H$  before you begin):

$$L = \text{_____} \pm \text{_____} \quad H = \text{_____} \pm \text{_____}$$

$$x = \text{_____} \pm \text{_____} \text{ (cm)}$$

Current $I$ (A)	Mass $m$ (g)	Force $F$ (N)
1.0		
2.0		
3.0		
4.0		
5.0		

### Experiment 2

**Goal:** Verify that the force of attraction between two wires varies as  $1/r$ .

1. With the current off, make sure the loop is hanging vertically and adjust the distance between the hanging loop and the coil ( $r$ ) to be 1.5 cm as accurately as you are able.
2. Turn the current to 5 Amps and balance the wire to be vertical as described above.
3. Repeat for increasing  $r$ , and record your results using the data table below:

Distance $r$ (cm)	Mass $m$ (g)	Force $F$ (N)
1.5		
1.8		
2.3		
3.2		
5.0		

$$x = \text{_____} \pm \text{_____} \text{ (cm)}$$

### Experiment 3

**Goal:** Verify that the force of attraction between the wires increases proportionally with the length of the wire  $L$ .

1. With the current off, make sure the loop is hanging vertically and adjust the distance between it and the coil ( $r$ ) to be 1.5 cm as accurately as you are able.
2. Turn the current to 5.0 Amps and balance the wire to be vertical as described above.



3. Repeat for the hanging loops with shorter length ( $L$ ), and record your results using the data table below:

Length $L$ (cm)	Mass $m$ (g)	Force $F$ (N)

$x = \text{_____} \pm \text{_____} \text{ (cm)}$

### 3 Lab Questions

1. Make a plot of force ( $F$ ) vs. current squared ( $I^2$ ) for the data you took for experiment #1. Perform a linear fit to the data. Does the data appear to be well fit by a linear regression? (It should be, if it is not, make some suggestions as to the reason why not.) Determine and report the slope and intercept along with their respective uncertainties and with proper units. Show your uncertainty calculations. What significant conclusion(s) can you draw from this plot?
2. Make a plot of force ( $F$ ) vs. inverse distance ( $1/r$ ) for the data you took for experiment #2. Perform a linear fit to the data. Does the data appear to be well fit by a linear regression? If not, consider checking your work or retaking your data. Determine and report the slope and intercept along with their respective uncertainties and with proper units. What significant conclusion(s) can you draw from this plot?
3. Make a plot of force ( $F$ ) vs. wire length ( $L$ ) for the data you took for experiment #3. Perform a linear fit to the data. Does the data appear to be well fit by a linear regression? If not, consider checking your work or retaking your data. Determine and report the slope and intercept along with their respective uncertainties and with proper units. What significant conclusion(s) can you draw from this plot?

4. All three of your plots should show straight lines, meaning you have demonstrated that a force ( $F$ ) exists between two parallel current-carrying wires (with equal current  $I$ ) which has the form:

$$F = \frac{kI^2L}{r}$$

where  $k$  is a currently undetermined constant of proportionality. Use your data from the previous three questions to calculate three values of this  $k$ , and report  $k$  along with its uncertainty and proper units, using the fit parameters from the linear fits in each of your three plots.

Show and explain your work in finding the  $k$  values and your uncertainty calculations. **Do not just use one single data point to find  $k$ ! This is not the correct method. You need to use the slopes from your linear fits to your plots.**

Even if your plots do not show particularly linear relationships you should still do this part and just do this as best you can.

5. Comparing the equation for  $F$  from Problem 4 to the magnetic force  $F$  we expect from the discussion in the Introduction (or in class), we see that  $k$  should be equal to  $\frac{\mu_0 N}{2\pi}$ .

Using the standard value for  $\mu_0$  and the average of your  $k$  values, what value do you calculate for  $N$ , the number of turns in the coil? Estimate the uncertainty in  $N$  and present your answer in the form  $N = \text{value} \pm \text{uncertainty}$  (making sure to use an appropriate number of significant digits). Comment on whether your value for  $N$  appears to be a reasonable num-

ber (given that you were in the lab looking at the apparatus so you know what it looked like).

# PHYSICS 130/130A - EXPERIMENT 8

## MAGNETIC INDUCTION

### 1 Introduction

In this lab, we will investigate the phenomenon of EMFs induced in coils of wire by time-varying magnetic fields.

