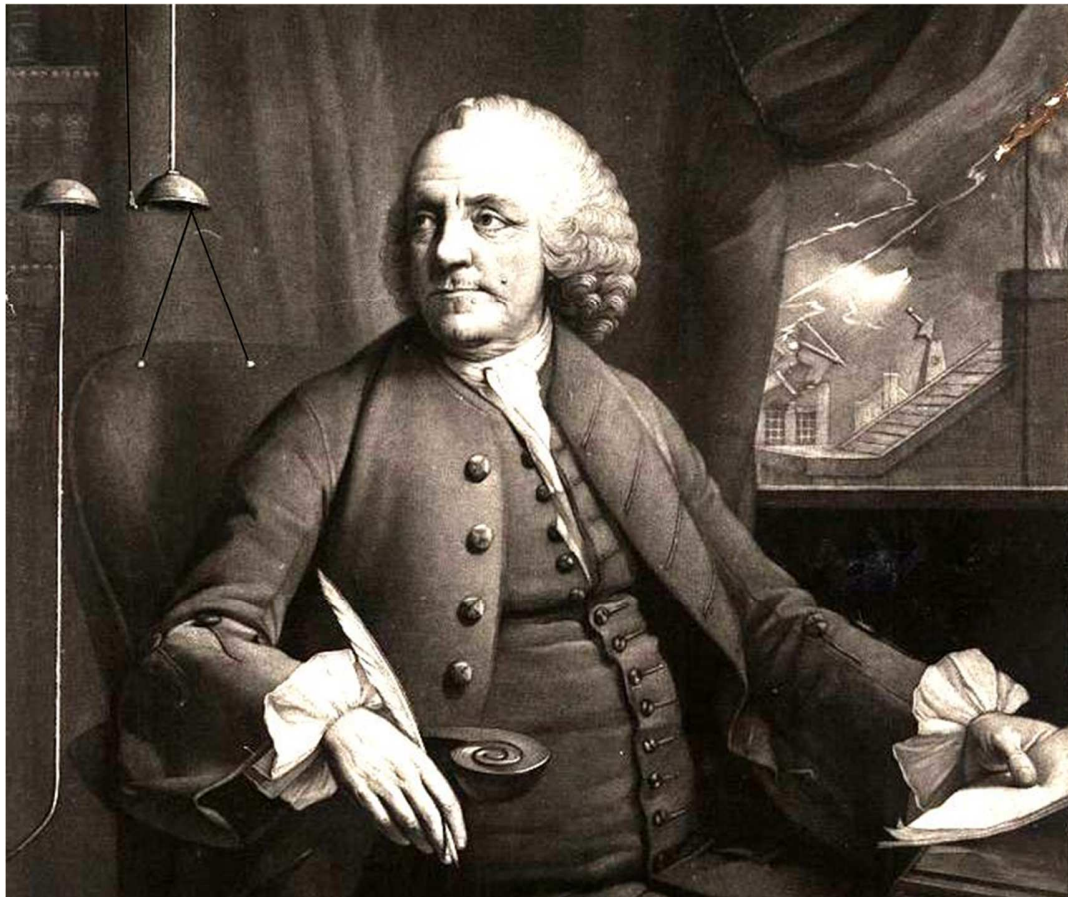


**Laboratory Manual**

**General Physics Laboratory II**  
**PHYS 118B**

**Summer 2015**



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# General Physics Laboratory II

## PHYS 118B

(Starting in the Fall of 2015, this lab will be referred to as PHYS 1602L.)

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## Introduction

### The Sermon

The speed of light is  $2.99792458 \times 10^8$  m/s. This is not science.

The Wikipedia entry on Newton's 2<sup>nd</sup> law of motion is not science.

Nor is the periodic table of the elements.

Science is not a collection of facts. (Not even true facts!) Rather, science is a **process** for figuring out what is really going on. *What is the underlying principle here? How does this relate to some other observation?* If you are not involved in such a process, you are not doing science. A brilliant, dedicated, A+ student memorizing a list of equations is not doing science. A baby dropping peas on the floor to see what happens: now *that's science!!* (Does oatmeal fall too? Let's find out!!)

This is a science lab. I expect you to do some science in it.

*"Yeah, yeah, Dr. Charnock, I've heard this sermon before."*

Perhaps so, but I have seen too many brilliant and dedicated students who have learned to succeed in their other science classes by learning **lots of stuff**.<sup>\*</sup> So, they come into physics planning to memorize every equation they encounter and are completely overwhelmed. **You cannot succeed in physics by learning lots of stuff**. There are simply too many physics problems in the world. You cannot learn them all.

Instead, **you should learn as little as possible!**<sup>†</sup> More than any other science, physics is about fundamental principles, and those few principles<sup>‡</sup> must be the focus of your attention. Identify and learn those fundamental principles and then you can **derive** whatever solution that you need. And that **process** of derivation is the **process** of science.

*"OK, thanks for the advice for the class, but this is a lab!!"*

It's still about fundamental principles. Look, each week you will come to lab and do *lots of stuff*. By following the instructions and copying (. . . oh, I mean *sharing* . . .) a few answers from your lab partners, you can blunder through each lab just fine. The problem is that the at following lab session you will have a quiz, and you will not remember everything you did in that lab the week before.

When you are doing each lab, consciously relate your experiments to the underlying principles.

*How did I measure this? Where did this equation come from? Why are we doing this?*

On the subsequent quiz, instead of having to **remember what you did**, you can apply the principles to **figure out what you did**. Trust me. It really is easier this way.

---

<sup>\*</sup> To get through organic chemistry, sometimes you just have to memorize all those formulas.

<sup>†</sup> . . . but not less.

<sup>‡</sup>  $F = ma$ , conservation of energy and momentum, oscillations and waves. You will learn a few more in the second semester.

## GOALS AND OBJECTIVES

Physics is about the real world, not some idealized Platonic world that only exists in your head. The purpose of this lab is to relate the theories and equations you are learning in the classroom to the reality. Hopefully, we'll convince you that all that physics stuff actually does work. Of course, reality can be messy, and along the way you will learn to deal with experimental uncertainty, loose cables, dead batteries, blown fuses, temperamental software, temperamental lab partners, and your own awful handwriting.

Welcome to experimental physics!



xkcd.com

## CORRELATION WITH LECTURE

The topics covered in the lab will usually also be covered in your lecture, although not necessarily in the same sequence or at the same time during the semester. Given the scheduling of the different lecture sections (some are MWF and some are TR), and the different lab sections (the first lab is Monday at 1 PM, the last is Thursday at 4 PM), *perfect correlation of lecture and lab topics is not possible for all students at all times*. The TA will provide a brief overview of the physics concept being explored in the lab during the first part of each lab section.

Occasionally, to improve the correlation with the lecture, the order of the labs may be changed from the sequence in this lab book. If so, you will be informed by your TA. **Check your email.**

## PREPARATION

Prior to coming to lab, you should read over each experiment. Furthermore, for each laboratory, you must complete a “pre-lab” activity printed at the beginning of each lab in this manual. The pre-lab should be completed before the lab and turned in at the **beginning** of the lab. See the course syllabus for more details. In some labs, you may also be required to complete experimental

predictions and enter them in your lab manual before you come to lab. Your TA will discuss this with you when necessary. Bring the following to the lab:

- Your lab manual.
- Your completed pre-lab.
- A scientific calculator. Graphing calculators are nice but not necessary. For some calculations, you may find a spreadsheet more appropriate. You are welcomed and encouraged to use such tools.
- A pen, pencil and an eraser.

## PROCEDURE IN THE LABORATORY

In the laboratory, you will need to be efficient in the use of your time. We encourage a free exchange of ideas between group members and among students in the section, and we expect you to share both in taking data and in operating the computer, but **you should do your own work (using your own words) in answering questions in the lab manual and on the review questions handed out in lab.**

## HONOR CODE

The Vanderbilt Honor Code applies to all work done in this course. Violations of the Honor Code include, but are not limited to:

- Copying another student's answers on a pre-lab, lab questions, review questions, or quiz;
- Submitting data as your own when you were not involved in the acquisition of that data; and
- Copying data or answers from a prior term's lab (even from your own, in the event that you are repeating the course).

## GRADING

Your lab reports will be graded each week and returned to you the following week. Grades (including lab and quiz grades) will be posted on OAK.

- ***Mistakes happen!*** Check that the scores on OAK are correct. If you don't do this, *no one else will.*
- Retain your lab reports so that any such errors can be verified and corrected.
- Details of grading may be found on the online syllabus

**SYLLABUS:** available online

<https://my.vanderbilt.edu/physicslabs/documents/>

## The Greek Alphabet

The 26 letters of the Standard English alphabet do not supply enough variables for our algebraic needs. So, the sciences have adopted the Greek alphabet as well. You will have to learn it eventually, so go ahead and learn it now, particularly the lower case letters. (Just be glad you don't have to learn Cyrillic.)

Alpha	A	$\alpha$
Beta	B	$\beta$
Gamma	$\Gamma$	$\gamma$
Delta	$\Delta$	$\delta$
Epsilon	E	$\epsilon$
Zeta	Z	$\zeta$
Eta	H	$\eta$
Theta	$\Theta$	$\theta$
Kappa	K	$\kappa$
Lambda	$\Lambda$	$\lambda$
Mu	M	$\mu$
Nu	N	$\nu$
Xi	$\Xi$	$\xi$
Omicron	O	$\omicron$
Pi	$\Pi$	$\pi$
Rho	P	$\rho$
Sigma	$\Sigma$	$\sigma$
Tau	T	$\tau$
Upsilon	Y	$\upsilon$
Phi	$\Phi$	$\phi$ or $\varphi$
Chi	X	$\chi$
Psi	$\Psi$	$\psi$
Omega	$\Omega$	$\omega$





Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 1: Electrostatics

*“It is now discovered and demonstrated, both here and in Europe,  
that the Electrical Fire is a real Element, or Species of Matter, not  
created by the Friction, but collected only.”*

*--Benjamin Franklin, 1747*

### Objective:

To understand electrostatic phenomena in terms of the basic physics of electric charges.

To experimentally distinguish positive and negative charges.

Properties of conductors and insulators.

### Equipment:

Braun electroscope, polar electroscope, Faraday cage

Fur, Saran Wrap, 2 rubber balloons, tissue paper

Electrophorus

### Introduction

Electrostatic theory, while profound, is quite simple. Many otherwise mysterious phenomena can be understood by applying a few simple principles:

1. Electrical charges come in two types: *positive* (+) and *negative* (-).
2. Like charges repel. Opposite charges attract.
3. Electrical charges cannot be created or destroyed, but may be separated and moved.
4. If an object is observed to be electrically neutral, equal amounts of + and – charges are present. If it is positively charged, a surplus of + charges are present. If it is negatively charged, it has a surplus of – charges.
5. There are two types of materials:
  - a. *Insulators*: electrical charges are frozen in place in the material.
  - b. *Conductors*: electrical charges may freely move throughout the volume object like a gas in a container.

Franklin himself thought of these charges arising from an excess or deficiency of a single electric fluid. Today, we understand the charges are due to particles of protons (+) and electrons (-). *Usually*, it is the electrons (that is, the negative charges) that move around; however, it is often useful to think of positive charges moving as well. A negative charge moving to the left is equivalent to a positive charge moving to the right.

## Triboelectricity

First, you must move some electrons around to produce a net electric charge. You can do this with the *triboelectric effect*.<sup>§</sup>

1. Vigorously rub an inflated balloon with your hair.<sup>\*\*</sup>

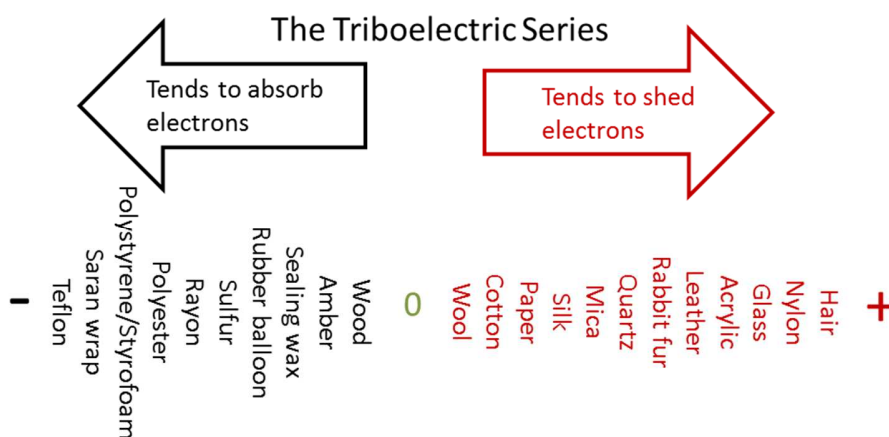


Fig 1

2. Tear off a few small pieces of tissue paper. Hold the balloon next to the chaff and observe the effect.
3. Touch the balloon to the electrosopes and observe the effect.

Some materials (such as hair) have a slight tendency to give up electrons. Other materials (such as rubber) can pick up a few extra electrons. Hence, if you rub a balloon with hair, electrons will be transferred, and a net electric charge will appear on each. When Ben Franklin did this, he declared the hair to have a “positive” charge and the rubber to have a “negative” charge.<sup>††</sup> Today, following Franklin’s convention, we declare electrons to have a negative charge.

The Triboelectric Series ranks different materials by their tendency to give up or absorb electrons.



For any two materials brought in contact, you can estimate the sign and relative strength of the triboelectric effect by the relative position of materials on the series. For instance, hair is to the right of

<sup>§</sup> *Tribo* is from the Greek term for rubbing.

<sup>\*\*</sup> If you are follicly challenged, use the fur.

<sup>††</sup> An unfortunate choice in retrospect. Electrical currents would be a little more intuitive if Franklin had declared the rubber (and hence, electrons) to be positive.

rubber on the series; hence, when rubbed against rubber, hair will acquire a positive charge. Rub hair against hair and nothing happens.

4. If hair is rubbed against Styrofoam, would you expect a stronger or weaker effect? What type of charge would appear on the Styrofoam? What charge on the hair? How would the magnitude of the charges compare?
  
  
  
  
  
  
  
  
  
  
5. What would be the sign of the charges on each of the following items if they were rubbed against each other:
  - a. Cotton \_\_\_\_\_ + Nylon \_\_\_\_\_
  - b. Fur \_\_\_\_\_ + Rubber \_\_\_\_\_
  
6. Why are artificial fabrics typically more prone to static cling?

Try this with several different materials on your table and your own hair. Observe the effect with the electroscope.

### **Charging an Electroscope by Contact**

As you have discovered, an electroscope is used to detect an electric charge. You will be using two different electroscopes. While the Braun electroscope is more sensitive to small charges, its reaction time is slow due to the relatively large mass of its needle. Be patient with it.

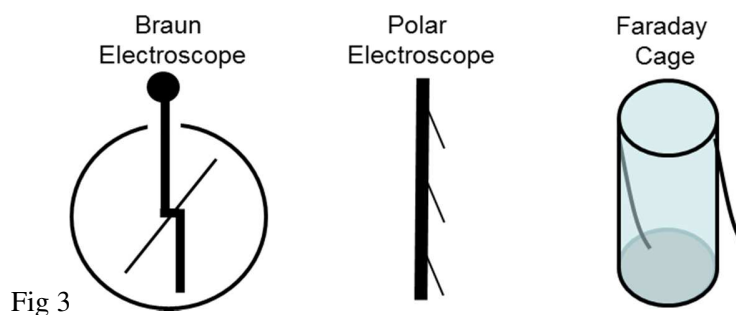


Fig 3

1. Verify that there is no charge on each device by touching them with your finger. This is called **grounding** the device. Any excess charge on the device will dissipate through your body to the ground.<sup>‡‡</sup>
2. Charge one side of the balloon by rubbing it with your hair.
3. Gently rub the balloon along the top of the Braun electroscope to transfer some charge, then remove the balloon.

Note: Charges on insulators tend to be sticky, so it may take a fair amount of rubbing to transfer a significant charge.

4. Using the principles above, explain why is the needle deflected?

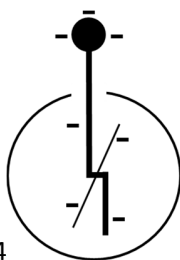


Fig 4

<sup>‡‡</sup> The human body is essentially a bag of salt water and therefore a fairly good conductor.

**Charging an Electroscope by Induction**

1. Bring the balloon close (but not touching) the top of the negatively charged electroscope, then pull it away. Describe the effect.
2. Repeatedly cover and remove the second balloon with the Saran Wrap<sup>§§</sup>. Bring it close to (but not touching) the top of the negatively charged electroscope. Describe the effect.
3. What does this indicate about the sign of the charge on the second balloon?

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<sup>§§</sup> It is simply physical contact more than rubbing that stimulates the transfer of charge.

## The Electrophorus and Electrostatic Induction

The electrophorus is a simple device for easily generating and transferring electrostatic charges. It consists of an insulating plate (the Styrofoam plate) and a conductive plate (the aluminum pie pan) with an insulated handle. \*\*\* The cartoon below illustrates how to use the electrophorus to charge the metal plate.

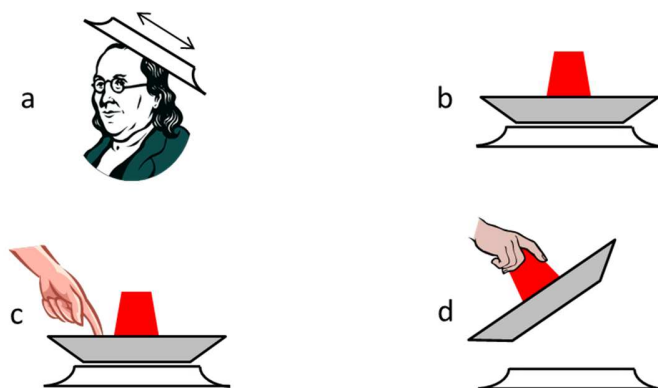


Fig 5 Charging an electrophorus

- a. Rub the **underside** of the Styrofoam plate with an appropriate material<sup>†††</sup> to produce a large negative charge on the plate.
  - b. Place metal plate on top.
  - c. Touch the metal plate to remove excess charge.
  - d. Remove the metal plate with the insulated handle.
1. Experimentally determine the sign of the final charge on the metal plate. What happened when you touched the top of the metal plate?

\*\*\* We use the term *electrophorus* because that sounds much more impressive than *picnic supplies*.

††† Refer to the triboelectric series above.

2. What happened to the charges on the metal plate when placed on the charged plastic plate?
3. What happened to the charges on the plate when you touched it?
4. For each step, add + and – symbols to the cartoons in Fig. 5 to illustrate the distribution of charges on the plates. Discuss these distributions with your lab partners and finally with your TA

### The polar electroscope

1. Ground the polar electroscope to verify that it is neutral. Then for each of the following steps, sketch the position of the three foil leaves.
  - a. Charge the metal plate of the electrophorus, and touching it to the polar electroscope, transfer some charge.
  - b. Remove the plate and.
  - c. Hold the charged metal plate close to, but not touching, the top of the polar electroscope.
  - d. Hold the charged insulating plate close to, but not touching, the top of the polar electroscope.

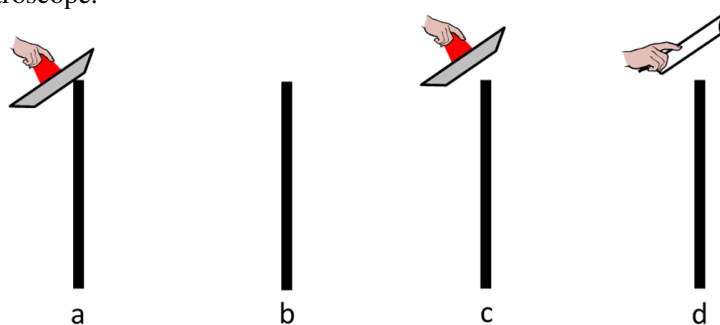


Fig 6

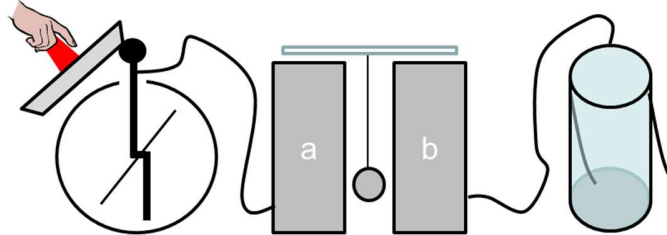




4. Exactly where on the cage does the charge reside? Applying the principles above, think of an intuitive explanation for this and discuss it with your TA.
5. What is the electric field inside the cage?
6. Have one member of your group wrap a cell phone with foil. Have another member make a call to the wrapped phone. Explain the result.

### Franklin's Bells

1. Attach an electroscope to each side of the Franklin Bells (that is, the soda cans) as shown below. Each bell should be about 0.5 cm from the clapper. Ground each electroscope to ensure the system is neutral.



2. Using the electrophorus, transfer enough charge to the electroscope for the bells to start ringing.
3. When the motion stops, briefly ground one of the electroscopes with your finger.
4. Using the principles from the introduction, explain what you observed. <sup>†††</sup>

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<sup>†††</sup> With one bell attached to a lightning rod and the other grounded, Franklin used his bells to detect approaching electrical storms; thus letting him know when he could perform his experiments. This is illustrated on the cover.

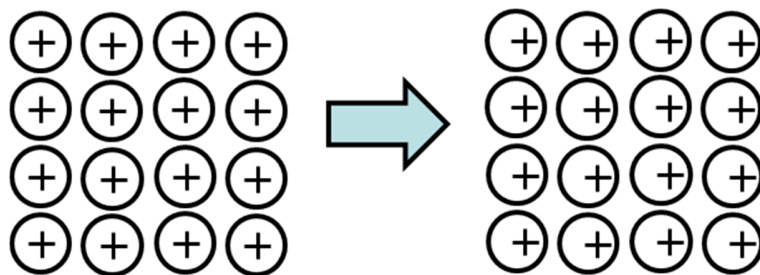
*“I was one night awaked by loud cracks on the staircase. . . I perceived that the brass ball, instead of vibrating as usual between the bells, was repelled and kept at a distance from both; while the fire passed, sometimes in very large, quick cracks from bell to bell, and sometimes in a continued, dense, white stream, seemingly as large as my finger, whereby the whole staircase was inlightened (sic) as with sunshine . . .”*

Wisely, Franklin also invented fire insurance.

**Induced Polarization of Insulators**

1. Charge the electrophorus.
2. Hold metal plate close to, but not touching, the hanging wooden dowel.
3. Hold the insulating plate close to, but not touching, the hanging wooden dowel.
4. Describe the effects below.

Even though electrical charges are not free to move through the insulating wood (unlike a conductor), the wood can still be slightly polarized. Model each atom in the wood as a positive nucleus surrounded by a negative shell of electrons. In the presence of an external electric field, the electrons will be slightly pulled one way and the nuclei are pulled the other way. This polarizes each atom, and hence the entire object, by having just a little more positive charge on one side, and a little more negative charge on the other.





Name\_\_\_\_\_ Section\_\_\_\_\_ Date\_\_\_\_\_

## Pre-Lab Preparation Sheet for Lab 2: Introduction to Circuits (Due at the beginning of lab)

**Directions:**

Read over the lab and then answer the following questions.

1. What is the name of a device that measures electrical resistance?
2. Make a simple diagram of a battery and two resistors in parallel with each other.
3. What must you never do with an ammeter?



WE WERE GOING TO USE THE TIME MACHINE TO PREVENT THE ROBOT APOCALYPSE, BUT THE GUY WHO BUILT IT WAS AN ELECTRICAL ENGINEER.

xkcd.com

Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 2: Building and Analyzing Simple Circuits

*Freddy: Throw the third switch!*

*Igor: Not the third switch???*

*Freddy: THROW IT, I SAY! THROW IT!*

*-- Young Frankenstein*

### Objective:

To learn how to build simple circuits and analyze them with a multimeter.

To understand the xkcd joke above.

### Equipment:

2 multimeters

Vernier circuit board

Two batteries

Two battery holders

4 banana cables

Package of alligator jumpers

### Introduction






The simplest electronic circuits contain three measurable parameters.

1. **Potential (V)**, measured in **Volts (V)**. Potential can be naively understood as the electrical pressure that pushes charges through the circuit.
2. **Current (I)**, measured in Coulombs/second or **Amperes (A)**. Current measures the rate at which charges move through the circuit.
3. **Resistance (R)**, measured in **Ohms ( $\Omega$ )**. It measured how strongly particular circuit elements resist the flow of charge. An ideal conductor has zero resistance. An ideal insulator has infinite resistance. Resistance is defined by the expression:

$$R \equiv \frac{V}{I} \quad (1)$$

**Note:** This is the definition of resistance. This is not Ohm's law. That will be defined later.

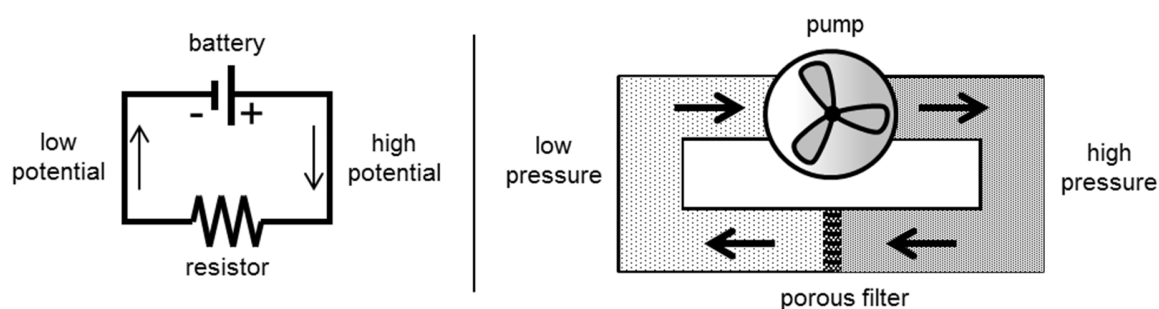
In this lab, you will assemble and analyze some very simple circuits using only the following elements:

	A conductive wire. For our purposes, the resistance of a wire is essentially zero.
	A resistor.
	A battery or dc voltage source. The long line indicates the positive side of the battery.
	A switch.
	Ground.

We will also define symbols for a voltmeter  $\textcircled{V}$ , ammeter  $\textcircled{A}$ , and ohmmeter  $\textcircled{\Omega}$  since these may also be included in circuit diagrams.

### A simple loop

The simplest possible electric circuit contains three elements: a battery, conductive wires, and a resistor.

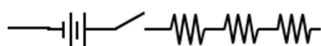


A useful analogy to this circuit is a hydraulic system. The pipes represent the wires, the pump the battery, and a dense filter the resistor. The flowing water is analogous to the electric current.<sup>§§§</sup> Much as a pump produces the pressure to push the water through the filter, the battery produces the potential to push the current through the resistor. Even as the water in the pipes is does not disappear but returns to the pump, whatever current flows out of the battery must flow back in.

This analogy applies to more complicated circuits as well. Keep it in mind as you work with circuits in this and future labs.

### Series and Parallel design

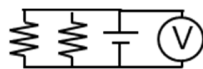
In a series design, the circuit elements are placed one after the other along the wire. For example, below we have 2 batteries, a switch, and 3 resistors arranged in series:



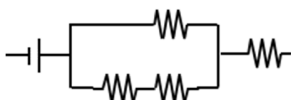
<sup>§§§</sup> Note that I speak of the current, not the electrons. Electrons, being negative, move in the opposite direction of the current. You can blame Ben Franklin for this absurdity.



In parallel design, the ends of each element are connected to the same two wires. Below, we elements arranged in parallel:



However, circuits will not always fit neatly into these two categories. For example:



We will deal with such circuits later in the semester.

## The Multimeter

The Digital Multi-Meter (DMM) is *the* go-to device for measuring the important properties of almost any electrical circuit, whether it's a motherboard for the latest super-computer or an old string of Xmas lights. Generally, they can measure **voltage** (ac or dc), **current** (ac or dc), **resistance** and **continuity**\*\*\*\*. Depending on the particular model, other quantities may also be measured such as: capacitance, frequency, inductance, temperature, diode tester, transistor tester, battery tester, alien life detector††††, . . . . Basically, anything that strikes the fancy of the meter's designer (and the wallet of the purchaser).

Our DMM's are very well engineered devices that are designed to withstand common abuse without failing and uncommon abuse without failing catastrophically. So, be careful with these meters, but don't be paranoid. You will be using two DMM's in this lab. The specific instructions in the text refer to the EZ DM-332, but the operation of the second meter is very similar.

## Activity 1: Measuring Potential, the Voltmeter

In class, you have learned how electric fields create the forces that cause charged particles to move. However, in practice one rarely actually measures the electric field. Instead we measure the **electric potential** (also called **voltage**). You will study the theory explaining potential in your class and how this relates to the field. For now, we will naively define potential as the pressure on charged particles which causes them to flow.

There are many sources of electric potential: an electrical generator, a solar cell, even a charged rubber comb. But the easiest source to think about is a battery  $\text{---}| \text{---}$ .

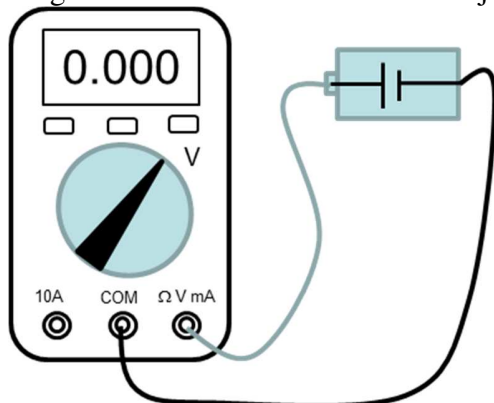
- a. Turn the dial to **4** on the voltage **V** setting. This will allow you to measure up to 4 V. On the left side of the display, you will see either a  $\text{---}$  (for dc measurements) or a  $\sim$  (for ac measurements). Press the  $\text{---} \sim$  button (upper right on the meter) to switch between these settings. Today, we will limit ourselves to dc measurements, so leave the meter on  $\text{---}$ .

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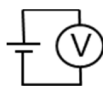
\*\*\*\* We will define continuity in a bit.

†††† No, wait. That last one is only on a tricorder. I get them confused sometimes.

- b. Plug the black test lead into the **COM** jack. Plug the red lead into the **V** jack.



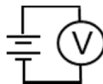
- c. Insert batteries into the individual battery holders. By placing the probe leads to the ends of each battery, measure the potential of each.



Battery 1: \_\_\_\_\_ Battery 2: \_\_\_\_\_

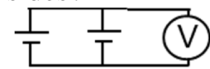
Electric potential is always a relative measurement. One does not measure the absolute potential of some point  $a$ , but rather the difference in potential between point  $a$  and some other point  $b$ . Thus, *a voltmeter is placed in parallel with the circuit element* whose potential you wish to measure. *A voltmeter's resistance is practically infinite*, and very little current moves through it. Note what happens when you reverse the leads.

- d. Attach the batteries in series. What is the potential across the pair of batteries?



Potential in series = \_\_\_\_\_

- e. Attach the batteries in parallel. What is the potential between the positive and negative sides?



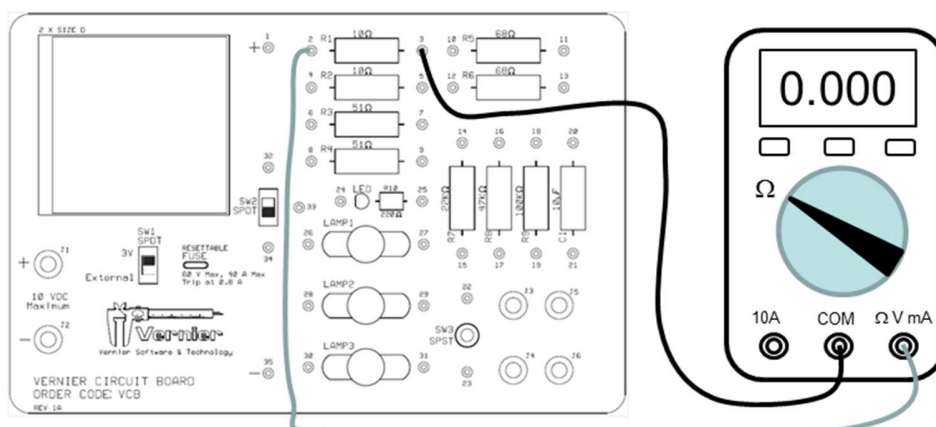
Potential in parallel = \_\_\_\_\_

**Note:** As long as the resistance of a wire is negligible, the potential everywhere along a single wire will be constant.

## Activity 2: Measuring Resistance, the Ohm Meter

Electrical resistance is a kind of friction inhibiting the flow of charge.


- Plug the black test lead into the **COM** jack. Plug the red lead into the  **$\Omega$**  jack.
- Turn the dial to **400  $\Omega$** . At this setting, you can measure resistances up to 400 $\Omega$ .



- c. Touch the leads to each side of R1 on the circuit board. Verify that the resistance is  $10\Omega$ .
- d. Do the same with the rest of the resistors. Increase the range as needed by rotating the dial to  $4k\Omega$ ,  $40k\Omega$ , etc.

The Ohm Meter works by applying a known voltage to the leads and measuring the resulting current:  $R=V/I$ . For this to work, ***the resistor you are measuring must be isolated from the rest of the circuit***. If an external voltage is applied to the leads, you will not get a correct reading (and you *might* damage the meter).

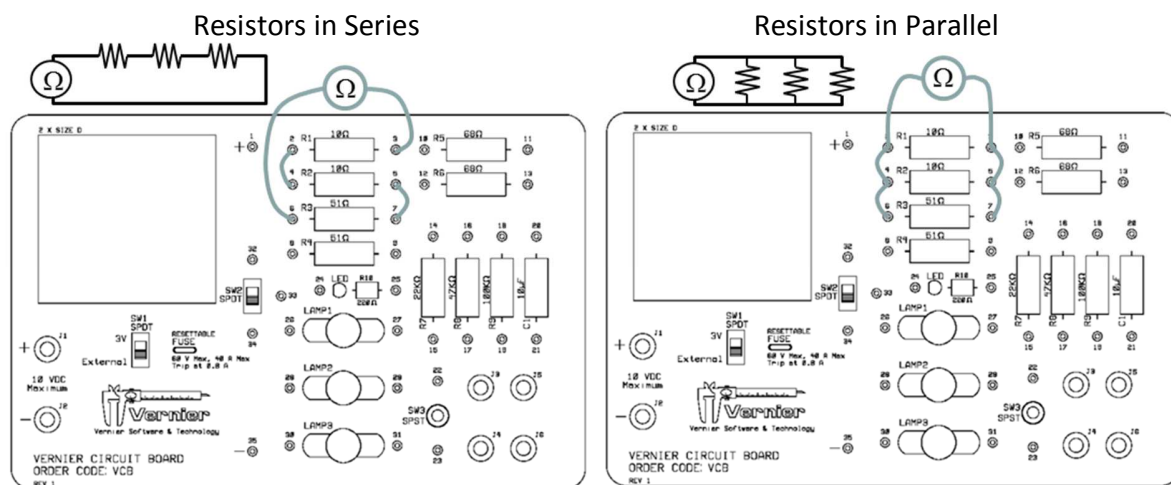
### Continuity

- e. Turn the dial to .
- f. Touch the leads together. You should hear a buzz, and the displayed resistance should be nearly zero.
- g. Touch the leads to each end of a single wire.
- h. Touch the leads across a  $10\Omega$  resistor.
- i. Touch the leads across a  $51\Omega$  resistor.

This is the continuity test, a variation on the Ohm Meter setting. As long as the resistance between the two probes is  $<40\Omega$ , it will buzz. This is a great way to see if your wires are actually connected or if there is a break somewhere in the middle. This is arguably the single most useful feature on a multimeter.††††

---

†††† Wondering if a fuse is blown? Is this light bulb any good? This is the setting you want.



### Resistors in series

- j. Using the wires provided, place R1, R2, and R3 in series. Reference the figure above. Measure the combined resistance.

Resistance = \_\_\_\_\_

- k. What is the effective resistance of several resistors in series?

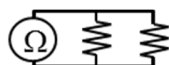
### Resistors in Parallel

- l. Using the wires provided, place R1, R2, and R3 in parallel. Reference the figure above. Measure the resistance.



Resistance = \_\_\_\_\_

- m. Now place R1 and R2 in parallel. Measure the resistance.



Resistance = \_\_\_\_\_

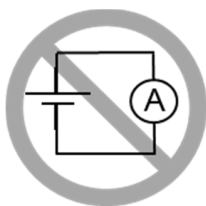
- n. How does the effective resistance of resistors in parallel differ from resistors in series?

#### Activity 4: Measuring Current, the Ammeter

The algebraic symbol used for current is  $I$ .<sup>§§§§</sup> The current setting on your meter is marked with an **A**. Note that your meter has separate ac  $\sim$  and dc  $==$  ranges. In this lab we will only perform dc measurements.

To measure current, ***an ammeter must be placed in series with the element*** whose current you wish to measure. Since the ammeter itself must not affect the current being measured, ***the resistance of the ammeter is nearly zero.***

**CAUTION!** If you touch the probes of an ammeter directly across a battery or power supply, the resulting current surge would likely blow a fuse and possibly damage the meter.



Turn the dial on the multimeter to the 40 mA dc setting. Leaving the black probe in **COM** jack, move the red plug to the **10A** jack.

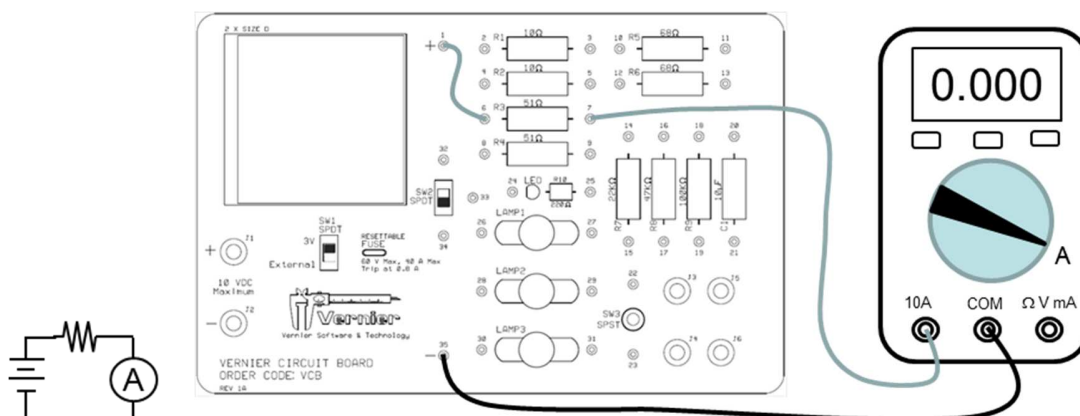
**Note:** There are two jacks for the ammeter setting: **10A** and **mA**.

The **10A** jack is a low precision setting that can handle currents up to 10 A. The **mA** jack is a more precise setting, but it can only handle currents up to 400mA. Always start your measurements using the **10A** jack. If the measured current is safely below 400mA, you may *then* move to the **mA** jack.

- Verify that the power supply is set to 3V. Connect the color coded wires to the Vernier Circuit Board. The switch SW1 should be set to External.
- Construct the following circuit using a  $51\Omega$  resistor. Refer to the above figure. Measure the resulting current.

---

<sup>§§§§</sup> . . . because *that* makes perfect sense.



Measured Current = \_\_\_\_\_

- c. Reverse the plugs going into the **COM** and **mA** jacks. Measure the resulting current.

Measured Current = \_\_\_\_\_

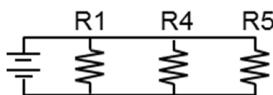
Current flowing into the **COM** jack is positive. Current flowing out of the **COM** jack is negative.

### Activity 5: Bringing it all together

- a. With the ohmmeter, verify the resistances of R1, R4, and R5.

R1 = \_\_\_\_\_ R4 = \_\_\_\_\_ R5 = \_\_\_\_\_

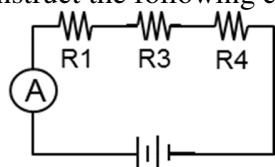
- b. Construct the following circuit.
- c. With a voltmeter, measure the potential across the power supply, and then measure the potential across each resistor.



$V_{\text{power supply}} = \text{_____}$   $V_{R1} = \text{_____}$

$V_{R4} = \text{_____}$   $V_{R5} = \text{_____}$

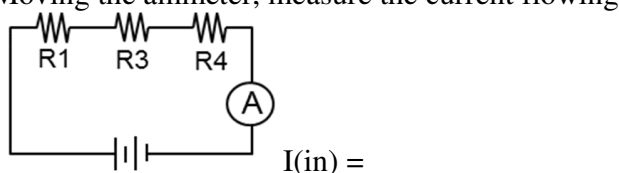
- d. Construct the following circuit.



- e. Measure the potential across R1, R3, and R4.

$V1 = \text{_____}$   $V3 = \text{_____}$   $V4 = \text{_____}$

- f. How do these potentials relate to the potential of the power supply?
- g. Measure the current coming out of the power supply.  $I(\text{out}) = \underline{\hspace{2cm}}$
- h. Moving the ammeter, measure the current flowing into the battery.



- i. Measure the current between the resistors. How are all of these currents related?
- j. Using the definition of resistance and the measured voltages, calculate the expected current through each resistor.

$$I1 = \underline{\hspace{2cm}} \quad I3 = \underline{\hspace{2cm}} \quad I4 = \underline{\hspace{2cm}}$$

### Activity 6: Grounding

While potential is always a relative measurement, it is useful to define a point of zero potential for a circuit. This point is called the **ground**. Exactly where we define the ground to be is arbitrary.<sup>\*\*\*\*</sup> One may select a particular wire in the device, the metal frame of the device (a chassis ground), or a metal rod driven deeply into the earth (an earth ground).<sup>††††</sup> If a circuit element is not somehow connected to ground (either directly or through a resistor), it is said to be “floating”.

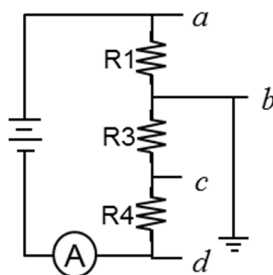
**Note:** The third socket of a standard North American electrical outlet is connected to a metal rod driven deeply into the earth.



For the circuit in the previous activity, declare ground to be the point between R1 and R3.

<sup>\*\*\*\*</sup> Similarly, the zero for gravitational potential energy is arbitrary.

<sup>††††</sup> By convention, grounding wires are green or bare, positive wires are red, negative wires are black.



- a. Connect the **COM** (or ground) probe of your multimeter between R1 and R3. Then measure the potential at points *a*, *b*, *c*, and *d*.

$V(a) =$  \_\_\_\_\_  $V(b) =$  \_\_\_\_\_

$V(c) =$  \_\_\_\_\_  $V(d) =$  \_\_\_\_\_

- b. Suppose that no part of the circuit may be more than 2 V from ground. Where should the ground be placed?

- c. Move the ground. Then measure the potentials to verify the circuit meets the requirement.

$V(a) =$  \_\_\_\_\_  $V(b) =$  \_\_\_\_\_

$V(c) =$  \_\_\_\_\_  $V(d) =$  \_\_\_\_\_



Name\_\_\_\_\_ Section\_\_\_\_\_ Date\_\_\_\_\_

## Pre-Lab Preparation Sheet for Lab 3: Current in Simple Circuits (Due at the beginning of lab)

**Directions:**

Read over the lab and then answer the following questions.

1. If a circuit element obeys Ohm's Law, what does that imply about the resistance of the element?
2. Why must a resistor be removed from a circuit to measure its resistance with an Ohm meter?



OHM NEVER FORGOT HIS  
DYING UNCLE'S ADVICE.

xkcd.com

Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 3: Building and Analyzing Simple Circuits II

*“I am endeavoring, ma'am, to construct a mnemonic  
memory circuit using stone knives and bearskins.”*

*--Spock, The City on the Edge of Forever*

### Objective:

To develop a detailed understanding of voltage, current, and resistance in simple circuits.

### Equipment:

2 multimeters

Vernier circuit board

4 banana cables

Package of alligator jumpers

### Introduction

The resistance of a device is defined to be

$$R = \frac{V}{I} \quad (1)$$

However, strictly speaking, this is not Ohm's Law. This lab will clarify the distinction.

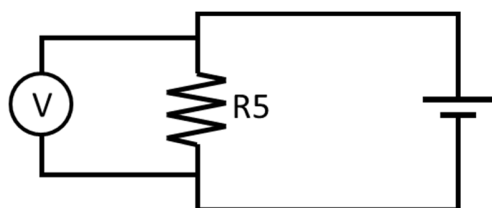
Note: Instead of using batteries, we will use the DC power supply for the voltage source. Verify that it is set to 3V. This setting will be used throughout this lab.

### Exercise 1

With a multimeter, measure the resistance of R5 on the Vernier circuit board.

R5 = \_\_\_\_\_

Now, construct the following circuit.



Using the definition of resistance, calculate the value of R5.

R5 measured = \_\_\_\_\_

Is this consistent with the value measured above?

Now repeat these measurements using LAMP1 instead of R5.

$R_{\text{LAMP1}}(\text{ohmmeter}) = \underline{\hspace{2cm}}$        $R_{\text{LAMP1}}(\text{calculated}) = \underline{\hspace{2cm}}$

Are these results consistent? What may explain any discrepancy?

**Ohm's Law states that the voltage across a resistor is *linearly* proportional to the current.** In other words, **the resistance is constant.**

$$V = IR, \text{ where } R \text{ is constant.} \quad (2)$$

Such devices are said to be "*ohmic*". Ohm's Law is not a fundamental law of nature, and many devices do not follow it: for example, diodes, transistors, and even common light bulbs.

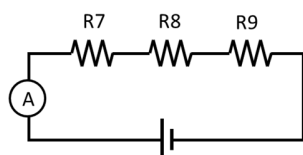
- a. To better illustrate this, connect the R5 resistor directly to the OUTPUT jacks on the PASCO interface.
- b. From the desktop, go to Labfile/B Labs/Lab 3 Simple DC Circuits II  
Run the application IVcurve.
- c. What does the slope of this line represent?
  
- d. Replace the resistor with LAMP1 and repeat the experiment. What is the relationship between the brightness of the lamp and the resistance? Can you think of a simple explanation for this behavior?

- e. Replace the lamp with the yellow LED (light emitting diode) found in the lower right corner of the board. Repeat the experiment. How is a diode analogous to turnstile?

f. Print out your I-V curves on a single sheet. Label each curve with the corresponding device. For the rest of the lab, we will use the resistors on the Vernier board. These devices obey Ohm's law quite well.

### Exercise 2: Series circuits

- g. Construct the following circuit. With an arrow, indicate the direction of the current.



Current = \_\_\_\_\_

- h. Move the ammeter between R7 and R8. Current (R7,R8) = \_\_\_\_\_  
i. What does this imply about the currents in a series circuit?

- j. Using the definition of resistance, the applied potential, and the measured current, calculate the effective resistance of the combined resistors. How does this relate to the value of the individual resistors?

$R(\text{total}) = \underline{\hspace{2cm}}$

- k. Using the definition of resistance and the labeled value of each resistor, calculate the potential across each resistor in the circuit.

Calculated potentials:

$V(R7) =$  \_\_\_\_\_  $V(R8) =$  \_\_\_\_\_  $V(R9) =$  \_\_\_\_\_

- l. With the voltmeter, measure each potential. How do they compare to the values above?

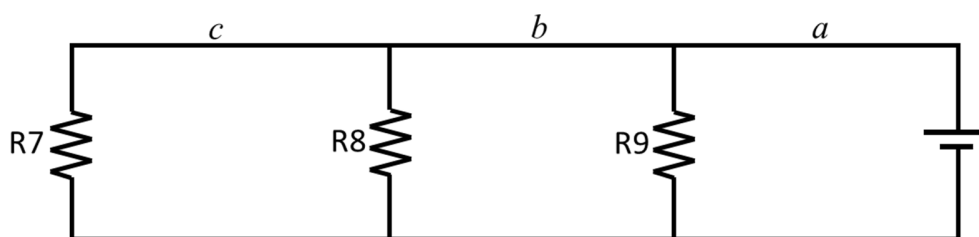
Measured potentials:

$V(R7) =$  \_\_\_\_\_  $V(R8) =$  \_\_\_\_\_  $V(R9) =$  \_\_\_\_\_

- m. How do these potentials relate to the total applied potential?