We define the flux of a *uniform* magnetic field  $\vec{B}$  through a loop as  $\Phi_B = \vec{B} \cdot \vec{A}$ , where  $A$  is the area of the loop and it is assumed the loop lies in a plane. (A more general expression which applies to non-uniform magnetic fields and arbitrary surface areas is  $\Phi_B = \int \vec{B} \cdot d\vec{A}$ .) An intuitive way of thinking about the flux is that it measures the number of magnetic field lines passing through the loop. A whole series of experimental results is summarized in Faraday's Law:

$$\mathcal{E} = -\frac{\Delta\Phi}{\Delta t}.$$

In words, Faraday's Law says there will be an induced EMF (voltage)  $\mathcal{E}$  between the ends of the loop of wire that is proportional to the rate at which the flux of the magnetic field through the loop is changing. This EMF will be created regardless of the cause of the change of flux.

Examples of ways to change the magnetic flux and thus generate an EMF include:

- Move the coil into (or out of) the region of a permanent magnet or electromagnet.
- Weaken (or strengthen) an external field by turning down (or up) the current in an electromagnet.
- Reduce (or increase) the area of the coil.
- Rotate the coil so there are fewer (or more) field lines passing through it.

There will be two parts to our study of induced EMFs. In the first part, we will observe the phenomenon of *self-induction*. A coil with a current flowing around it will naturally have magnetic flux due to its own current. If that current gets larger (or smaller) the magnetic flux will get larger (or smaller) proportionally. Thus, according to Faraday's Law, there should be an EMF proportional to the rate at which the current is changing:

$$V = -L\frac{\Delta I}{\Delta t} = -L\frac{dI}{dt}.$$

This is the equation that describes the behavior of a circuit element called an inductor, and the constant of proportionality  $L$ , called the **inductance**, is measured in Henrys.

Note that any real coil will, in addition to its inductance, also have the usual resistance to current flow due to the resistivity of the wire:  $R = \frac{\rho \cdot \text{length}}{\text{area}}$ . Therefore the total voltage difference between two output leads will be

$$V_{total} = L\frac{dI}{dt} + RI. \quad (1)$$

- If the current is constant or only changing very slowly, the contribution to  $V_{total}$  due to the inductance will be very small, so the coil will act just like a resistor.
- If we apply a sinusoidal voltage, then the current and the change in the current with respect to time will also be sinusoidal, though not necessarily with the same phase as the voltage. If we apply a sinusoidal voltage with a very low frequency, the voltage and current sine waves will be **in phase**.
- On the other hand, if the applied voltage is changing very rapidly (e.g. a high frequency sine wave) then the EMF due to the inductance will be very large. If we apply a sinusoidal voltage with a very high frequency, the voltage and current sine waves will be **out of phase**.

Below is a graph of a voltage that is proportional to the rate of change of the current. Note that the current and voltage waveforms are out of phase.

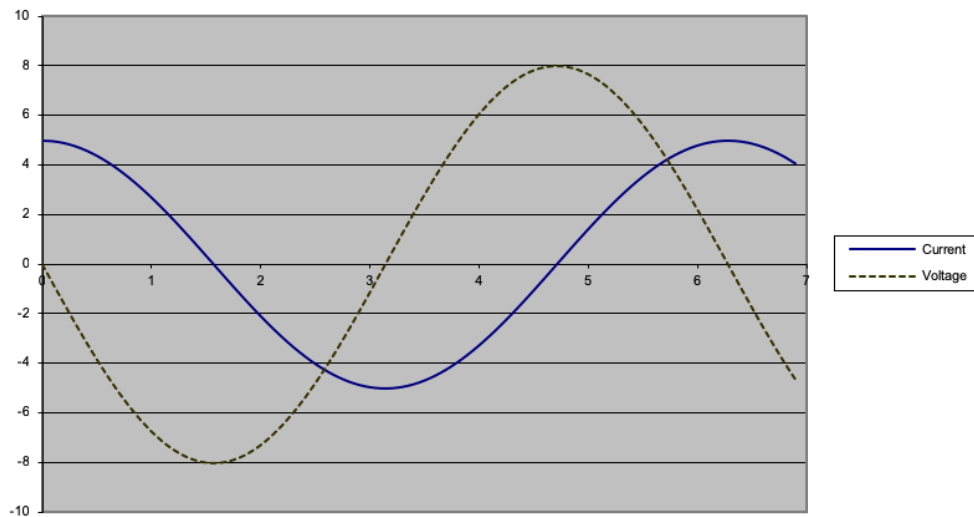


Figure 1: Illustration of the current and voltage waveforms that are out of phase.