### Exercise 3: Parallel Circuits

Construct the following circuit.



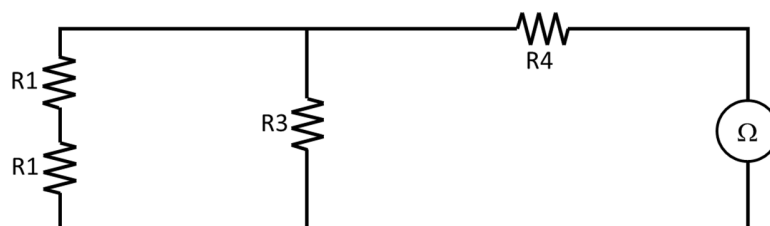
- n. Measure the current coming out of the battery ( $I_a$ ), through wire segments  $b$  and  $c$  ( $I_b$ ,  $I_c$ ), and through each resistor ( $I_7$ ,  $I_8$ ,  $I_9$ ). Label each segment of the above diagram with the appropriate current. Also, with an arrow, indicate the direction of the current along each segment.
- o. How are the at each circuit node (for example [ $I_c$ ,  $I_b$ ,  $I_8$ ] ) mathematically related to each other?
- p. How are the currents in the resistors ( $I_7$ ,  $I_8$ ,  $I_9$ ) mathematically related to the current coming out of the battery?

- q. Given  $I = \frac{V}{R}$ , rewrite the expression in part c in terms of the values of the individual resistors and the effective resistance of the circuit seen by the battery.

- r. In general, what is the effective resistance of a set of resistors in parallel?

#### Exercise 4: Combined Series and Parallel Circuits

Construct the following circuit.



- s. The effective resistance of the circuit from the ohmmeter

$R(\text{effective}) =$  \_\_\_\_\_

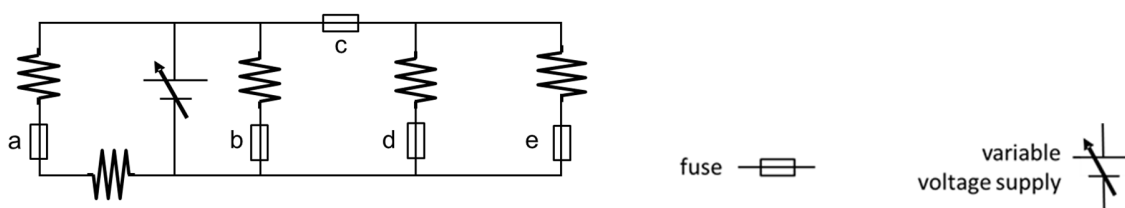
- t. Using the rules for you discovered previously for adding series and parallel resistors, calculate the expected resistance of the circuit. Find the percent difference from the value above.

$R(\text{expected}) =$  \_\_\_\_\_      % difference = \_\_\_\_\_

### Exercise 5: Fuses

As many of you have already discovered, a fuse is a safety device to prevent excessive current from damaging a circuit (or worse). It typically consists of a fine wire with a relatively low melting temperature. When the current exceeds a rated value, the fuse *blows*. That is, the fine wire inside the fuse melts and breaks the circuit.

Consider the following circuit:



All of the resistors have the same resistance, and each fuse has the same maximum current. The voltage is steadily increased.

- u. Which of the fuses is the first to blow? Explain.

- v. Which is the 2<sup>nd</sup> fuse to blow? Explain.





3. Given Equation (5) and definition of current  $\left(I \equiv \frac{dQ}{dt}\right)$ , derive an expression for the current across a charging capacitor.

Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 4: Introduction to Capacitors

*"I have lately made an Experiment in Electricity that I desire never to repeat. Two nights ago being about to kill a Turkey by the Shock from two large Glass Jarrs containing as much electrical fire as forty common Phials, I inadvertently took the whole thro' my own Arms and Body."*  
--Benjamin Franklin, 1750

### Objective:

To observe the basic physics of capacitors

To understand the exponential behavior of charge, current, and voltage as capacitors charge and discharge.

### Equipment:

Multimeter

Textbook

2 20 cm x 40 cm sheets of aluminum foil

Caliper

22000  $\mu\text{f}$  capacitor

Vernier circuit board

4 banana cables + 4 alligator clips

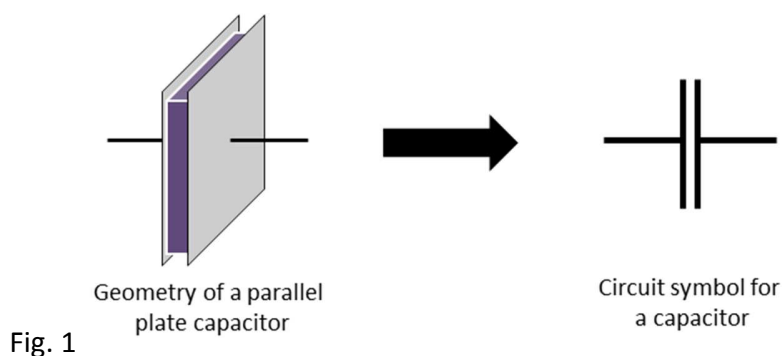
1 PASCO voltage probe connected to port A

1 PASCO current probe and cable connected to port B

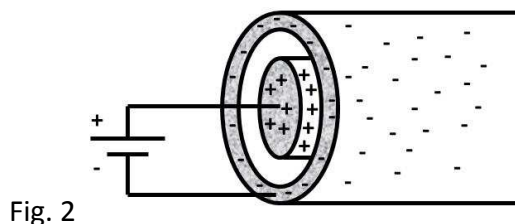
DC power supply

### Introduction

A capacitor is *any* device that can store and release an electric charge: a metal plate, a low hanging cloud, a cat, or your finger. However, the most common configuration is two sheets of metal separated by an insulator (also called a dielectric). This description leads to the capacitor circuit symbol shown below.



In practice, these sheets may be folded, rolled up or stacked in any number of ways.



When a DC voltage is applied across the capacitor, the insulator prevents current from flowing between the two plates leading to the production of equal and opposite charges on each capacitor plate. The capacitance  $C$  is a measure of a device's ability to store charge. It is defined as:

$$C \equiv \frac{Q}{V} \quad (1)$$

where  $Q$  is the amount of charge stored on one side of the device, and  $V$  is the applied voltage. The SI unit of capacitance is the Farad (F).

$$F \equiv \frac{\text{Coulomb}}{\text{Volt}}$$

Typically, capacitors are measured in  $\mu\text{F}$  to  $\text{pF}$ .\*\*\*\*\*

The value of the capacitance depends on the dielectric material, area of the plates, and gap between the plates. For a parallel plate geometry, the capacitance is

$$C = \frac{\kappa \epsilon_0 A}{d} \quad (2)$$

where  $\kappa$ : the dielectric constant of the insulating material;  $\epsilon_0$ : the permittivity of free space;  $A$ : the surface area of the metal sheets; and  $d$ : the thickness of the dielectric. Note that it does not depend on the particular charge or applied voltage, but only on the device itself.

### Exercise 1

You are now going to construct your own capacitor using your textbook and two sheets of aluminum.

- Cut the two sheets of aluminum foil to about 20 cm x 30 cm. Cut the sheets as straight as possible so you can calculate the area easily. Do not wrinkle the sheets.
- Follow the diagram below to make your capacitor

---

\*\*\*\*\* The technical term for a 1 F capacitor is a “*freakin’ huge capacitor!*” Such capacitors must be handled with caution.

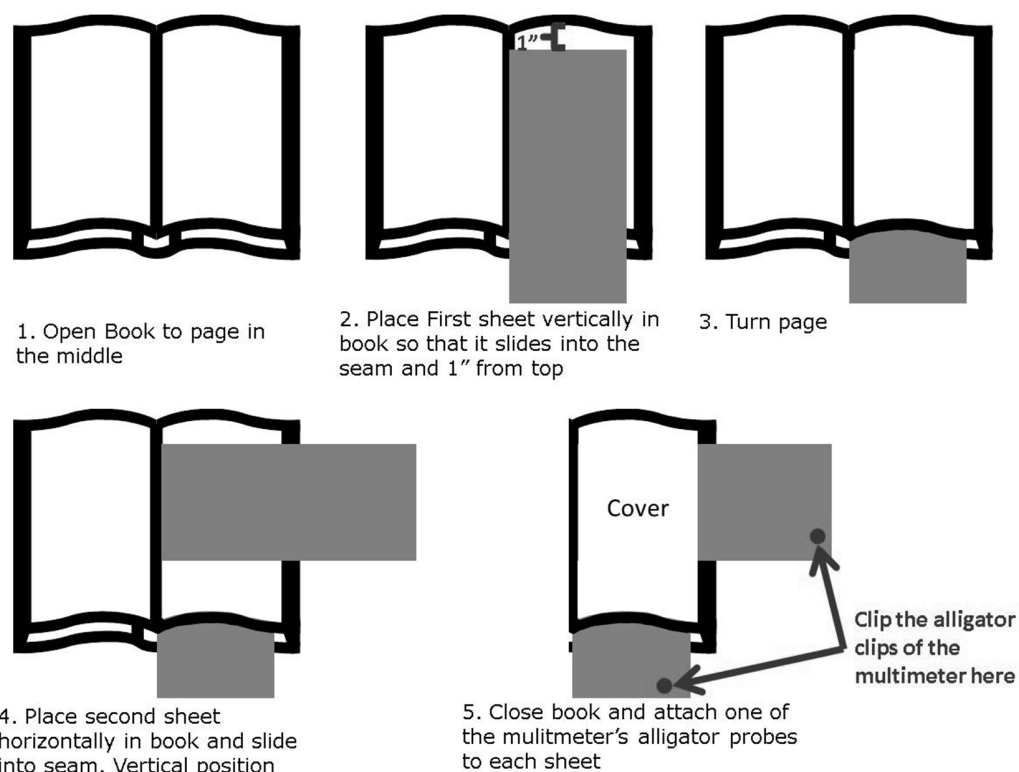


Fig. 3

- c. Set your multimeter to measure capacitance
- d. Press down firmly on the front cover
- e. Observe the capacitance of your homemade capacitor and record your results

$C_{1 \text{ page}} = \underline{\hspace{2cm}}$

- f. Now perform the same experiment but with two pages in between the sheets of aluminum foil and record your results.

$C_{2 \text{ pages}} = \underline{\hspace{2cm}}$

- g. Finally, perform the same experiment a third time with three sheets and record your results

$C_{3 \text{ pages}} = \underline{\hspace{2cm}}$

- h. What do you observe about the capacitance as you add more pages?

- i. Now measure the thickness of the three book pages used in a. through h. using the caliper, average the thicknesses, and record your results.

Page 1 Thickness = \_\_\_\_\_

Page 2 Thickness = \_\_\_\_\_

Page 3 Thickness = \_\_\_\_\_

Average Thickness = \_\_\_\_\_

Area<sup>§§§§§</sup> of the capacitor = \_\_\_\_\_

- j. The dielectric constant for paper is about 3. Using the average page thickness and the area, calculate the capacitance value found for your 1 page capacitor.

$C_{1\text{page}} =$  \_\_\_\_\_

- k. Now repeat the calculation for your 2 and 3 page capacitors.

$C_{2\text{pages}} =$  \_\_\_\_\_

$C_{3\text{pages}} =$  \_\_\_\_\_

- l. How do these values compare to the measured values?

- m. What could be possible factors that would cause the measured values to deviate from your predictions?

- n. Based on what you know about parallel plate capacitors, what would you expect to happen if you folded one of the sheets of aluminum foil in half?

- o. Now examine the effect by folding the horizontal sheet in half and measure the capacitance with one 1 page of separation. Record your results.

$C =$  \_\_\_\_\_

---

§§§§§ Carefully consider what part of the area of these sheets you care about.

## Charging a Capacitor: Theory

Consider the circuit below. Assume that initially the capacitor is discharged.

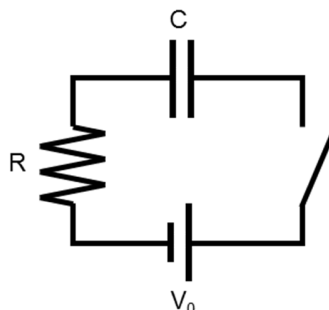


Fig. 4

When the switch is closed, current will flow from the battery and charge the capacitor. We know the voltage across the capacitor must equal the sum of the voltages across the resistor and capacitor.

$$V_0 = V_R + V_C \quad (3)$$

Applying the definitions of resistance, capacitance, and current:

$$\begin{aligned} V_0 &= IR + \frac{Q}{C_c} \\ &= R \frac{dQ}{dt} + \frac{Q}{C} \end{aligned} \quad (4)$$

$$\frac{dQ}{dt} = \frac{V_0}{R} - \frac{Q}{RC}$$

The solution<sup>\*\*\*\*\*</sup> to this differential equation for  $Q(t)$  is

$$Q(t) = Q_0 (1 - e^{-t/\tau}) \quad (5)$$

where

$$Q_0 \equiv CV_0 \quad \text{and} \quad \tau \equiv RC$$

$\tau$  is known as the *time constant*<sup>†††††</sup> and is a measure of how quickly the capacitor is charged. From your work on the pre-lab, now have expressions for  $Q(t)$ ,  $V(t)$ , and  $I(t)$  for the capacitor.

1. Write an expression for the current as a function of time across the resistor:

2. Write an expression for the voltage as a function of time across the resistor:

---

\*\*\*\*\* To verify this, just plug this expression for  $Q(t)$  into the differential equation above. (No, you don't *have* to do this.)

††††† It is basically the same concept as *half-life*.

3. After a very long time, what is the current flowing through the capacitor?
4. After a very long time, what is the charge on the capacitor?
5. After a very long time, what is the voltage on the capacitor?
6. When  $t = \tau$ , what fraction of the final charge has accumulated? When  $t = 4\tau$ ?

These exponential functions are very common<sup>\*\*\*\*\*</sup>, so it is worth your time to get familiar with them. These functions are illustrated below.

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<sup>\*\*\*\*\*</sup> They are found in applications as divergent as bank accounts, bacterial growth, and radioactive decay.



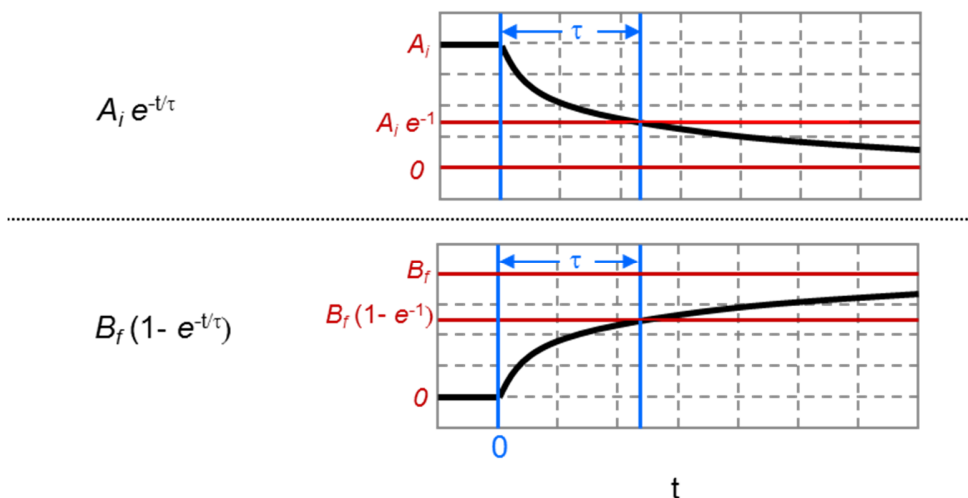


Fig. 5

### Discharging a Capacitor: Theory

Discharging a capacitor works much the same way. Consider the following circuit:

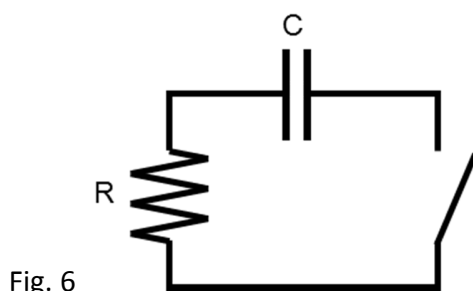


Fig. 6

Before the switch is closed, the capacitor has an initial charge  $Q_0$ . With the equations illustrated in Fig. 5 in mind, think about how one should expect the charge, voltage, and current on the capacitor to behave as it discharges. §§§§§§§§ Now write expressions for these quantities:

$$Q_C(t) =$$

$$V_C(t) =$$

§§§§§§§§ I'm not looking for a rigorous proof here. Just apply the Stephen Colbert method and use your gut.

$$I_C(t) =$$

Write an expression for the voltage across the resistor:

$$V_R(t) =$$

Verify these expressions with your TA.

### Charging and Discharging a Capacitor: Experiment



current probe



voltage probe

Carefully construct the following circuit using the Vernier circuit board and the large 22000  $\mu\text{F}$  capacitor. This particular capacitor is polarized, having defined negative and positive terminals. The negative side is indicated by a stripe running down the side of the capacitor.

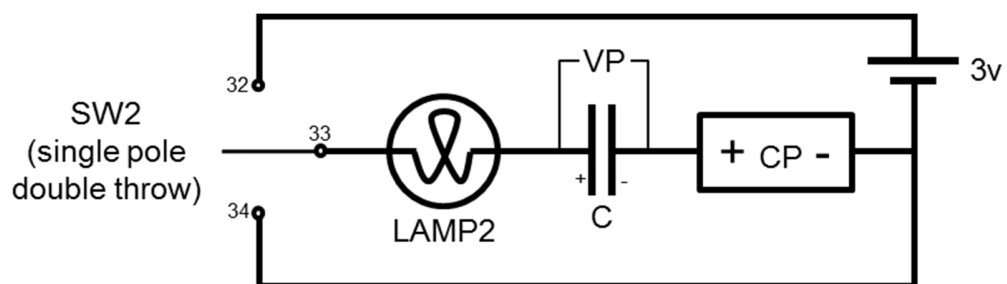


Fig. 7

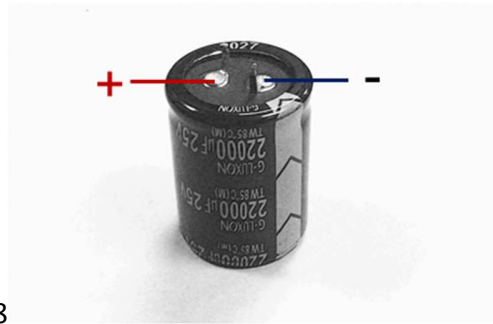


Fig. 8

Here, CP is the PASCO current probe and VP is the PASCO voltage probe. Start with the switch in the lower position (#34 pin).

### Exercise 2

1. Run the following Capstone program:  
Physicslabs\B Labs\Lab 4 Capacitors\Capacitor charging discharging.cap
2. Slowly, flip the switch back and forth several times and observe the behavior of the circuit.
3. Describe the behavior of the lamp below. A sketch of the brightness vs. time may be useful.

**Exercise 3**

1. Return the switch to the lower position to discharge the capacitor.
2. Replace the lamp with a  $51\Omega$  resistor.
3. Clear the previous data then restart the recording.
4. Flip the switch to charge the capacitor.
5. When the capacitor is fully charged, reverse the switch and discharge the capacitor. Stop recording when it is fully drained.
6. Print your current and voltage plots. Annotate each segment of the plots as charging or discharging.
7. Using the mathematical fitting tool, fit each segment of the data with the appropriate function. Annotate each segment of the printout with the corresponding time constant from the fit. **Take care to interpret the results of the fit properly.** Capstone's fitting function is slightly different from the functions described above.
8. What is the average value of these time constants?

$$\tau_{\text{avg}} = \underline{\hspace{2cm}}$$

9. With this value of  $\tau$ , calculate the value of the capacitance and the % variance from the listed value. \*\*\*\*\*

$$C(\text{from } \tau) = \underline{\hspace{2cm}} \quad \% \text{ diff} = \underline{\hspace{2cm}}$$

Consider the charging phase of capacitor. From the definition of current

$$\begin{aligned}
 I &= \frac{dQ}{dt} \\
 dQ &= I dt \\
 \int_0^{Q_0} dQ &= \int_0^{\infty} I dt \\
 Q_0 &= \int_0^{\infty} I dt
 \end{aligned} \tag{6}$$

Thus, the area under the  $I(t)$  curve is equal to the final charge on the capacitor  $Q_0$ .

10. Using the integration tool, measure  $Q_0$ .
11. From the definition of capacitance, again measure  $C$ .

$$Q_0 = \underline{\hspace{2cm}} \quad C(\text{from } Q) = \underline{\hspace{2cm}}$$

---

\*\*\*\*\* Electrolytic capacitors, like the one you are using, are notorious for varying from their nominal values.

**Exercise 4**

1. Replace the 51W resistor with a 10W resistor.
2. What is the expected time constant for this circuit?
3. Charge the capacitor and find the resulting time constant by fitting the current plot.

$\tau(\text{expected}) =$  \_\_\_\_\_  $\tau(\text{from fit}) =$  \_\_\_\_\_



Name\_\_\_\_\_ Section\_\_\_\_\_ Date\_\_\_\_\_

## Pre-Lab Preparation Sheet for Lab 5: Magnetism

(DUE AT THE BEGINNING OF LAB)

Watch the following videos,

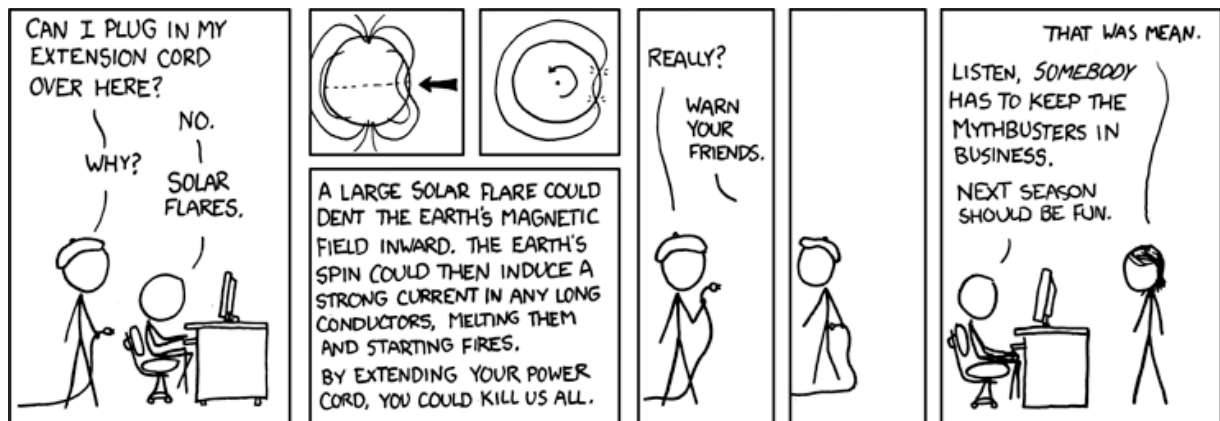
<https://www.youtube.com/watch?v=1TKSfAkWWN0>

<https://www.youtube.com/watch?v=hFAOXdXZ5TM>

Then read over the lab, and answer the following questions.

1. An electron travels next to a current carrying wire. From the *perspective of the electron*, what is the force that pulls it toward the wire?
2. You are an electron moving forward. You enter a region where the magnetic field is to your right. What is the direction of the magnetic force?

3. The North end of a magnetic compass points North. What does this imply about the Earth's magnetic field?



xkcd.com



Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
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## Lab 5: Magnetism

*MAGNET, n. Something acted upon by magnetism.*

*MAGNETISM, n. Something acting upon a magnet.*

*The two definitions immediately foregoing are condensed from the works of one thousand eminent scientists, who have illuminated the subject with a great white light, to the inexpressible advancement of human knowledge.*

*--Ambrose Bierce, The Devil's Dictionary*

### Objectives

To understand the basic physics of magnets and magnetic fields.

To understand the Lorentz force.

To understand flux and Lenz's Law.

### Equipment

800 turn coil	Magnaprobe	pair of cow magnets
horseshoe magnet	large PASCO magnet	toothed aluminum plate
current probe	voltage probe	iron filings

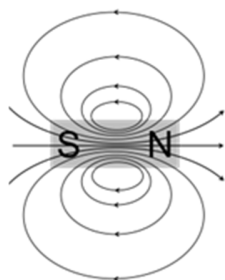
**CAUTION:** The cow magnets (the cylindrical bar magnets with the rounded ends) are quite strong. Keep them away from any hard drives, credit cards, or other magnetic media.

### Introduction

Like Electric fields, magnetic fields are often illustrated with lines. The density of these lines reflects the magnitude of the field at any point. Unlike electric fields, these lines always come in closed loops, a consequence of Gauss' Law for Magnetism<sup>††††††</sup>:

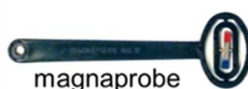
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<sup>††††††</sup> In the modern convention, **B** is the standard algebraic symbol for magnetic field because *that* makes perfect sense. We used to use **H** for magnetic field, but not anymore 'cause that's just silly.



$$\oint_{\text{surface}} \vec{B} \cdot d\vec{S} = 0 \quad (1)$$

By convention, the magnetic field lines of a bar magnet run from the north pole to the south pole outside the magnet. Inside the magnet, the loop is completed from south to north. A secondary magnet will tend to align along these field lines.



Play with the cow magnets and note the forces between them.

**Note:** Throughout this lab, red indicates the North pole of a magnet.

### Exercise 1: Mapping fields

1. Place a bar magnet in the middle of Figure 1. Using the Magnaprobe, indicate the **direction** of the magnetic field with **a short arrow at each dot**. Which end of the Magnaprobe points in the direction of the field of the larger magnet?
2. We can also visualize the magnetic field with iron filings.
  - a. Shake the filing container so the filings are scattered across the bottom.
  - b. Then place the container over the magnet, and tap the top of the container several times until a clear pattern appears. Verify that the direction of the field lines match the arrows drawn above.

3. Then, place two cow magnets end to end with opposite poles facing each other. Note the force between them. Using the iron filings, observe the field pattern and sketch the result.



4. Place two cow magnets end to end with like poles facing each other. Note the force between them. Using the iron filings, observe the field pattern and sketch the result.



## Magnetic Circuits

The energy of a magnetic field is reduced inside of ferrous metals (such as iron and nickel). Or to put it another way, given the option of going through air or a ferrous metal, Magnetic field lines *prefer* to go through ferrous metal. This is analogous<sup>\*\*\*\*\*</sup> to a current *preferring* to go through a low resistance material over a high resistance material.

1. Attach two iron bars along each side of a bar magnet, then observe the field with the iron filings. Describe how this compares to the isolated magnet. Apply the concept of magnetic circuits to explain the difference.
2. Attach one end of a cow magnet to one end of a steel bar. Then, use the steel rod to pick up some paper clips.
3. Remove the magnet. What happens to the paper clips?

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<sup>\*\*\*\*\*</sup> It's a weak analogy; so, don't read too much into it.

Using the Magnaprobe, indicate the direction of the magnetic field at each dot with a short arrow.

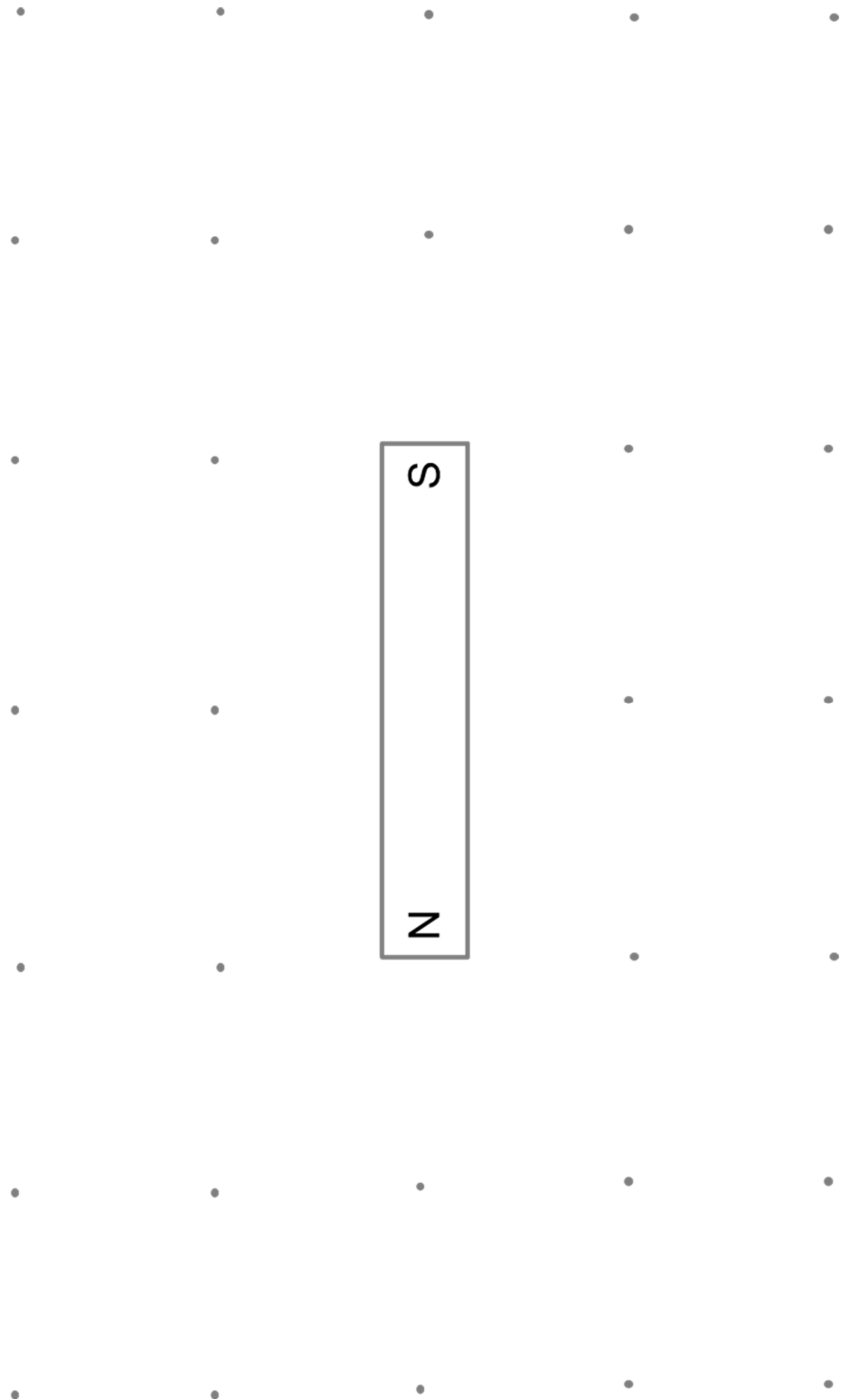


Figure 1

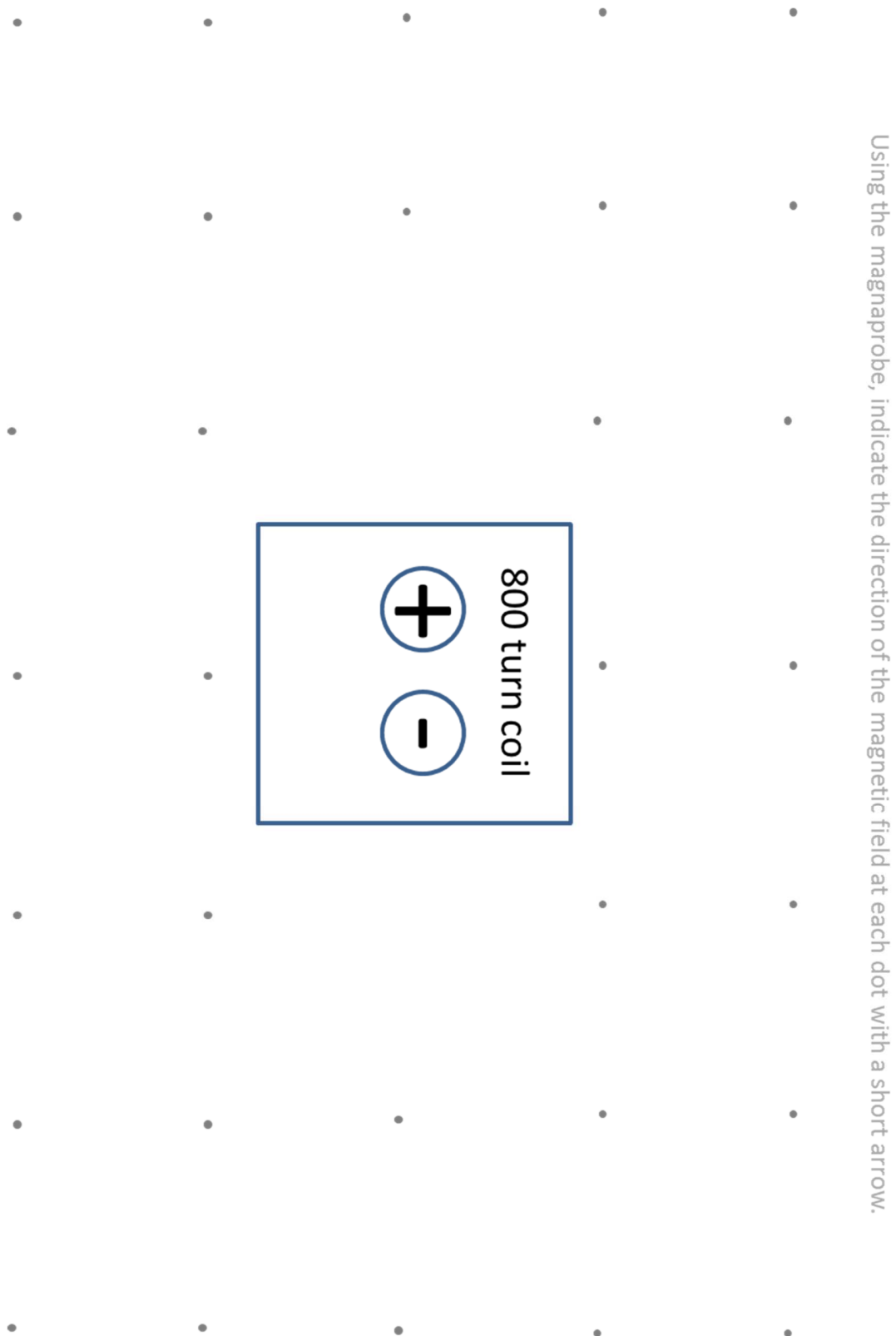


Figure 2

4. Place the attached magnet and steel bar on a white sheet of paper. Using the iron filings, observe the field pattern around the nail. Sketch the result below.
  
  
  
  
  
  
  
  
  
  
5. Remove the cow magnet and sketch field surrounding the isolated steel bar. Explain the temporary magnetization of the bar in terms of magnetic circuits.

### Exercise 2: Creating magnetic fields

A current carrying wire will be ringed by a magnetic field. The direction of the magnetic field can be determined by the right hand rule. (See Figure 3A)

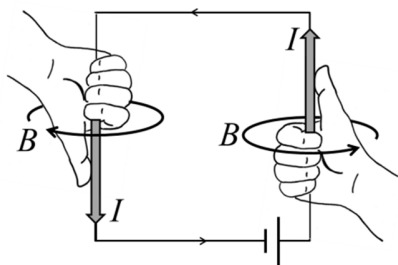


Figure 3 A

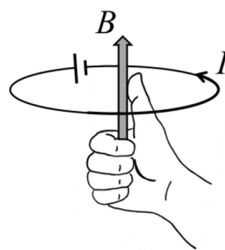


Figure 3 B

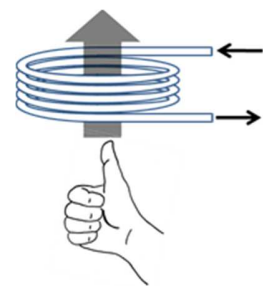


Figure 3 C

Alternatively, you can think of the loop of current. With your right hand, wrap your fingers in the direction of the current. Your thumb points in the direction of the magnetic field in the center of the loop.

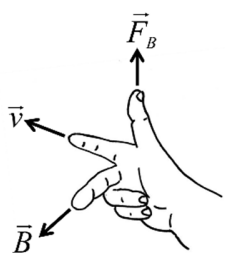
For reasonable currents (less than 1 Amp), the magnetic field is fairly weak. But the field can easily be amplified by looping the wire multiple times.

1. Note the direction of the in which the coil was wound. With the connectors facing up, place the 800 turn coil in the center of Figure 2
2. With the power supply set to 3V, connect the coil to the supply.
3. Using the Magnaprobe, indicate the direction of the magnetic field at each dot with a short arrow.
4. Verify that the right hand rule correctly describes the field direction. How does the field of the coil compare to the field of the bar magnet? On the diagram, note which side of the coil corresponds to the N pole.

### Exercise 3: Magnetic forces on charges

#### *Part 1: Applying a force to produce a current*

A magnetic field exerts no force on a stationary charge. If the charge is moving, the force is



$$\vec{F}_B = q\vec{v} \times \vec{B}$$

(2)

The direction of this force is determined by the *Right Hand Rule*.

5. Open the Capstone file Magnetism. Select the page Current Oscilloscope.
6. Connect a single cable across the inputs of the current probe.

A conducting wire is basically a pipe filled with gas of electrons. We can give these electrons a velocity by physically moving the wire.



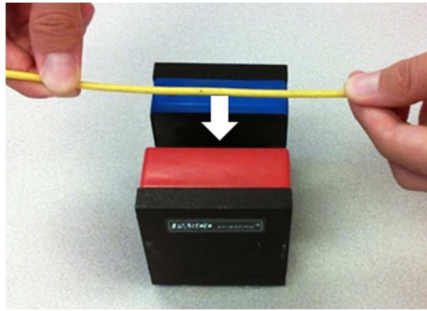


Figure 4 A

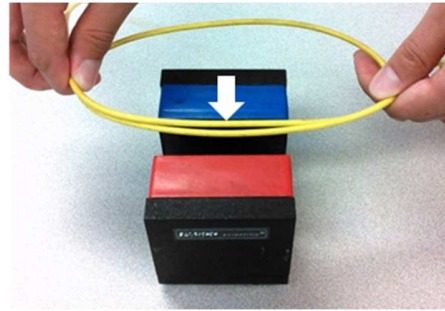


Figure 4 B

7. Quickly move the wire down between the poles of the large magnet. (See the Figure 4 A above.) Using the right hand rule, determine . . .
  - a. . . the direction of the force on the electrons? (Label the figure.)
  - b. . . the direction of the resulting current? (Label the figure.)
8. Is this consistent with the results from the current probe?
9. Quickly remove the wire. What happens to the current?
10. Repeat while moving the wire more and less quickly. Describe the results.
11. Add a loop to the wire and repeat the experiment. (See Figure 4 B above.)
12. Add a third loop to the wire. Describe the results.

### Part 2: Applying a current to produce a force

Consider the magnetic force on a tiny charge. §§§§§§§§

$$\begin{aligned}
 d\vec{F}_B &= dq \vec{v} \times \vec{B} \\
 &= dq \frac{d\vec{x}}{dt} \times \vec{B} \\
 &= \frac{dq}{dt} d\vec{x} \times \vec{B} \\
 &= I d\vec{x} \times \vec{B}
 \end{aligned}
 \tag{3}$$

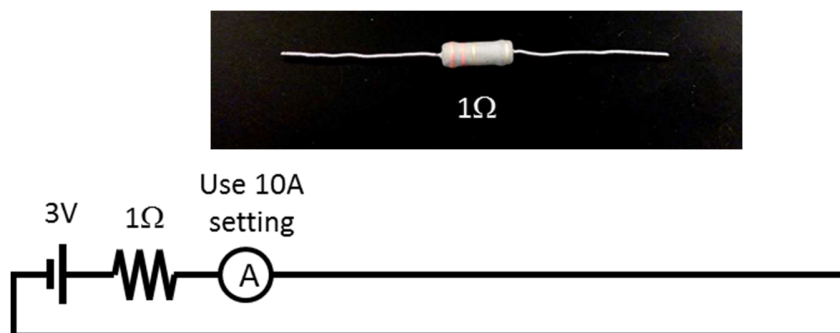
Here,  $d\vec{x}$  is a tiny segment of the current carrying wire inside a magnetic field. Integrating, we get

$$\vec{F}_B = I \vec{L} \times \vec{B} \tag{4}$$

where  $\vec{L}$  is the length of wire inside the magnetic field.

13. Turn on the digital mass balance.
14. Place the large magnet on the balance, then zero the display.
15. Using the long patch cable and the  $1\Omega$  resistor, construct the circuit below.

**Caution!!** The  $1\Omega$  resistor will get hot!

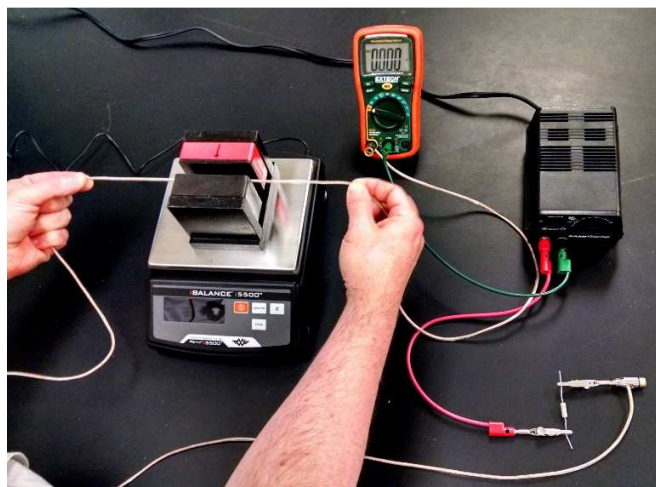


16. Holding the wire inside the magnet, measure the force on the magnet. (See the figure below.)  
Verify that the direction of the force is consistent with the right hand rule.

**Note:** The balance will measure the “force” in grams.  
You must convert this to Newtons.

---

§§§§§§§§ No, don't roll your eyes!! Follow through and learn how to do differential algebra. It's actually pretty easy.



17. Reverse the current and measure the force again.
18. Loop the wire three times and measure the force again.
19. Using Equ. (4), calculate the average magnetic field inside the magnet.

Table 1

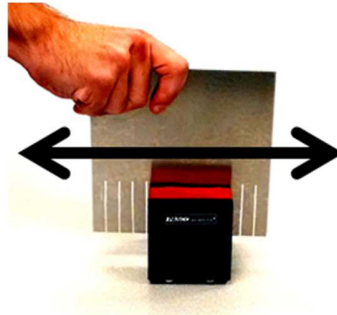
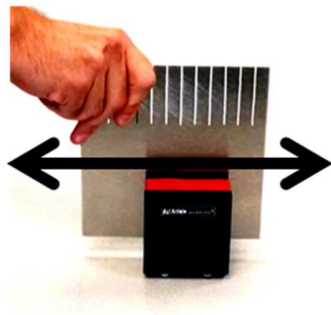
Turn Count	Magnetic Force (N)	Magnetic Field (T)
1		
-1		
3		

#### Exercise 4: Magnetic Damping

So, a magnetic force can create a current, and a current creates a magnetic force. But it's not either / or. Both are happening at the same time. This exercise will illustrate this.

20. Move the aluminum plate back and forth, and in and out of the magnet. Describe the effect on both the solid side and the cut side of the plate. (See figure below.) Then explain the results in terms of the underlying physics.

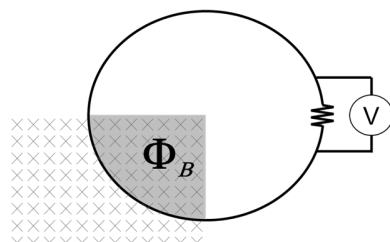
**Hint:** Think of the electrons as a fluid which is free to move inside the plate.  
How will this fluid flow when the plate is pulled through the magnetic field?  
Make a sketch of this motion.



### Exercise 4: Magnetic flux and Faraday's Law

The current generation you observed above can also be understood in terms of magnetic flux and Faraday's Law.

Magnetic flux is defined as



$$\Phi_B \equiv \oint_{\text{area of loop}} \vec{B} \cdot d\vec{A} \quad (5)$$

As the loop of wire moves between the poles, the magnetic flux through the loop increases.

Faraday's Law relates the changing magnetic flux  $\Phi_B$  to the voltage <sup>\*\*\*\*\*</sup>  $V_{\text{coil}}$  across the coil of wire

$$V_{\text{coil}} = -N \frac{d\Phi_B}{dt}, \quad (6)$$

where,  $N$  is the number of turns in the coil.

Applying Faraday's law is equivalent to applying Equation (2); however, it involves an important change in perspective. Equation (2) makes you think about the interaction of the magnetic field with the periphery of the coil. Faraday's Law makes you think about the interaction of the magnetic field with the coil as a whole.

Figuring out the current direction using Equation (2) can be awkward. Often it is easier to apply *Lenz's Law*. When the magnetic flux in a coil changes, the induced current will create its own magnetic field.

#### Lenz's Law:

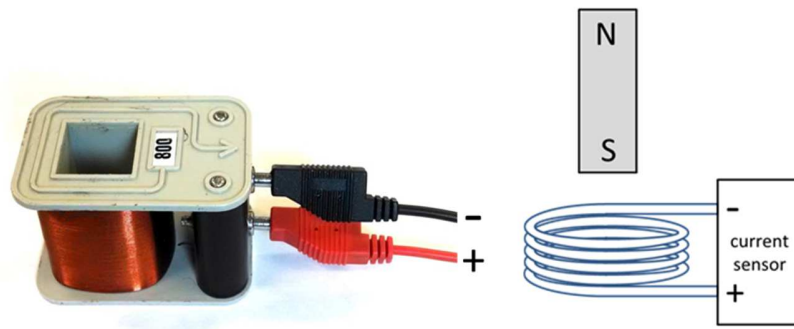
*The induced current will try to keep the magnetic flux through the coil from changing.*

If pushing a coil into a magnetic field causes the flux to increase, the current in the coil will flow to create its own magnetic field in the opposite direction.

21. Connect the 800 turn coil to the current sensor. (See the figure below.)
22. Return to the Current Oscilloscope.

---

\*\*\*\*\* This voltage is also called the *electromotive force* or *EMF*. This is a **terrible** term and should be banned from your vocabulary! The *EMF* is not a force at all!! It is an **electric potential**. It is measured in Volts, not Newtons!



23. Insert the bar magnet (S pole down) into the coil, then quickly remove it. (See the figure above.) Sketch the plot of the resulting current vs. time. Annotate the sketch to indicate insertion and removal. Is the sign of the current consistent with Lenz's Law?

24. Reverse the magnet (N pole down), and repeat the step above.







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TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 6: Inductors and RL Circuits

*Can't stop a train, can't stop a heart;  
I'm feeling pain when it's falling apart  
Can't keep the one you love from changing;  
When it's rolling, can't stop a train*

*--The Derailers*

### Objectives

Understand the behavior of an inductor as a circuit element.

Understand the analogous behavior of inductance and mass.

Understand the complementary behavior of capacitors and inductors.

### Equipment

800 turn coil	1600 turn coil	steel bar
current probe	voltage probe	multimeter
Vernier circuit board	knife switch	gaggle of wires
33 $\Omega$ resistor	~40 $\mu$ F cap	

### Introduction

Cast your mind back to your first semester of physics.

Newton's 1<sup>st</sup> Law of motion (The Law of Inertia): An object at rest tends to remain at rest. An object in motion tends to remain in motion. Mass  $m$  measures the amount of inertia of an object.