## 2 Procedure

### 1. Procedure 1

In the first part of the experiment, you will apply a sinusoidal voltage to coil 1 and measure both the applied voltage waveform on coil 1 and the voltage waveform induced in coil 2, positioned near to coil 1. Use the picoscope's waveform generator to apply a sine wave voltage of amplitude 1.0 V to coil 1. Measure the voltage waveform on coil 1 on picoscope input channel A and the waveform on coil 2 on channel B. You can obtain improved accuracy by using picoscope's built-in signal averaging ability to filter out low-frequency electrical noise. To do so, click on the A icon (upper left of menu bar), check the box to Activate Filtering under Lowpass Filtering, and enter "2 kHz". Repeat the process for channel B, setting the filter frequency to ten times the frequency of the applied waveform. You will need to reset the channel B filter frequency each time you change the frequency of the applied voltage waveform, but you can leave the channel A filter frequency at 2 kHz throughout the experiment.

- A change in current in coil 1 is proportional to a change in the magnetic field from coil 1,
- which is proportional to the magnetic flux through coil 2,
- which is proportional to an induced EMF in the second coil.

Both the applied voltage and the induced voltage will be recorded using computers with LoggerPro software.

Here's what you should expect to see. At very low frequencies, the current in coil 1 will be in phase with its voltage since the first term on the RHS of Equation (1) will be small. Since the EMF in coil 2 is proportional to the rate of change of its flux, it should have a peak voltage when the current in coil 1 is changing most quickly. Thus, in the low-frequency limit, a peak of voltage 2 should correspond to a zero-crossing of voltage 1. Said another way, the zero-crossing of voltage 1 should be out of phase with respect to voltage 2 by  $90^\circ$ .

As the high-frequency limit is approached, the two voltages should appear more and more in phase. If  $\Delta t$  is the time interval between the two zero-crossings, the phase difference (in degrees) between the two sine waves can be calculated as

$$\phi = 360^\circ f \Delta t.$$

Fill in the following data table:

$R$  of coil \_\_\_\_\_  $\pm$  \_\_\_\_\_

## 2. Procedure 2

For the second part of the experiment, you will experiment with other non-sinusoidal waveforms. You will use the Pasco function generator to apply a voltage waveform to coil 1, and the Vernier Labpro interface to measure the applied waveform on coil 1 and the induced waveform on coil 2. (The internal impedance of the picoscope's waveform generator makes it unsuitable for this part of the experiment.) Use a frequency of 1 Hz, which should be in the low-frequency limit for the coils you are using.

Apply a **triangle wave** rather than a sine wave and observe the induced waveform in coil 2. Make sketches of the graphs on your LoggerPro screen. [Or take photos of them, or do screen captures and save them.]

Then apply a **square wave** of frequency 1 Hz and make sketches of the resulting waveforms.

Frequency (Hz)	Zero Crossing $t_1$	Zero Crossing $t_2$	$\phi$ (calculated)
0.5			
1.0			
2.0			
4.0			
8.0			
12.0			
16.0			
24.0			
32.0			
64.0			
100.0			
200.0			
400.0			

### 3 Lab Questions

- Based on your data from procedure 1, plot the phase angle ( $\phi$ ) as a function of frequency. Choose the *logarithmic scale* for your  $x$ -axis.
- What frequencies would you describe as being clearly in the high-frequency limit? In the low-frequency limit? (Take “in the high-frequency limit” to mean a phase shift within ten degrees of the asymptotic high-frequency phase.) Note some of your data are neither high nor low frequency - they are intermediate.
- What shape is expected for the graph of the EMF induced in coil 2 by the **triangle** wave voltage applied to coil 1? Why? Your explanation should include
  - a discussion of the rate of change of magnetic flux and
  - an explanation of why the low-frequency limit is important here.

Did your observed shape meet those expectations? If not, try to suggest a possible source of error.

- What would your prediction for the time dependence of the EMF induced in coil 2 be if the triangle-wave voltage were applied in the high-frequency limit? Sketch a graph of your prediction.  
*Hint:* First work out the shape of the current vs. time in coil 1, then decide what effect that current will have on the EMF in coil 2.

5. What shape is expected for the graph of the EMF induced in coil 2 by the **square** wave voltage applied to coil 1? Why? Your explanation should include
- (a) a discussion of the rate of change of magnetic flux and
  - (b) an explanation of why the low-frequency limit is important here.

Did your observed shape meet those expectations? If not, try to suggest a possible source of error.