Newton's 2<sup>nd</sup> Law of motion: To change the velocity ( $v = \frac{dx}{dt}$ ) of an object, a force  $F$  must be applied. The change in velocity is inversely proportional to the mass of the object

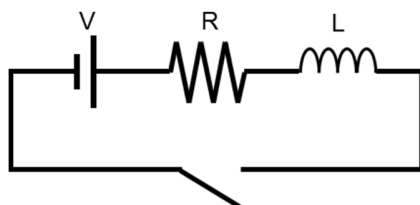
$$F = m \frac{dv}{dt}$$

*Kinetic energy* is the energy due to the motion of an object:

$$K = \frac{1}{2}mv^2$$

Now, back to the present semester.

Consider the following RL circuit: a battery, resistor, and an ideal (zero resistance) solenoid in series.



When a current  $I$  flows through a solenoid (or coil), a magnetic field surrounds the coil. This magnetic field requires energy. If the switch is suddenly closes, the *current cannot instantly start flowing* because the energy in the *magnetic field cannot be instantly delivered*. It will take some time to get the current flowing and build up the magnetic field.

So, after closing the switch, what exactly is the current in this circuit?

The voltage across an inductor is given by

$$V_L = -L \frac{dI}{dt},$$

where  $L$  is the inductance of the circuit. The voltage drop across a resistor is

$$V_R = -IR.$$

Applying Kirchhoff's rule for loops,

$$\begin{aligned} 0 &= V - V_R - V_L \\ &= V - IR - L \frac{dI}{dt} \end{aligned}$$

After a semester of Differential Equations, you could easily solve this to find that

$$I(t) = \frac{V}{R} (1 - e^{-t/\tau}),$$

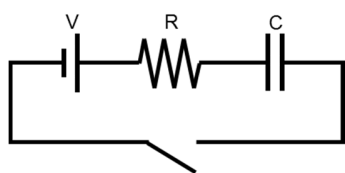
Where  $\tau$  is the time constant of the RL circuit:

$$\tau \equiv \frac{L}{R}.$$

- a. Sketch a plot of  $I(t)$ . On the plot, note the maximum current and the time constant.

This *should* look familiar. To rub your nose in it, . . .

- b. . . recall the circuit below. Sketch the corresponding plot of  $I(t)$ ; note the maximum current.



### A mechanical analogy: *Newton's Laws of Circuits.*

1<sup>st</sup> Law (The law of inertia): Charges at rest tends to remain at rest. Charges in motion tend to remain in motion. The inductance  $L$  measures the amount of inertia of the circuit.

2<sup>nd</sup> Law: To change the current ( $I = \frac{dQ}{dt}$ ) in a circuit, a voltage  $V_L$  must be applied. The change in the current is inversely proportional to the inductance of the circuit.

$$V_L = -L \frac{dI}{dt}$$

The Magnetic Potential Energy  $U$  is the energy in the magnetic field due to the current in the circuit

$$U = \frac{1}{2} LI^2$$

This inertia of inductance is another manifestation of Lenz' Law: the inertia of the solenoid *tries* to keep the magnetic field from changing. This is because **magnetic fields are *real things* and are made with *real energy***. They cannot just appear at the flip of a switch but must be built up or torn down over time.

- c. Now, you tell me: If an inductor is analogous to mass, what is a *resistor* analogous to? Justify your argument.

### Exercise 1: Real Solenoids

Real solenoids are made of long strands of wire, and real wire has resistance. So, in addition to inductance, a solenoid also acts as a resistor. A real solenoid can be modeled as an ideal solenoid ( $R=0$ ) in series with a resistor.

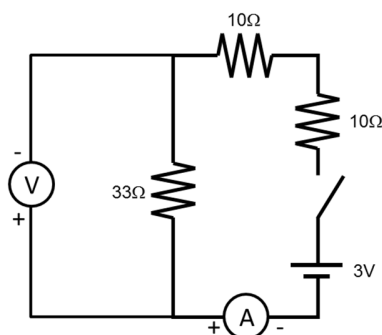


- d. With an ohmmeter, measure the resistances of your two solenoids. Record the values below.

### Exercise 2: Resistor Circuits

First, let's remind ourselves of what we know and love.

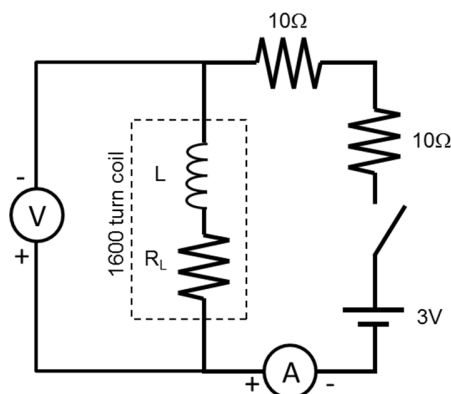
- e. Construct the following circuit. Use the knife switch to open and close the circuit. Use the PASCO current and voltage probes to monitor the current and the voltage across the coil. Make sure the polarity of the probes is set correctly.



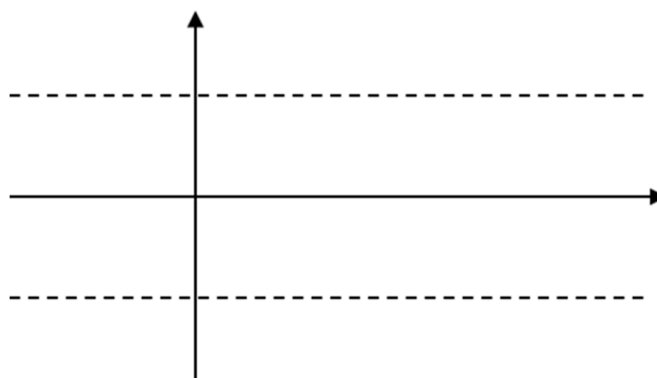
- f. Run the Capstone program Switching Circuit to monitor the voltage and current as the switch is closed and opened. When the switch is closed . . .
- . . the *current should be **positive***.
  - . . the *voltage across the resistor should be **negative***. This is to reflect the fact that voltage decreases as the current flows from one side of the resistor to the other. Adjust the voltage and current probes as necessary to reflect this.
- g. Calculate the time constant for this circuit.
- h. Adjust the time axis so that you can clearly see the onset of the current and voltage as the switch is closed. Sketch the result below.
- Note:** You can adjust the time axis by moving the cursor to the time axis and turning the scroll wheel.
- i. How does the polarity of the voltage across the  $33\Omega$  resistor compare to the polarity of the battery?

**Exercise 3: Starting up the inductor**

- j. Replace the 33W resistor with the 1600 turn coil to create the following circuit.



- k. Again, use Switching Circuit to monitor the voltage and current as the switch is closed and opened.
- l. Calculate the time constant to energize the inductor. (*Be careful with the resistance!*)
- m. Adjust the time axis so that you can clearly see the onset of the current and voltage as the switch is closed. Sketch the result below.

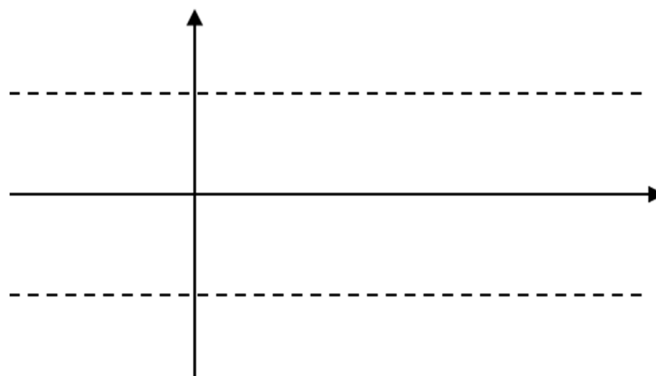


- n. How does the polarity of the inductor voltage compare to the polarity of the current after the switch is closed?

- o. How does the polarity of inductor voltage before the switch compare to the polarity of the inductor voltage after the switch?
- p. Measure the time constant for the current in the solenoid.
- q. Given the resistance of the circuit, calculate the inductance of the solenoid.

### Exercise 4: Shutting off the inductor

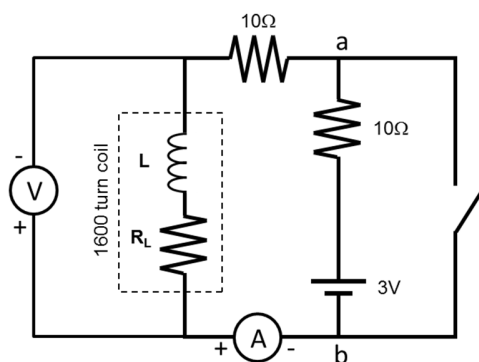
- r. Now, adjust the time axis to that you can clearly resolve the voltage and current as the switch is opened. Sketch the result below.



To anthropomorphize the situation, the inductor desperately wants the current to keep flowing (Lenz' Law), but with the switch open it literally has *nowhere* to go. So, the *voltage cannot behave in a smooth predictable way*. Instead, the voltage goes crazy for a few micro-seconds<sup>††††††††</sup>, and the physics of this response is beyond the scope of this lab.

What we need is a way to shut off the battery while still giving the current from the inductor *somewhere* to go.

- s. Create the circuit shown below.



- t. With the switch closed, what is the potential difference from a to b?

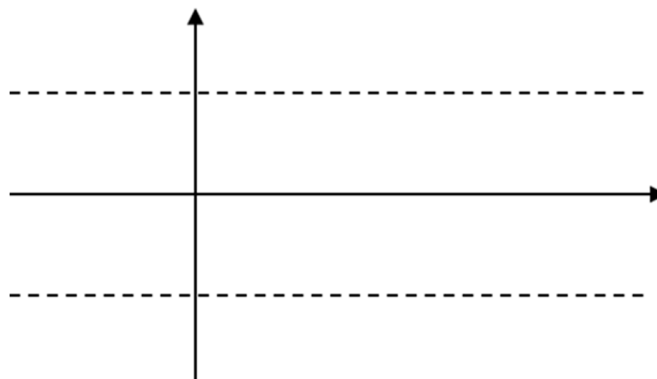
- u. With the switch closed, sketch the equivalent circuit from the perspective of the solenoid.

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†††††††† Think of Wile E. Coyote running into the painted tunnel.



- v. Using Switching Circuit, observe the current and voltage as the switch is quickly opened and closed.
- w. Calculate the time constant for de-energizing the inductor. (*Again, careful with your resistance!*)
- x. Adjust the time axis so you can clearly observe the curve as the current shuts down. Sketch the results below.



- y. How does the polarity of inductor voltage compare to the polarity of the current after the switch is closed?
- z. How does the polarity of inductor voltage before the switch compare to the polarity of the inductor voltage after the switch?

- aa. Measure the time constant for the current in the solenoid.
  
  
  
  
  
  
  
  
  
  
- bb. Given the resistance of the circuit, calculate the inductance of the solenoid.

### Exercise 5: Changing the Inductance

The inductance of a tightly wound solenoid is

$$L = \frac{\mu_0 \pi N^2 r^2}{d},$$

where  $N$  is the number of turns,  $r$  is the radius of the solenoid, and  $d$  is the length of the solenoid.

- cc. Given your measured value of  $L$  for the 1600 turn coil, what would be your expected value of  $L$  for the 800 turn coil?
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
- dd. Measure the inductance of the 800 turn coil.
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
  
- ee. Place a steel bar inside the 800 turn coil, and again measure the inductance. How does steel affect the inductance?

Name\_\_\_\_\_ Lab/Section\_\_\_\_\_ Date\_\_\_\_\_

## Pre-Lab Preparation Sheet for Lab 7: Alternating Current and Impedance (Due at the beginning of lab)

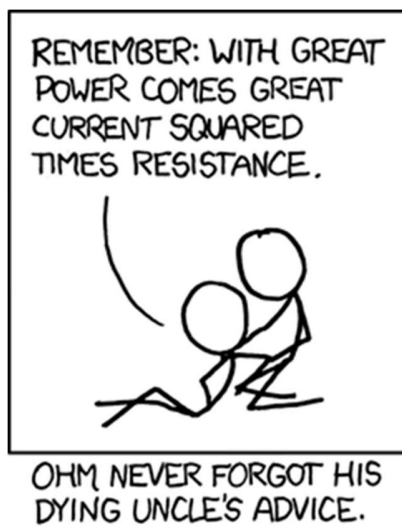
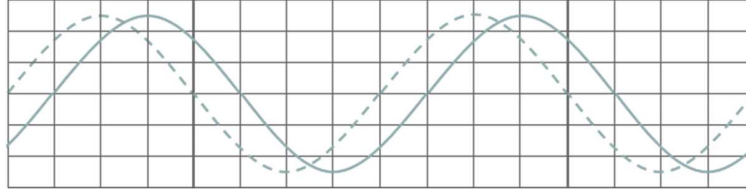
**Directions:**

Read over the lab, and then answer the following questions.

1. What distinguishes resistance and reactance?

2. What defines the resonant frequency of an LRC circuit?

3. What is the phase difference (in cycles, degrees, and radians) between the two curves illustrated below?



xkcd.com

Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
TA \_\_\_\_\_ Lab/Section \_\_\_\_\_

## Lab 7: Alternating Current and Impedance

*“Alternating (current) machines, manufactured principally in this country by George Westinghouse.”*

*--Thomas A Edison recommending an electrical generator for executing condemned prisoners by “electrocide”*

### Objectives

To develop a basic understanding of *Resistance*, *Reactance*, and *Impedance*

To observe and understand resonance in an electric circuit.

### Equipment:

800 and 1600 turn coils  
~40  $\mu\text{F}$  capacitor  
Vernier circuit board  
A steel rod and an aluminum rod  
Multimeter  
6 banana cables + 2 alligator clips

### Introduction

In the first few labs, you learned that *resistance* is the “*thing*” that restricts the flow of current. But resistance only applies to resistors. For capacitors and inductors, there is something else that can restrict the flow of current: *reactance*. You received a taste of this over the last couple of labs as you observed the changing current in capacitors and inductors. Now, we will go into more detail.

First, a few definitions:

For an AC voltage, the voltage is constantly changing, usually in a sinusoidal pattern:

$$V(t) = V_0 \cos(\omega t) \quad (1)$$

where  $\omega$  is the angular frequency,

$$\omega = 2\pi f \quad (2)$$

The circuit symbol for sinusoidal (AC) voltage source is .

Likewise for an AC current, except that there may be a phase difference  $\phi$  from the applied voltage:

$$I = I_0 \cos(\omega t + \phi) \quad (3)$$

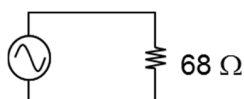
The instantaneous power drawn by a circuit element is the instantaneous voltage across the device times the instantaneous current

$$P = IV \quad (4)$$

## Resistance

First, we will look at the simplest case.

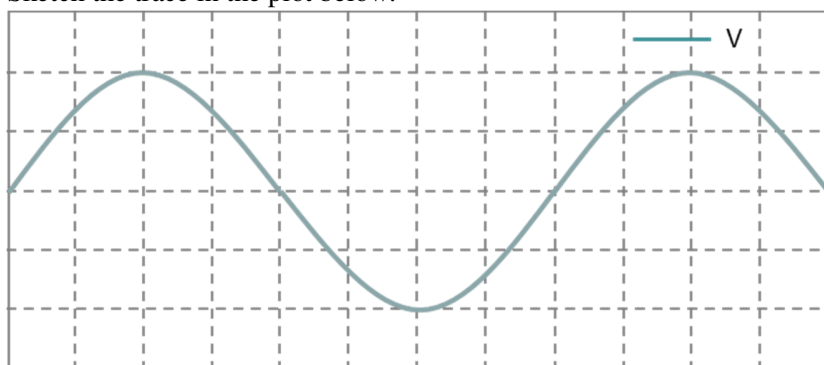
1. Using the OUTPUT of the PASCO interface as an AC voltage supply, assemble the following circuit.



2. Run the Capstone program IVscope. Click the Monitor button (lower left corner of the window). From the Output window, you can control the frequency and amplitude of the AC voltage.

The Capstone software is now acting as an oscilloscope observing the voltage and current in the circuit in real time.

3. Adjust the frequency and amplitude of the OUTPUT and observe the effect.
  - a. Sketch the trace in the plot below.



- b. Are the current and voltage in phase with each other?
  - c. Does the circuit obey Ohm's Law?

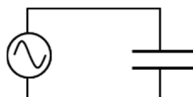
4. Set the amplitude of the voltage to 1 V.
  - a. What is the *maximum* power consumed by the circuit? What is the *minimum* power consumed? Does this vary with the frequency?
5. From the tabs at the top, select Page #2: Voltage, Current, and Power. Click Record to view a trace. Now, in addition to the I and V traces, you should see a trace for the power.

Note: In this mode, Capstone is not running continuously. With any change in settings, you must click Record to refresh the display.

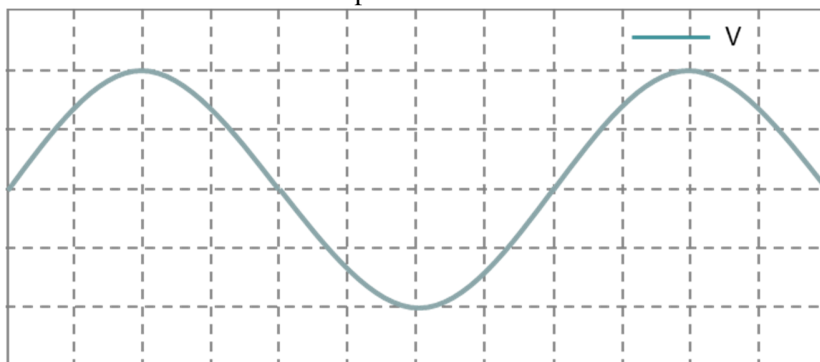
Verify your above answers. How does the frequency of the power compare to the frequency of the voltage?

### Capacitance

1. Return to the Oscilloscope tab.
2. With your multimeter, measure the value of the capacitor.
3. Lower the frequency to 100 Hz and set the voltage amplitude to 1 V. Replace the resistor with the capacitor.



4. Turn the Output back on, and Monitor the signal.
5. Sketch the current trace in the plot below.



6. Steadily increase the frequency to 500 Hz and observe the response.
  - a. How does the amplitude of the current vary with frequency?

- b. What is the phase difference between the voltage and current?

Even though there are no resistors in the circuit, the current does not flow freely.\*\*\*\*\* For capacitors, the current is not limited by the resistance, but by the *reactance*  $X_C$ .

$$X \equiv \frac{V_{\max}}{90^\circ \text{ out of phase component of } I_{\max}} \quad (5)$$

Note that reactance has the same units as resistance  $\left( \frac{\text{Volts}}{\text{Ampere}} = \text{Ohms } \Omega \right)$ , but it is NOT resistance. **The phase shift of the current is the signature of a reactive circuit.**

7. With the amplitude of the voltage set at 1V, measure the **current amplitude** and calculate the **reactance** from 100 Hz to 500 Hz at 50 Hz intervals.
8. Enter this data into an Excel spreadsheet.
9. From Page #2: Voltage, Current, and Power, observe the power consumption of the circuit.
  - a. At a fixed frequency, how do the maximum and minimum power consumption compare?

- b. What is the *average* power consumption?

- c. What does the changing sign mean?

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\*\*\*\*\* Well, this is not quite true. The capacitor does have some internal resistance, but it is quite small and can be ignored.



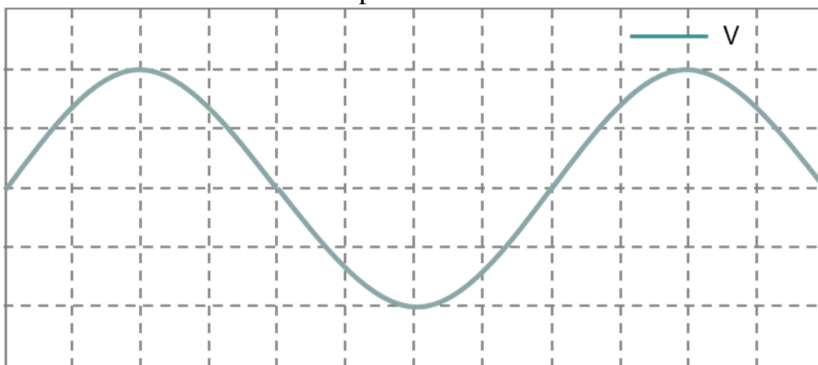
**Inductance**

Consider the circuit below

10. Replace the capacitor with the 800 turn coil. Set the frequency to 500 Hz.



11. Sketch the current trace on the plot below.



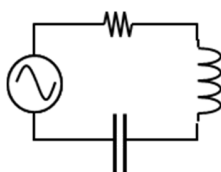
12. What is the phase shift between the applied voltage and the current? How does the direction of the phase shift compare to the phase shift of the capacitor?

13. How does this power trace compare with the power trace of the capacitor?

As with capacitors, inductors also exhibit a reactance  $X_L$ . Of course, as you have noticed in the past, the coils also exhibit a non-trivial amount of resistance, and this causes the average power consumption that you observed. But let's set that aside for the time being.

14. With the amplitude of the voltage set at 1 V, measure the current amplitude and calculate the reactance of the inductor from 100 Hz to 500 Hz at 50 Hz intervals.
15. Add this data to the Excel spreadsheet.
16. How does the power trace vary with frequency?

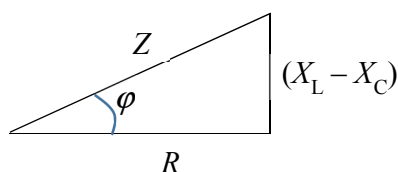
### Impedance



For a circuit containing both resistive and reactive elements, the net effect is called *impedance*. For an LRC (inductor, resistor, capacitor) circuit, the impedance  $Z$  is given by

$$Z = \frac{V_{\max}}{I_{\max}} = \sqrt{R^2 + (X_L - X_C)^2} \quad (6)$$

This can be illustrated graphically.



Here,  $\phi$  is the phase between the voltage and current.

1. With the multimeter, measure the resistance of the coil.

R = \_\_\_\_\_

2. Assemble the coil and capacitor in series with the OUTPUT of the PASCO interface. **Do not include the resistor.** For this LRC circuit, the resistance will be the inherent resistance of the components.

3. With the amplitude of the voltage set at 1V, measure the phase shift  $\phi$  and current amplitude and calculate the impedance  $Z$  for the following frequencies. Then add this data to the table on Page #3. Print out the resulting plot
4. With the amplitude of the voltage set at 1V, measure the **current amplitude** and calculate the **reactance**  $Z$  and **phase shift**  $\phi$  from 100 Hz to 500 Hz at 50 Hz intervals.
5. Add this data into the Excel spreadsheet.
6. Using the oscilloscope (Page #1), finely adjust the frequency to locate the resonant frequency to within 1 Hz. (That is, the frequency with the maximum current.) Explain this resonance in terms of Equ. (6) and your plot on Page #3.

$f_0$  (800 turns, capacitor) = \_\_\_\_\_

7. What is the phase angle  $\phi$  at resonance?
8. What is the impedance at resonance? What circuit element is largely responsible for this minimum impedance? Explain.
9. When is the average power consumption maximized?

### Tunable Circuits

It can be shown that the resonant frequency of a circuit is

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}} \quad (7)$$

1. Replace the capacitor with the 10  $\mu\text{F}$  capacitor (C1) on the Vernier board. With the oscilloscope on Page #1, measure the resonant frequency and the inductance.

$f_0$  (800 turns, 10  $\mu\text{F}$ ) = \_\_\_\_\_  $L$ (800 turns)=\_\_\_\_\_

2. Replace the 800 turn coil with a 1600 coil. Measure the resonant frequency and inductance.

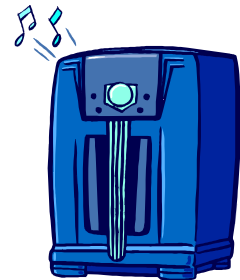
$f_0$  (1600 turns, 10  $\mu\text{F}$ ) = \_\_\_\_\_  $L$ (1600 turns)=\_\_\_\_\_

3. Move a steel rod (in this case the socket wrench) inside the coil while watching the oscilloscope.
  - a. What happened to the resonant frequency?

- b. What happened to the inductance?

- c. Move an aluminum rod inside the coil while watching the oscilloscope. Speculate on the difference.

- d. How does the tuning circuit of an old fashioned radio work? When you rotate the tuning knob of an antique Zenith set, what are you mechanically doing?§§§§§§§§



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§§§§§§§§ “Be sure to drink your Ovaltine™!”