6. Use the data you acquired in procedure 1 to estimate the inductance  $L$  of the coils in your experiment.

*Hint:* Consider the condition under which the phase angle is  $45^\circ$ . At that phase shift, the *amplitudes* of the two contributions to  $V$  (Equation 1) are equal. If the current is given by  $I = I_o \sin(2\pi ft)$  then the slope of the  $I$  vs.  $t$  graph is given by:

$$\frac{\Delta I}{\Delta t} = I_o 2\pi f \cos(2\pi ft).$$





# PHYSICS 130/130A - EXPERIMENT 9

## HYDROSTATICS

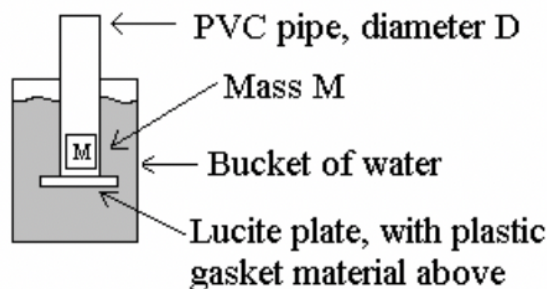
### 1 Introduction

A fundamental result of hydrostatics is that the pressure  $P$  in a fluid increases with depth in that fluid:  $P = \rho gh$ , where  $\rho$  is the mass density of the fluid,  $g$  is the acceleration due to gravity near the Earth's surface  $9.80 \text{ m/s}^2$ , and  $h$  is the depth in the fluid.

### 2 Procedure

- **Experiment 1:**

In the first experiment we will attempt to verify the above relationship, and simultaneously determine the density of a particular fluid (water). The apparatus you will use looks somewhat like this:



Consider the forces exerted on the Lucite plate. With some consideration, one should conclude that the Lucite plate will be sealed against the PVC pipe as long as the upward force across the plate due to the water pressure is greater than the total downward force on the plate from the mass  $M$ . We want to determine how pressure varies with depth in the fluid (water), so we will place different masses in the pipe, hold the plate to the bottom and immerse them deep in the water. When the pipe is deep in the water, release your hand from the Lucite plate - the plate should remain firmly against the pipe. Slowly pull the pipe up, and carefully note the depth of the pipe's bottom edge at which the plate (and the mass  $M$ ) drop from the bottom of the pipe. Take several (at least 3) runs and average them.

Inner Diameter of Tube: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Outer Diameter of Tube: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Mass of Plate plus Gasket: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Thickness of Plate Plus Gasket: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Length and Width of Plate: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Mass ( $M$ )	Depth 1	Depth 2	Depth 3	Avg. Depth
50 g				
100 g				
150 g				
200 g				
250 g				
300 g				
350 g				
400 g				

• **Experiment 2**

In this experiment you will make use of Archimedes' principle which states: *the buoyant force on a body in a fluid is equal to the **weight** of the water displaced.* We will use this principle (as Archimedes did) to determine the density of some of odd-shaped objects. There will be a pair of metal objects at each table. You will determine the density of each.

1. Suspend one of the objects from the underside of the pan on the triple-beam balance and carefully find its weight.
2. Repeat your measurement from (1) with the object immersed in water. Carefully consider the *meaning* of the scale's reading. It is not telling you mass - what is it telling you?

**Object 1:**

Dry Weight: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Immersed Weight: \_\_\_\_\_  $\pm$  \_\_\_\_\_

**Object 2:**

Dry Weight: \_\_\_\_\_  $\pm$  \_\_\_\_\_

Immersed Weight: \_\_\_\_\_  $\pm$  \_\_\_\_\_

### 3 Lab Questions/Analysis

#### Experiment 1 Questions:

1. Plot the average drop-off depth in the water (y-axis) as a function of the added mass (not including the plate mas) on the plate (x-axis).
2. Find the slope and uncertainty of the slope of your plot. Report the slope and y-intercept values along with their uncertainties and proper units, in standard form: value  $\pm$  uncertainty [units].
3. Use this slope (along with  $g$ , and the diameter of your tube) to find the density of the water in your experiment. Calculate the uncertainty, and report your result in standard form: value  $\pm$  uncertainty [units]. Be careful of unit conversions in your calculation! Clearly articulate your reasoning. Do your results agree with the expected value of the density of water?
4. What  $y$ -intercept (and its uncertainty) did you find with the fit to your data? Does it agree with the expected value? (The expected value is not zero—you should derive the expected value of the  $y$ -intercept.)

#### Experiment 2 Question:

5. Calculate the density of each object. You may assume the density of the water you're using is  $1000.0 \text{ kg/m}^3$ . Clearly explain the logic behind your calculation and include uncertainty. Report you results in standard form: value  $\pm$  uncertainty [units].