Name\_\_\_\_\_ Section\_\_\_\_\_ Date\_\_\_\_\_

**Pre-Lab Preparation Sheet for Lab 8:**  
**Geometric Optics – Reflection and Refraction**  
(DUE AT THE BEGINNING OF LAB)

Watch the following video,

<https://www.youtube.com/watch?v=FOWDgpKTqdY>

Then read over Lab 8, and answer the following questions.

1. The refractive index of titanium dioxide (aka white pigment) is 2.614, one of the largest of any material. What is the speed of light in  $\text{TiO}_2$  ?
2. What is the critical angle for  $\text{TiO}_2$  ?
3. Define dispersion.





Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_

TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 8: Geometric Optics – Reflection and Refraction

*All that is now  
All that is gone  
All that's to come  
and everything under the sun is in tune  
but the sun is eclipsed by the moon.*

--Pink Floyd, Dark Side of the Moon

### Objectives

To understand Snell's law, reflection, refraction, and total internal reflection

### Equipment

2 equilateral prisms	1 right angle glass prism
1 right angle acrylic prism	Light box
Clear plastic cup half filled	Aluminum block
Protractor and ruler	Paper towels
1 retroreflector	

### Introduction

Waves may travel at different speeds in different media. When a wave travels from one medium into another with different wave speeds, two things will occur:

1. Part of the wave will *reflect* off the interface. The reflected angle is equal to the incident angle.

$$\theta_i = \theta_r \quad (8)$$

2. Part of the wave will transmit into the 2<sup>nd</sup> medium, but its direction of travel will be bent or *refracted*. The angle of the transmitted wave is given by Snell's Law

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{v_i}{v_t}, \quad (9)$$

where  $v_i$  and  $v_t$  are the speeds of the incident and transmitted waves.

This is true of all waves: sound waves, light waves, tsunamis, . . . *any kind of wave*.

When dealing with light waves, we define a value called the *index of refraction*:

$$n \equiv \frac{c}{v}, \quad (10)$$

Where  $v$  is the velocity of light in a particular material, and  $c$  is the velocity of light in a vacuum

$\left(2.998 \times 10^8 \frac{m}{s}\right)$ . Hence, we can write Snell's Law as

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_t}{n_i} \quad (11)$$

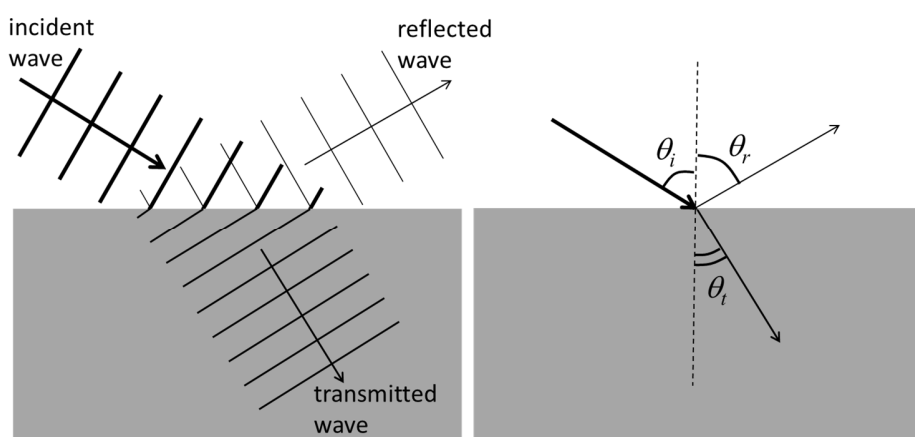


Figure 1

### Exercise 1: Reflection and Refraction

1. Place the semi-circle of acrylic on the printed protractor. Adjust the light box so that a single beam of light is produced. Shine the beam on the center of the flat surface with the incident angle  $\theta_i$  (listed in Table 1A) and measure the corresponding reflected  $\theta_r$  and transmitted  $\theta_t$  angles. (See Figure 2.) Fill in Table 1A below.
2. Next, reverse the semi-circle as illustrated in Figure 2B. Again, Measure the angles and fill in Table 1B below.

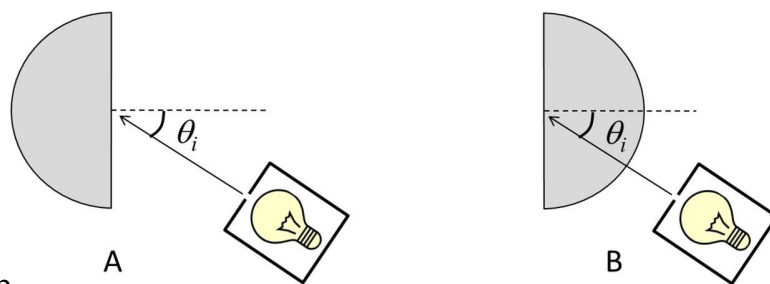


Figure 2

3. Using Excel, plot the refracted angle as a function of the transmitted angle.
4. Assuming that the speed of light in air is  $c$ , what is the index of refraction of acrylic?
5. You will notice that light may be bent toward the normal or away from the normal. (See the figure below.) What determines the direction?

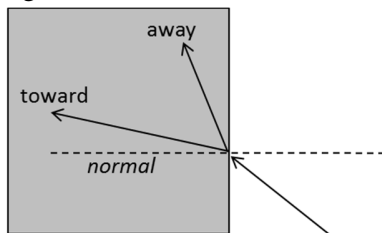


Figure 3

For some of your measurements, there was no transmitted light beyond a particular angle. Instead, all of the light is reflected off the interface. This condition is called *total internal reflection*. The minimum angle at which this occurs is called the *critical angle*  $\theta_c$ .

6. Carefully measure the critical angle of acrylic.
7. What are the required conditions for total internal reflection? Explain in English and derive an expression for  $\theta_c$ .

$\theta_i$	$\theta_r$	$\theta_t$	$\frac{\sin(\theta_i)}{\sin(\theta_t)}$
0°			
10°			
20°			
30°			
40°			
50°			
60°			
70°			
80°			

Table 1A: Air to Acrylic

$\theta_i$	$\theta_r$	$\theta_t$	$\frac{\sin(\theta_i)}{\sin(\theta_t)}$
0°			
10°			
20°			
30°			
40°			
50°			
60°			
70°			
80°			

Table 1B: Acrylic to Air

**Exercise 2: A glass of water**

You should find a clear plastic cup on the table. The bottom of the cup is painted white.

8. Fill half with water, and place it on the black surface of the table.
9. Looking straight down into the cup, observe the reflections on the side.
10. Place a dry finger against the side of the cup and observe the effect on the reflection.
11. Place a wet finger against the side of the cup and observe the effect on the reflection.
12. Describe and explain your observations.

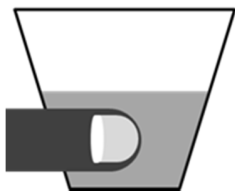


Figure 4

### Exercise 3: Right Angle Prism and Retro-reflectors

13. Arrange the right angle glass prism with the beam as shown below. Describe and explain your observation. What is the minimum index of refraction for the prism to act as a  $45^\circ$  mirror?

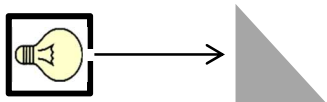
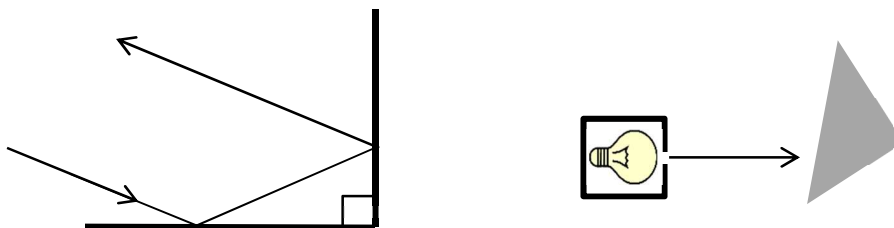


Figure 5

14. Consider the figure below. A beam of light is incident on two mirrors at right angles to each other. With high school geometry, prove that the incident beam is parallel to the outgoing beam. Then, verify this experimentally. \*\*\*\*\*

Figure 6



15. Look at the prism as shown below. Slightly rotate the prism while observing the reflection of your eye. Describe and explain your observation.



Figure 7

---

\*\*\*\*\* This is called a retro-reflector. (The taillights covers of your car use this principle.)

16. While looking at the reflection of your eye in the prism, lower the prism into the water. (See the figure below.) Describe and explain your observation.

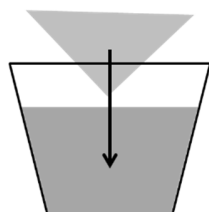
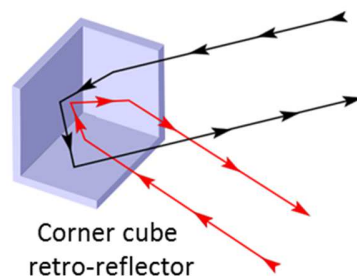


Figure 8

A right angle prism forms a simple type of retro-reflector. A light ray striking a retro-reflector is reflected back along the same direction it came. It happens, that a corner cube mirror acts as a retro-reflector for a light ray coming from any direction, not just the plane. (See the figure below.) This is how a bicycle reflector or a tail-light reflector works.

17. Observe the texture of surface of the bicycle reflector.  
Observe how it reflects light at different angles.
18. For a retroreflector to work properly, what optical properties must it have?



**Exercise 4: Dispersion**

19. Using Google, study the cover art for Pink Floyd's *The Dark Side of the Moon*. Then, attempt to reproduce it with an equilateral prism. †††††††† Which color is bent the most? The least?
20. What does this imply about the speed of light and the index of refraction of the different colors in glass?

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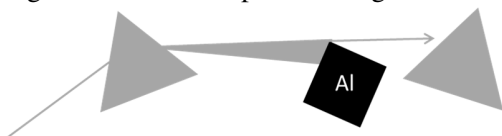
†††††††† This is best done while humming *The Great Gig in the Sky*.



21. Using a 2<sup>nd</sup> prism, can you recombine the colors? Can you separate them more? Using colored pencils, diagram your results.

22. Position the aluminum block after the 1<sup>st</sup> prism so that only red light can pass. Then send the single color through the 2<sup>nd</sup> prism. Does the 2<sup>nd</sup> prism have any effect on the color or dispersion of the red beam? How about blue light?

Again, with colored pencils, diagram the result.



Name \_\_\_\_\_ Section \_\_\_\_\_ Date \_\_\_\_\_

## Pre-Lab Preparation Sheet for Lab 9: Geometric Optics - Lenses (Due at the beginning of lab)

1. Explain the Thin Lens Approximation.
2. What is the approximate focal length (order of magnitude) of your eye? (Just look at your eyeball and think about it.)
3. Light rays coming from an object are observed to be parallel. What does this imply about the distance to the object?



Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
 TA \_\_\_\_\_ Section \_\_\_\_\_

## Lab 9: Geometric Optics – Lenses

*"... it is not yet twenty years since there was found the art of making eyeglasses which make for good vision, one of the best arts and most necessary that the world has."*

*--Giordano da Rivalto of St. Catherine's Monastery, 1306*

### Objectives:

To understand the basic properties of lenses: focal length and aperture.

To apply the rules of ray optics to understand imaging and the effects of combining lenses.

### Equipment

Mounted Lenses: 20 cm, 10 cm, -15 cm

Unmounted Lenses: 20 cm, 4 cm

Optical track

Screen

Light box with power supply

Aperture card

Meter stick and ruler

### Introduction

With geometric optics, we treat light as rays which travel in straight lines until they . . .

- reflect off a surface (angle of reflection = angle of incidence), or
- refract at an interface (Snell's Law).<sup>\*\*\*\*\*</sup>

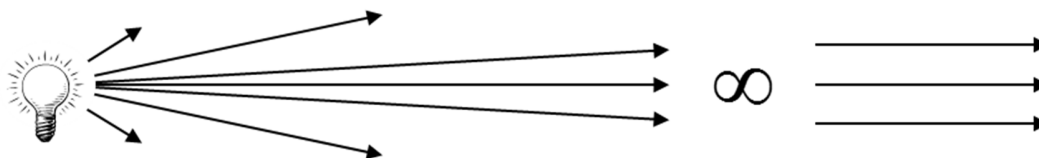
The wave-like properties of interference and diffraction are ignored. This is equivalent to saying that your optical elements (mirrors, lenses, apertures<sup>§§§§§§§§§§</sup>, etc.) are much larger than the wavelength of light.

---

<sup>\*\*\*\*\*</sup> In principle, you could design a telescope with nothing but a straight edge, a protractor, and a *really* sharp pencil.

<sup>§§§§§§§§§§</sup> An aperture is the opening through which light can pass.

As light rays move further from a point source, they diverge from their neighboring rays. However, at large distances the rays diverge slowly, and they become more parallel. As the range approaches infinity, the rays become perfectly parallel.



With a lens, we can modify the direction of these rays to create one of two devices

1. A camera.
2. An eyepiece (such as a magnifying glass).

### Focal Length

Consider Figure 1 below. A set of parallel beams are bent in different directions depending on the incident angle of the glass.

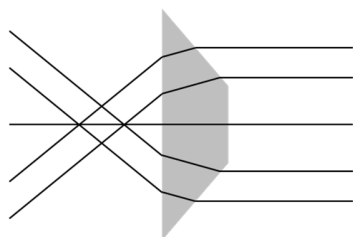


Fig. 1

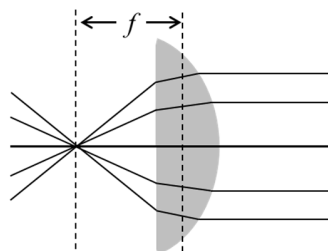
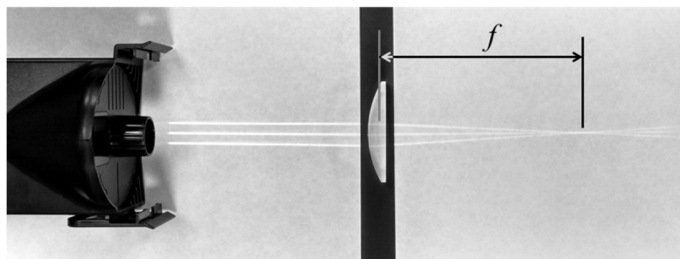


Fig. 2

The distance from the lens to the focal point of the parallel rays is the **focal length  $f$**  of the lens.

### Exercise 1: Focal length

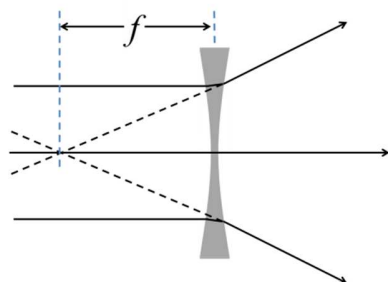


- a. Adjust the light box to produce three slits of light. Send the beams through one of your 2D lenses and measure the focal length.
- b. Reverse the direction the lens faces and measure the resulting focal length. Does this significantly affect the result?
- c. Place the other 2D lens beside the first and measure the focal length of the combined lenses.



A **concave** (or **negative**) **lens** diverges the light rays. We measure the focal length of such lenses by tracing the rays backward to the point where they appear to come to a focus. We define such a focal length to be negative.

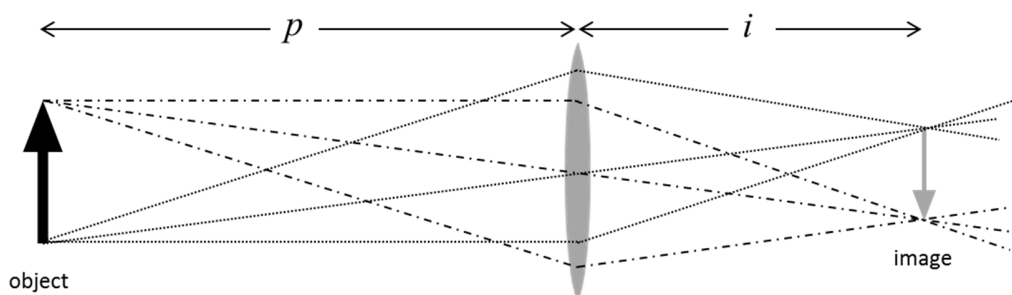
d. Measure the focal length of the concave lens.



**Note:** Throughout this lab, we will apply the **thin lens approximation**: *The thickness of the lens is much less than the focal length.* Most of the errors you will find in your calculations arise from the shortcomings of this approximation.

## Imaging

A focused image is formed when light rays from each point on an object converge at a corresponding point on the image. This is called a **real image**, as the light rays *really* do converge at a point in space.



Note in the middle of the lens, the glass is flat. Hence, rays passing through the center of the lens are not deflected. The position of the object and image are given by the *Lens Maker's Equation*:

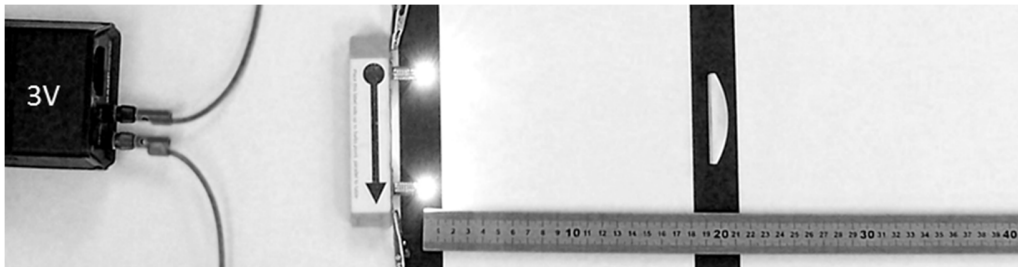
$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad (1)$$

Suppose the object were very far away. What would be the image distance?

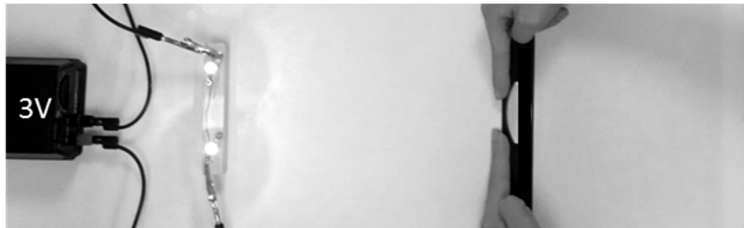


**Exercise 2: 2-D Imaging**

1. Assemble one lens with the object (2 light bulbs on a stick) as illustrated below.



2. Locate the position of the image formed by the lens. Measure the object and image distances. Why is the image distance not equal to the focal length of the lens?
3. With the lens maker's equation, calculate the focal length of the lens. How does this compare with the measured focal length?
4. Suppose the object was very far away. What would be the image distance?



5. With your hands, form an aperture to partially block the light passing through the lens, as in the photo above. Move your hands back and forth to change the position of the aperture. How does this affect the image?
  
6. Adjust the object distance to 20 cm. What happens to the image distance?
  
  
  
  
  
  
  
7. Steadily move the lens toward the object. At what object-lens distance is a real image not formed?

**Exercise 3: 3D Imaging**

You will first image a “distant” object.

8. Attach the screen and the 10 cm lens to the track.



9. Project an image of *your neighbor's computer screen* on the opposite side of the lab. Describe the orientation of the image.

10. Measure the image distance and the size of the image.

11. How does the image distance compare to the focal length? Explain.

12. Replace the lens with the 20 cm lens.

13. Measure the image distance and size. How does the size of the image scale with focal length?

14. Replace the lens with the -15 cm lens. Describe and explain your observations.

Now, you will image a nearby object.

15. Assemble the object (light box), 20 cm lens, and screen on the track as shown below.



16. Measure the object  $p$  and image  $i$  distances and calculate the focal length  $f$ . Enter the data onto Table 1 below.
17. Calculate the magnification  $\left( M \equiv \frac{\text{image height}}{\text{object height}} \right)$  of the object and record the result in the table. Mathematically, how does the magnification relate to  $p$  and  $i$  found above?
18. Moving the lens, locate another point on the track where a focused image is formed. Again, record the results in the table. How do the image and object distances for this case relate to the previous focal position?

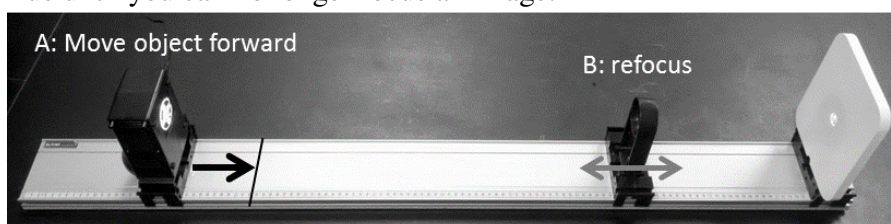
Table 1: 20 cm lens, fixed object

	$p$	$i$	$M$
Position 1			
Position 2			

**Exercise 4: Changing the object distance**

Continue using the 20 cm lens.

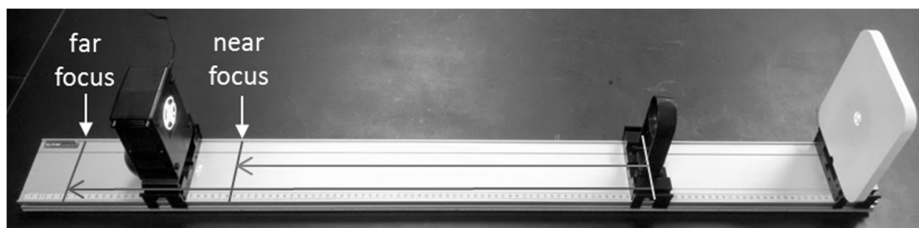
19. In approximately 5 cm increments, move the object forward, refocus, and record  $p$  and  $i$ . Continue until you can no longer focus an image.



20. Find the closest possible screen/object distance and record the result.
21. Create a scatter plot from the data points and print the result. Include all image distances from the **very distant object** (your neighbor's screen) to the **closest possible focus**. On the printout, annotate the plot noting the extremes of distant and close imaging. How far have you moved the lens?

### Exercise 5: Changing the aperture

22. Place the object 30 cm from the end of the track. With the lens relatively close to the screen, focus the image.
23. Move the object back and forth to note the range over which the object can move while remaining in focus. This range is called the *depth of field*. Record the result in Table 2 below.



24. With the aperture card (the card with the holes), cover the lens with the largest hole. Again, measure the depth of field and record the result. Repeat with the other holes.

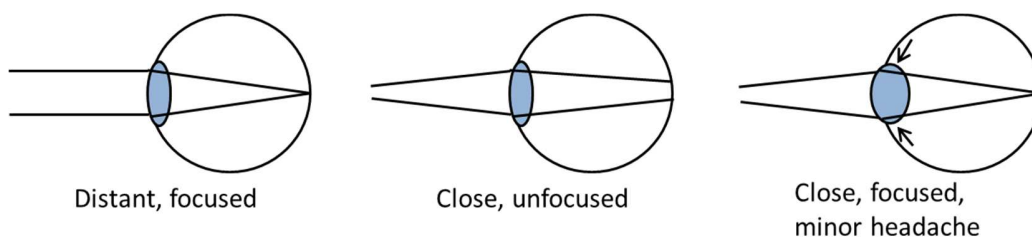
Table 2: Changing the aperture

	Near focus	Far focus	Difference
No masking			
Large aperture			
Middle aperture			
Small aperture			

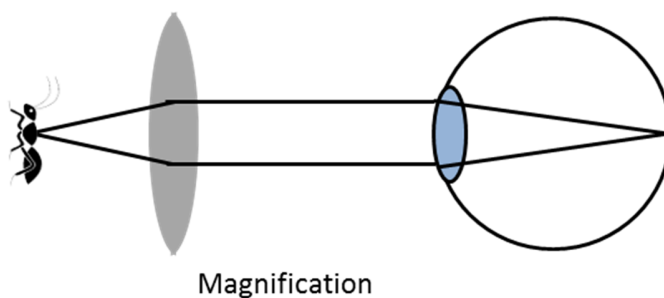
25. Now, remove the lens and form an image with just the aperture. This is a **pinhole camera**. Describe the result with the different apertures. What is the focal length of a pinhole “lens”? What is the depth of field?

**Exercise 6: The magnifying lens.**

A normal, relaxed human eye will focus on distant objects. That is, it will bring parallel light rays to a point on the retina (the back of the eyeball). To focus on close objects, muscles in the eye squeeze on the lens to shorten the focal length.



Of course, you can only squeeze your lens so much. A magnifying lens works by bending the rays from a nearby object so they are parallel. The relaxed eye can focus these parallel rays as though the object were infinitely distant.



27. Hold the 10 cm lens just in front of you eye and observe your fingerprint. How close to the object must you hold the lens?

28. Repeat with the 20 cm lens. Which lens provides more magnification? Why?



**Exercise 7: Combining lenses**

Suppose two lenses  $a$  and  $b$  are placed side by side. What is the effective focal length of the combined lenses? If the lenses are in contact and the thin lens approximation applies:

$$\frac{1}{f_{\text{effective}}} = \frac{1}{f_a} + \frac{1}{f_b} \quad (2)$$

29. Calculate the effective focal length of the combined 10 and 20 cm lenses.

30. Measure the effective focal length of these combined lenses. Draw a diagram showing your procedure.

31. Calculate then measure the effective focal length of the 10 cm lens and the -15 cm lens.

**Exercise 8: Eyeglasses**

Myopia (near-sightedness) is when a person can only focus on nearby objects. That is, the focal length of the eye is too short.

32. How can this be corrected?

33. How can you correct far-sightedness (hyperopia)?

Name \_\_\_\_\_ Section \_\_\_\_\_ Date \_\_\_\_\_

**Pre-Lab Preparation Sheet for Lab 10:****Wave Optics**

(Due at the beginning of lab)

**Directions:**

Watch the following videos,

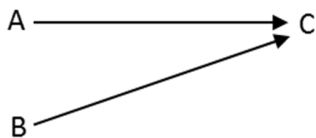
<https://www.youtube.com/watch?v=GgfKdVFfM28><https://www.youtube.com/watch?v=luv6hY6zsd0>

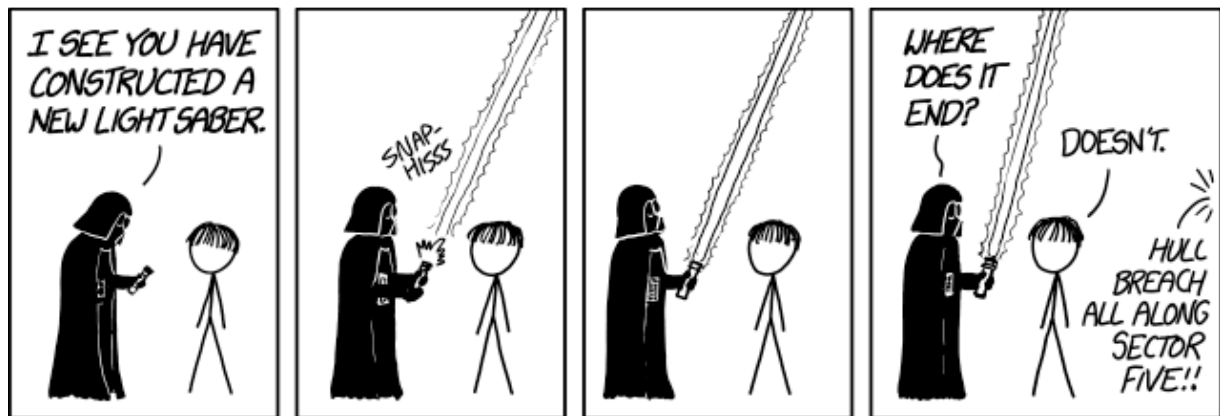
. . . then read over the lab. Answer the following questions.

1. A slit is illuminated first by red light, then by blue light. Which color will spread out the most? Explain.

2. Two sources (A and B) of red light (650 nm wavelength) destructively interfere on a screen. An observer sees a dark spot on the screen. What difference in path length (in nanometers) could account for this? Explain.

$$\Delta L = BC - AC$$





xkcd.com

Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_

TA \_\_\_\_\_ Lab/Section \_\_\_\_\_

## Lab 10: Wave Optics

*“And God said . . .*

$$\oint E \cdot dA = \frac{q}{\epsilon_0} \quad \oint E \cdot dS = \frac{-d\Phi_B}{dt}$$

$$\oint B \cdot dA = 0 \quad \oint B \cdot dS = \mu_0 \epsilon_0 \frac{-d\Phi_E}{dt} + \mu_0 i$$

*. . . and there was light.”*

*--Genesis 1:4*

**Objective:** To observe and understand diffraction and interference of light waves.

### Equipment:

Optics track	laser	10 cm lens
Single slit set	multiple slit set	corkboard & pins
Metal bead glued to a slide	steel/magnetic optics holder	
Ruler	phosphorescent calipers	
100 and 300 lines/mm gratings	Desk lamp	lab jack
One CD and one DVD		

### Introduction

Light is a wave. It exhibits frequency, wavelength, diffraction, and interference: all of the properties associated with waves. However, in our everyday experience, we rarely notice these effects. This is because the wavelength of light is so small: 400 – 750 nm. To easily observe the wave effects of light, one usually\*\*\*\*\* needs objects (apertures, films, antennae, etc.) with dimensions of a few microns or less.

**CAUTION: A laser beam hitting someone’s eye is no joke!! Practice proper laser safety throughout this lab!**

- Remove all watches and shiny jewelry from your hands and wrists. Secure any necklace so it will not fall into the beam.
- Always ensure that the primary and reflected beams are pointed in a safe direction.
- You are NOT Luke Skywalker!!!

---

\*\*\*\*\* . . . but not always, . . .

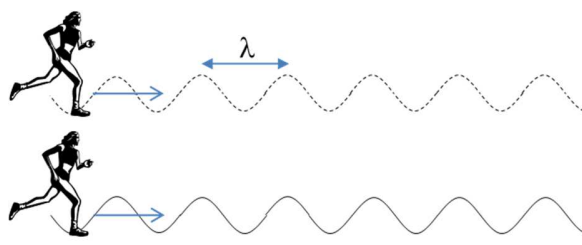
## Interference

When two (or more) waves overlap, the type of interference observed depends on the phase difference between the beams.

If the phase difference is  $0, 2\pi, 4\pi, 6\pi, \dots$ , (that is, the waves are *in phase*), one observes constructive interference. The amplitudes of the waves add together, and the intensity is maximized.

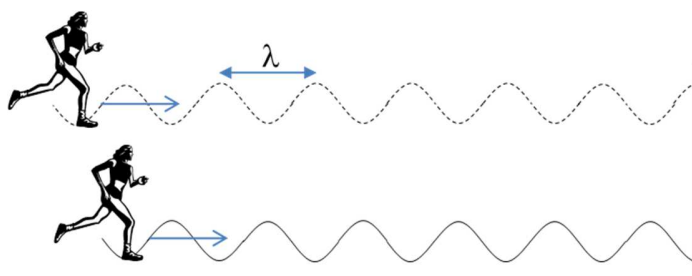
If the phase difference is  $\frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \dots$ , (that is, the waves have *opposite phase*), one observes destructive interference. One amplitude is subtracted from the other, and the intensity is minimized.

The simplest way to ensure that two waves are in phase is for the path length of the two waves to be the same. Imagine twin runners with identical strides. They start the race together and remain in step throughout the race, they both land on the finish line with their right foot. *In phase*.



However, if one runner starts *half a stride*  $\left(\frac{\lambda}{2}\right)$  behind the other, she will finish on her left foot.

*Opposite phase.*

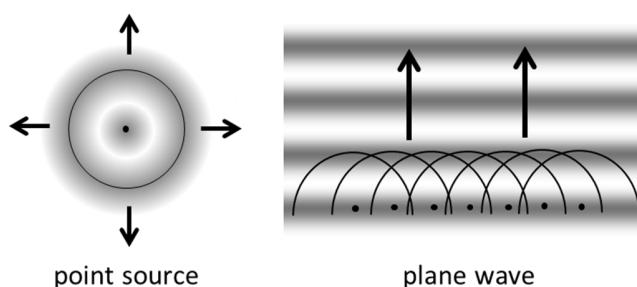


If one runner starts a *full stride* behind the other ( $\lambda$ ), she will finish on her \_\_\_\_\_ foot,

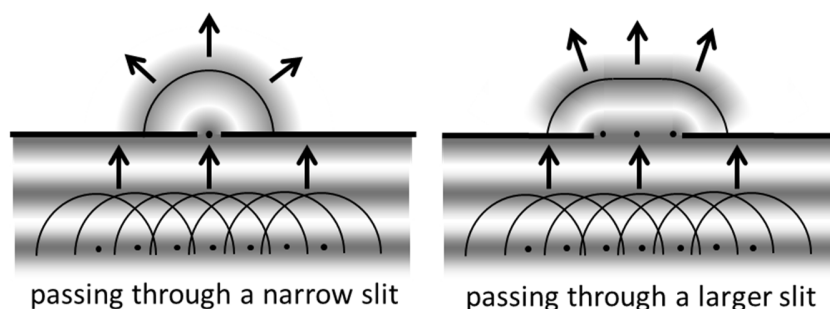
and the runners will be \_\_\_\_\_ phase.

## Huygens' Principle

Consider a plane wave moving upward. (See the image below.) Christiaan Huygens<sup>††††††††††</sup> observed that every point along a wavefront can be considered a point source of waves. That is, if you break up the wave front into an infinite number of point sources and then add all of those circular waves together, you will recreate the plane wave.

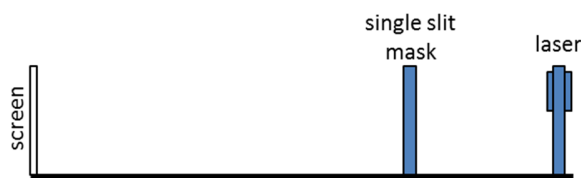


As a wave passes through a narrow<sup>\*\*\*\*\*</sup> slit, the wave front on the sides is eliminated. The remaining portion of the wave front acts as a point source for circular waves.



## Exercise 1: Diffraction

1. Arrange the components on the optical track as shown below.



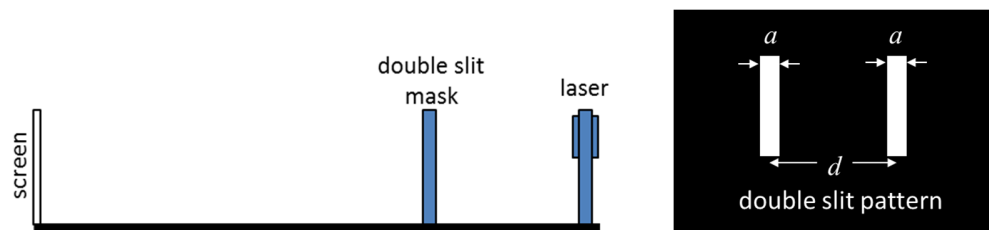
2. Adjust the single slit mask so that the variable slit is active. Using the thumb-screws on the back of the laser module, aim the beam so it passes through the slit.

<sup>††††††††††</sup> Only native Dutch speakers can pronounce his name properly, but it is something like *HOW-gkens*. That is *HOW* as in *house*, and *gkens* is just as unpronounceable as it looks.

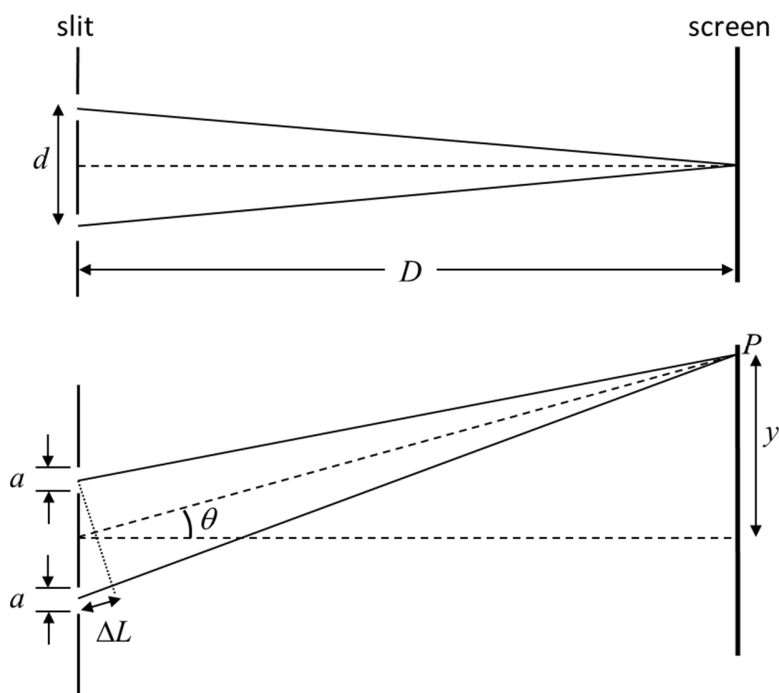
<sup>\*\*\*\*\*</sup> That is, the width of the slit is close to the wavelength.





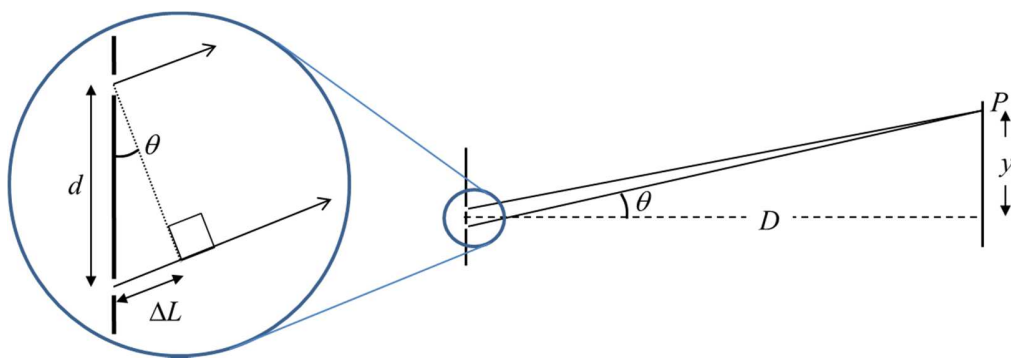
**Exercise 2: Double slit interference**

7. Replace the single slit mask with the double slit mask.
8. Adjust the mask so the variable slit is active.
9. Describe the pattern that appears on the screen. What is the effect of changing the separation between the two slits?
10. Sketch the observed pattern. What feature of the diffraction pattern is unique to the double slit mask? What feature is shared with the single slit mask?
11. Note the value of the width  $a$  of each slit and the separation  $d$  between the two slits. How do the sizes of these features ( $a$  and  $d$ ) relate to the size of the corresponding feature of pattern observed on the screen?



12. Select the following slit:  $a = 0.04$  mm,  $d = 0.25$  mm.

The difference in the optical path length  $\Delta L$  from each slit to point  $P$  on the screen depends on the angle  $\theta$  and the separation between the two slits  $d$ . As the separation between the slits is much smaller than the distance to the screen  $D$ , the lines from each slit to point  $P$  become essentially parallel.



We can then write the difference in path length  $\Delta L$  as

$$\Delta L = d \sin \theta \quad (1)$$

A similar triangle relates  $D$  and  $y$ .

$$\tan(\theta) = \frac{y}{D} \quad (2)$$

When the difference in path length  $\Delta L$  is a multiple of the wave length, light from the two slits will be in phase and a **maximum** of intensity will be observed on the screen.

$$\Delta L = d \sin \theta = m\lambda, \quad \text{where } m = 0, 1, 2, \dots \quad (3)$$

13. Derive an expression for the angles  $\theta$  at which a **minimum** of intensity will be observed.

14. Now, perform the experiment. Measure the distances from the center to the 5<sup>th</sup> dark spots on both the left and right side and average the values. (Or equivalently, measure the distance from the left spot to the right spot and divide by 2.) Estimate the uncertainty of this measurement.
15. Measure the distance from the slit to the screen. Again, estimate the uncertainty.
16. With the expression found for the angle above, calculate the wavelength of laser light. Then calculate the percent difference from the nominal value of the laser: 650 nm.
17. Select the  $a = 0.04$  mm,  $d = 0.50$  mm slit. Complete the table below.

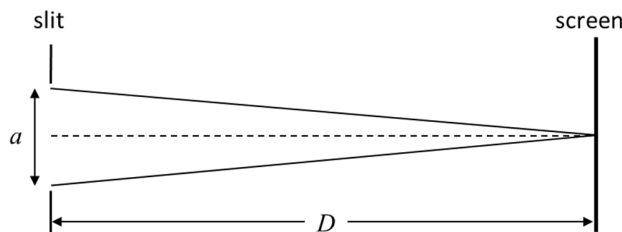
$D =$  \_\_\_\_\_

	Measured $y$	Calculated $\lambda$	% difference
0.25 mm separation			
0.50 mm separation			

18. Does your estimated uncertainty account for the observed percent difference?

### Exercise 3: Single slit interference

19. Replace the double slit with the single slit,  $a = 0.02 \text{ nm}$ .

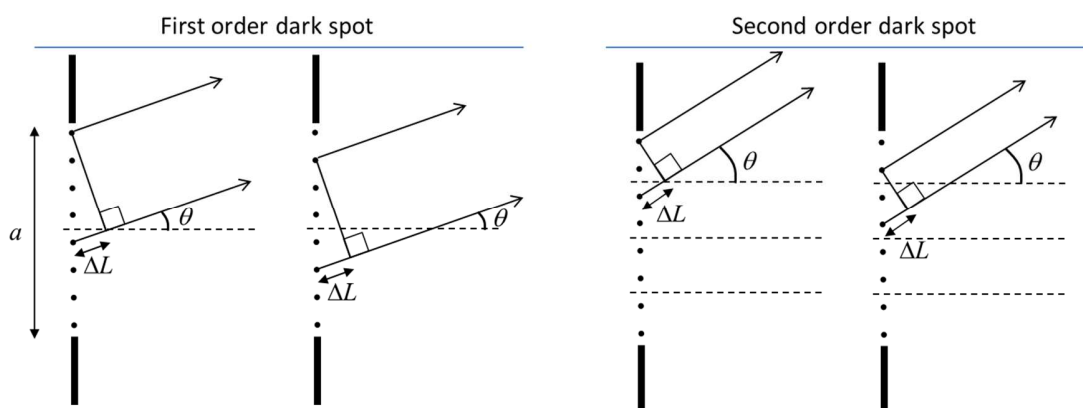


Understanding the dark spots in the single slit pattern is more a more subtle problem. Apply Huygens' Principle and represent the wave coming through the slit by a large even number of point sources. (See the figure below, First order.) Let's consider two of these points: one near the top of the slit and the other just below the middle of the slit. These points are separated by  $\frac{1}{2}$  the width of the slit  $\frac{a}{2}$ . For a particular angle  $\theta$ , these two point sources will destructively interfere on the screen, just as we observed with the double slit experiment.

$$\Delta L = \frac{a}{2} \sin(\theta) = \frac{\lambda}{2} \quad (4)$$

If these two points destructively interfere, so will the two points immediately below them. So, for every point in the top half of the slit, there is a corresponding point in the lower half that cancels it out. Thus, for this particular angle  $\theta$  we observe a dark spot on the screen.

$$\sin(\theta) = \frac{\lambda}{a} \quad (5)$$



If we break up the slit into *four* parts, the same logic applies. (See the figure above, Second order.) At a particular angle, the point near the top of the slit will destructively interfere with the point in the top of the

second quarter of the slit. Likewise, for every other point in the array, a corresponding point cancels it out. Another dark spot.

$$\Delta L = \frac{a}{4} \sin(\theta) = \frac{\lambda}{2} \quad (6)$$

$$\sin(\theta) = \frac{2\lambda}{a} \quad (7)$$

We can continue breaking up the slit by even numbers. In general, we find that a dark spot appears at the following angles:

$$\sin(\theta) = \frac{m\lambda}{a}, \quad m = 1, 2, 3, \dots \quad (8)$$

20. Measure the distance from the center of the array to the first and second dark spots. Fill in the table below. Note the uncertainty of each measurement.
21. With equation (8), calculate the laser wavelength (and corresponding uncertainty) for each spacing and the corresponding percent difference from 650 nm.

$D =$  \_\_\_\_\_

	first order	second order
Measured $y$		
Measured $\lambda$		
% diff		

22. Does the uncertainty of the measurement account for the percent difference?

#### Exercise 4: Multiple slits

23. Replace the single slit mask to the multiple slit mask. Rotate the mask to the MULTIPLE SLITS setting. Progressively observe the patterns produced by 2, 3, 4, and 5, slits. Record the width  $a$  and separation  $d$  of the slits.

Note: The width and separation of the slits do not change.

$$a = \underline{\hspace{2cm}} \qquad d = \underline{\hspace{2cm}}$$

24. How does the pattern change as the number of slits increases? What remains the same?

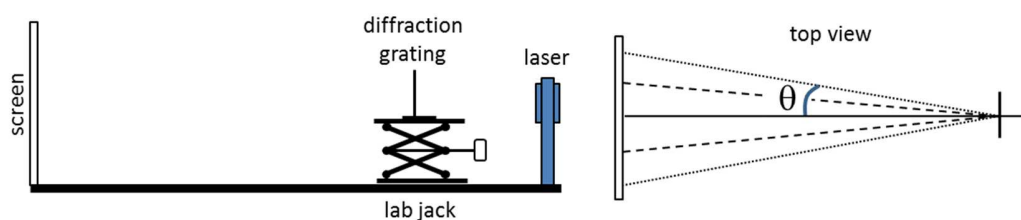
### Exercise 5: Diffraction Gratings

A **diffraction grating** is a sheet of glass or plastic with fine array of lines etched onto the surface. Each line effectively blocks part of the incident light. Basically, it's multiple slits on steroids: lots of *very* narrow slits *very* close together.

The **grating constant** tells you how many lines per millimeter are etched onto the surface. For the two gratings you are given, calculate the separation between adjacent lines.

**Caution:** Do **not** touch the surface of the diffraction gratings!

25. Look through the diffraction gratings at the lights in the room. Note the color patterns and the differences between the two gratings.
26. Remove the mask and place the 100 lines/mm grating in the path of the laser.



27. Note the pattern on the screen. Measure the average distance from the central spot to the first two bright spots on the screen. Then calculate the angle of the deflected beams. Record the results in the table below.
28. Repeat for the 300 lines/mm grating.

100 lines/mm grating:  $d =$  \_\_\_\_\_

$m$	$y$	$\theta$	$\lambda$	% diff
1				
2				

300 lines/mm grating:  $d =$  \_\_\_\_\_

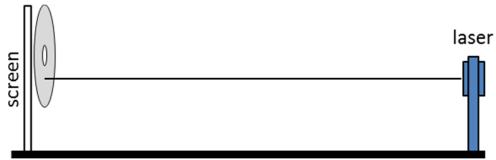
$m$	$y$	$\theta$	$\lambda$	% diff
1				
2				

The angle to the  $m^{\text{th}}$  bright spot is given by

$$\sin(\theta_m) = \frac{m\lambda}{d} \quad (9)$$

29. Using equation (9), calculate the wavelength for each angle.

30. CDs and DVDs are basically mirrored circular diffraction gratings. Consecutively, place each disk against the screen and observe the reflected pattern. Which device has the finer grating? Explain.

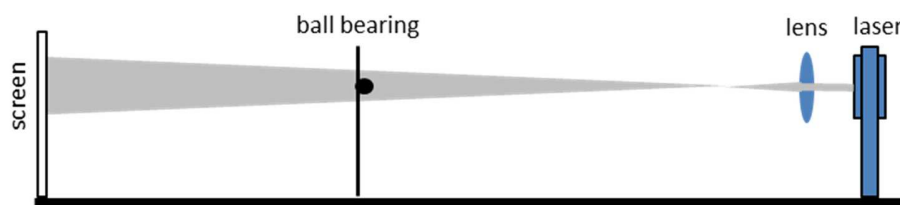




**Exercise 6: Poisson's Spot**

Wave effects are not limited to very small devices. Consider light illuminating a ball bearing glued to a glass slide. While the ball is small (a few millimeters), it is by no means microscopic.

Assemble these items on your optical track as shown below.



The laser illuminates the ball which casts a shadow on the screen. The only purpose of the lens is to increase the diameter of the laser beam.

With the enlarged laser beam, fully illuminate the ball bearing so that it casts a shadow on the screen.

31. Describe the appearance of the shadow on the screen. Make a sketch.

32. Applying the principles of wave optics, explain your observation.

Name\_\_\_\_\_ Lab/Section\_\_\_\_\_ Date\_\_\_\_\_

## Pre-Lab Preparation Sheet for Lab 12: Polarization of Light

(DUE AT THE BEGINNING OF LAB)

**Directions:**

Listen to the first 9 minutes of the following podcast<sup>ssssssssss</sup>:

<http://www.radiolab.org/story/122613-mirror-mirror/>

Then, read over the lab and answer the following questions.

1. What is the term for a polarizer that is used to determine the polarization of an optical system?

2. Define *birefringent*.

*See next page.*

##### Actually, the whole thing is quite interesting, but the first 9 minutes is relevant to the lab.

3. If Thalidomide naturally occurs in the human body, why did the artificial form of the drug form prove to be so toxic?

Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_  
 TA \_\_\_\_\_ Lab/Section \_\_\_\_\_

## Lab 12: Polarization of Light

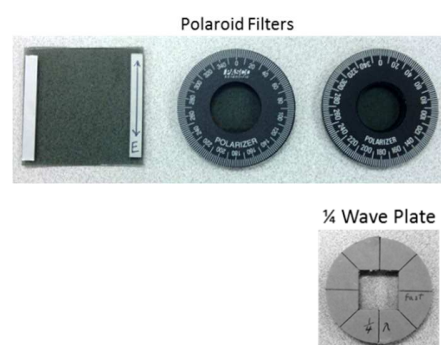
*“Now, if you'll only attend, Kitty, and not talk so much, I'll tell you all my ideas about Looking-glass House.”*

*--Alice, Through the Looking Glass*

**Objective:** To understand linear and circular polarization of light in terms of component waves.

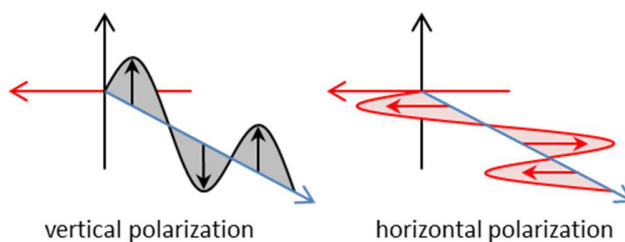
### Equipment:

Three polaroid filters  
 Two  $\frac{1}{4}$  wave plates  
 Magnetic optic rail  
 Three magnetic optic mount  
 One steel optic mount  
 White screen with magnetic mount  
 White light source



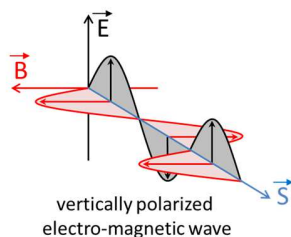
### Introduction

Transverse waves, *ipso facto*, have orientation dependence. Consider the case of someone shaking a rope to produce waves: the wave will be different if he shakes his hand *up and down* versus *left to right*. We call this difference **polarization**. Shaking the rope *up and down* will produce a *vertically* polarized wave. Shaking the rope *left to right* will produce a *horizontally* polarized wave.



In contrast, longitudinal waves have no such orientation dependence. One does not speak of polarized sound waves.

Electromagnetic waves, including visible light, are transverse waves. The orientation of the oscillating electric  $\vec{E}$  and magnetic  $\vec{B}$  fields are perpendicular to the travel direction  $\vec{S}$  of the wave.



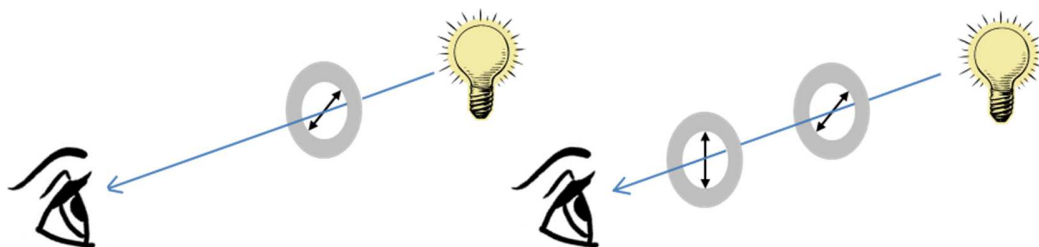
By convention, the polarization axis is defined by the orientation of the electric field. While we will not mention the magnetic component of the electro-magnetic wave for the rest of the lab, rest assured that it is still there.

*So if light is a transverse wave, and transverse waves are polarized, how can you have non-polarized light?*

Good question! I'm glad you asked. Imagine someone shaking a rope, but they are constantly changing the way they shake it. Say, three up and down shakes, followed by two horizontal shakes, and then four diagonal shakes. On average, there is no particular orientation to the waves. Similarly, most light sources (sunlight, light bulbs, and even some lasers) produce non-polarized (or more accurately *randomly polarized*) light. However, there are several methods to convert randomly polarized light into polarized light.

### Polaroid Filters and Linearly Polarized Light

A Polaroid<sup>\*</sup> filter works by absorbing light of one orientation (say, horizontal) while allowing the other orientation (say, vertical) to pass freely. You are provided with several such polarizers. The  $0^\circ$  angle marks the orientation of the electric field which can pass through the filter.



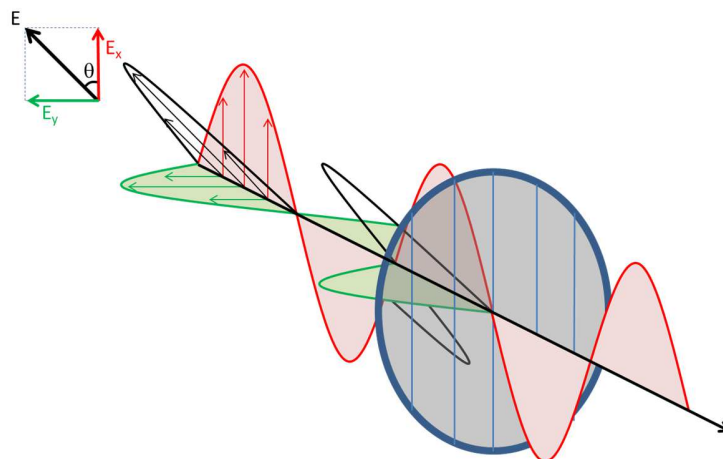
1. Look through one of your Polaroid filters. Rotate the polarizer in your hand. Since the room lights are randomly polarized, half of the light will be absorbed by the filter regardless of the orientation of the filter.

The other half of the light will pass through the filter. It will be polarized in the direction set by the filter.

2. Look through two polarizers. Rotate one polarizer with respect to the second.
  - a. What angles between the two polarizers maximize the light transmission?

<sup>\*</sup> The Polaroid filter was invented by Edwin Land, who also invented the instant camera.

- b. What angles between the two polarizers minimize the light transmission?



This Polaroid filter is oriented to block the y component of the incoming beam.

The electric field of the polarized beam is a vector, and like any vector you can break it into component vectors and treat each component separately.

- To better visualize this, run the program EMANIM from your desktop. You will see just the horizontal component of a light beam. Check the box for Wave 2 and Wave1 + Wave2.

If you orient a Polaroid filter along the x-axis, it will allow the x component to pass while blocking the y component.

- Look through a single Polaroid filter at desktop screen of your computer monitor. Rotate the polarizer and observe the effect. Using the protractor displayed on the monitor, measure the orientation angle of light coming from the screen.

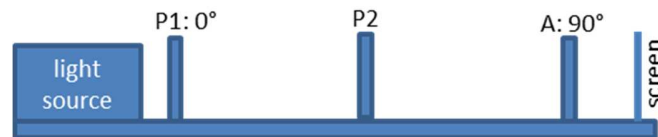
Polarization angle for the screen = \_\_\_\_\_

- Assemble two polarizers (P1 and A) on the optical bench as shown. Use the square polarizer for A1.

Rotate A relative to P1 and observe the effect on the transmitted light. The A filter is called the *analyzer*, for it is used to determine the final polarization of a system.



- Adjust the analyzer to  $90^\circ$ . Note the effect on the transmitted light.
- Suppose you were to add a third polarizer between P1 and A. What would be the effect on the transmitted light? Discuss this with your lab partner.
- Perform the experiment. Insert P2 as shown. Rotate P2 from  $270^\circ$  to  $90^\circ$  ( $-90^\circ$  to  $+90^\circ$ ) and record at what angles the transmitted light is maximized and at what angles it is minimized.

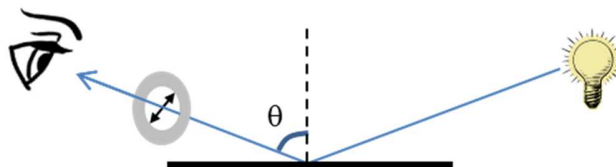


Maximum transmission:

Minimum transmission:

### Polarization by Reflection

Light can be polarized (or partially polarized) by specular reflection off an insulator (such as glass or water).



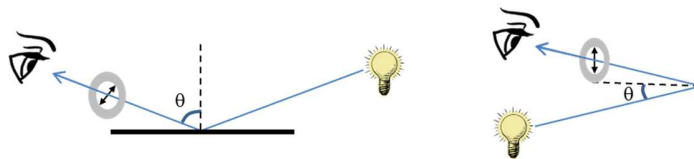
- Looking through a polarizer, observe the reflection of randomly polarized light off a glossy surface such as the floor or the table surface. Which orientation of light is preferentially reflected? Light oriented parallel to the plane of the glass, or its complement?
- How does the angle of incidence  $\theta$  affect the polarization?



3. Which way should a driver's polarized glasses be oriented to minimize the glare off a wet highway?

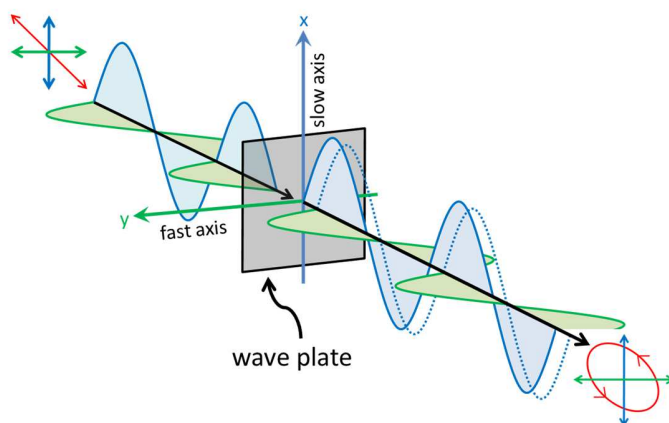
For polarization to be possible there must be an asymmetry in the system between perpendicular components of the light.

- With the Polaroid filter, the plastic is engineered so that long chain molecules are oriented along one direction in the filter.
  - For light reflecting off a surface, the orientation of the electric field to the surface of the glass versus the complimentary component.
4. **Applying this principle of symmetry**, explain the difference in the observed polarization of light with a large incidence angle  $\theta$  versus a small incidence angle.



## Circular Polarization

Consider a linearly polarized beam oriented  $45^\circ$  to the  $x$  axis. It will have components of equal amplitude in the  $x$  and  $y$  directions. (See the figure below.)



Let's pass this beam through a material where the speed of light of the  $x$  component is slower than the speed of the  $y$  component.\* This causes the  $x$  component to lag behind. Such materials are called *birefringent*. A birefringent material used in such a manner is called a *wave plate*.

Now, instead of oscillating up and down, the electric field spirals around in a helix. At no point is the electric field zero. The beam is *elliptically polarized*.

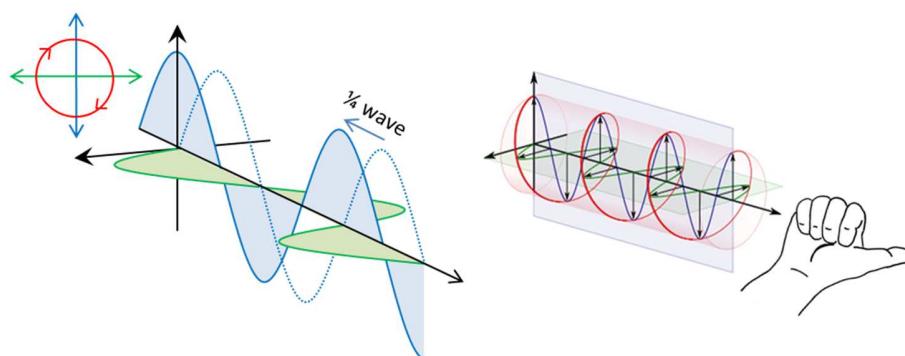
1. To better visualize this, return to the EMANIM program. Adjust the Phase difference slider for Wave2 and watch the effect on the resultant wave.

If we adjust the thickness of the material just right, we can delay the  $x$  component by  $\frac{1}{4}$  wavelength behind the  $y$  component (phase shift of  $-90^\circ$ ). Such a device is called a  $\frac{1}{4}$  wave plate. Now, the amplitude is constant as it rotates and the light is *left circularly polarized (lcp)*.<sup>†</sup> If we rotate the wave plate by  $90^\circ$ , the  $x$  component would be advanced by  $\frac{1}{4}$  wavelength ( $+90^\circ$  phase shift) and the light would become *right circularly polarized (rcp)*.

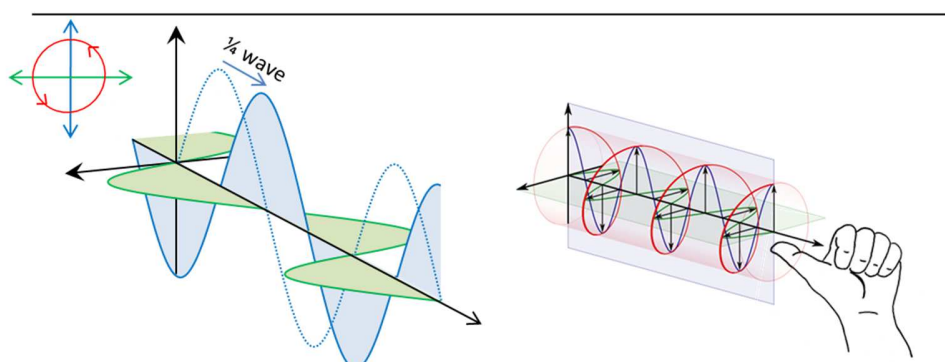
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\* Equivalently, we could say that the index of refraction for the  $x$  component is greater than the index of refraction for the  $y$  component.

<sup>†</sup> That is, the electric field vector would trace out a left handed helix through space. This is best seen in the animation.

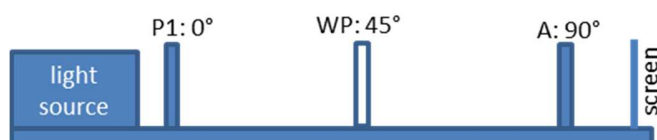


Right Circular Polarization (RCP)



Left Circular Polarization (LCP)

2. Examine the quarter wave plates. You will notice the fast axis is marked with a red line. Look through the wave plate at the room lights and your computer monitor. You should find it completely unremarkable.
3. Arrange your optical bench as shown below, with the  $\frac{1}{4}$  wave plate oriented at  $45^\circ$ .



4. Slowly rotate the analyzer and observe the effect on the screen. What happens to the intensity? Describe the result below.

You may also notice that the color changes slightly as you rotate the analyzer. The colors appear because the birefringence of the material varies with wavelength. This particular material is engineered to work as a  $\frac{1}{4}$  wave plate for 560 nm (green) light. But it is not quite a  $\frac{1}{4}$  wave plate for red or blue.

5. Explain why the circularly polarized light is no longer extinguished by the analyzer.

6. Orient the wave plate so that the fast axis is parallel ( $0^\circ$ ) to P1. Rotate the analyzer and observe the effect on the screen. Is the light linear or circular? If linear, what is the direction of the polarization?

7. Look at the light from your cell phone screen through an analyzer. Rotate the analyzer in your hand. Is the light from your cell phone or calculator linearly polarized or circularly polarized? Explain.

8. Hold up the U shaped plastic<sup>‡</sup> window to the computer screen. Then look at it through the analyzer. Gently squeeze on the arms and observe the changing color pattern.



In this case, the birefringence arises from internal stress in the material. The birefringence is also a function of wavelength. As different colors become more or less elliptical, they will be more or less blocked by the polarizer. Hence, the observed colors.

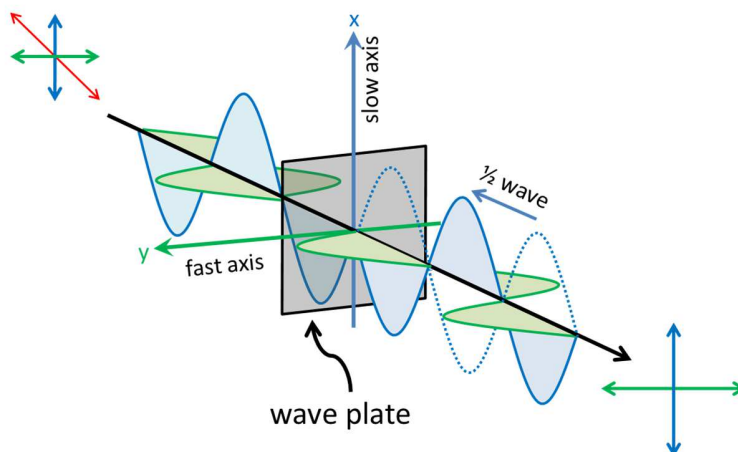
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<sup>‡</sup> Polycarbonate, in this case.

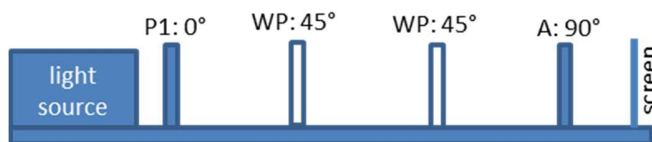
### $\frac{1}{2}$ Wave Plate

If we add a 2<sup>nd</sup>  $\frac{1}{4}$  wave plate oriented in the same direction as the first, you will create a  $\frac{1}{2}$  wave plate. Study the diagram below.

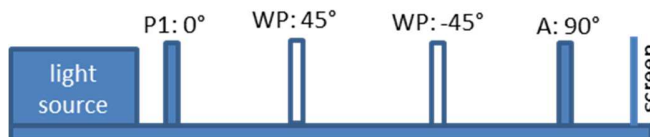
1. Predict what the polarization will be after the beam passes through the 2<sup>nd</sup> wave plate? Indicate this with an arrow in the diagram below.



9. Combine both  $\frac{1}{4}$  wave plates to create a  $\frac{1}{2}$  wave plate. Place this on the optical bench at  $45^\circ$  relative to P1. Is the light linear or circular? If linear, what is the direction of the polarization?

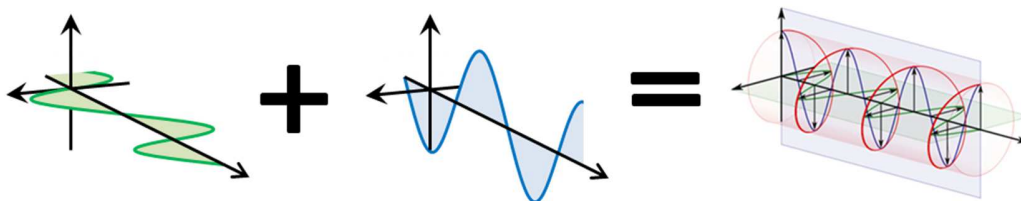


10. Orient the 2<sup>nd</sup> wave plate so that its fast axis is parallel to the slow axis of the 1<sup>st</sup> wave plate. Is the light linear or circular? If linear, what is the direction of the polarization?

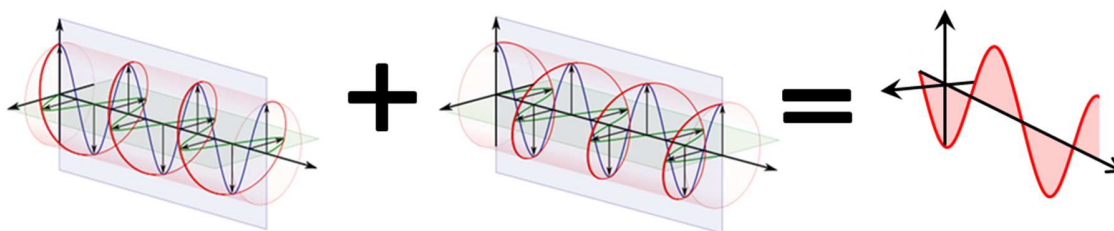


### Polarization and Components

We can think of an elliptically polarized beam as being the sum of a horizontally polarized beam and a vertically polarized beam. The phase shift between these two linear component beams determines the ellipticity of the resulting beam and whether it will be left or right handed.



Similarly, a linearly polarized beam can be thought of as the sum of a right circularly polarized beam and a left circularly polarized beam.



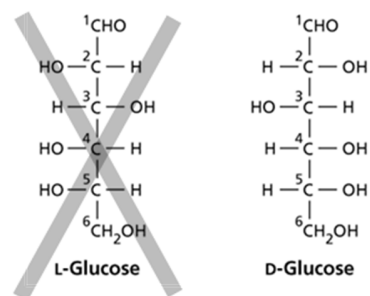
1. Return to the EMANIM program. Change the Polarization of Wave1 to Left circular and the polarization of Wave2 to Right Circular.
2. Adjust the Phase difference for Wave2. How does this affect the resultant wave?

### Circular Dichroism

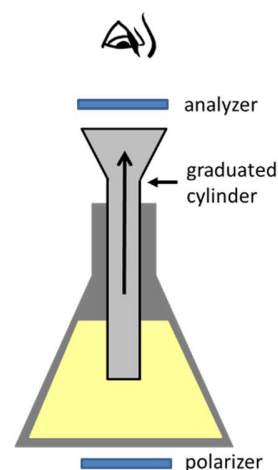
Some materials exhibit *circular birefringence*<sup>§</sup>. That is, the speed of left circularly polarized (lcp) light is different from the speed of right circularly polarized (rcp) light. If linearly polarized light passes through such a material, a phase shift will develop between the lcp and rcp components like you just simulated above.

<sup>§</sup> This is also called *optical activity* or *optical rotation*.

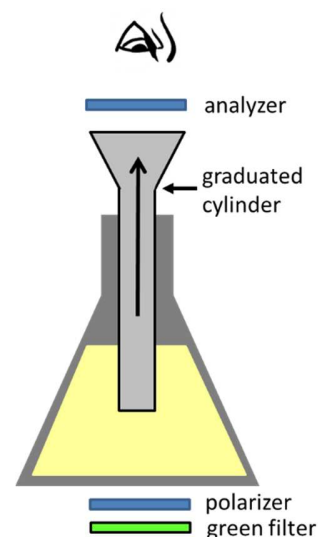
This birefringence is usually due to the presence of biological chiral molecules. A common example is glucose, the principle component of corn syrup. Chemically, glucose can exist in one of two forms: D-glucose and its mirror image L-glucose. Since these molecules have opposite chirality, they will have opposite birefringence effects. If these two forms were mixed together, the effects would cancel out. However, only D-glucose exists in nature.\*\*



1. Attach a polarizer to the bottom of the flask of corn syrup.
2. Looking through the analyzer, slowly lift the graduated cylinder, but **do NOT remove the cylinder<sup>††</sup>**. Note the changing colors as the path length through the corn syrup increases.
3. Why do these colors appear?



4. To simplify the analysis, add a green filter to the bottom of the system. This will allow fewer wavelengths of light through the syrup and minimize color effects.
5. Looking through the analyzer, slowly lift the graduated cylinder. Note the change in the polarization as the path length through the corn syrup increases.
6. After passing through the syrup, is the polarization linear or circular?



\*\* L-glucose can be created artificially.

<sup>††</sup> Do not make a mess! Let's keep the syrup in the flask.





## Useful Physical Constants\*

Speed of Light (exact)	$c$	$2.99792458 \times 10^8 \frac{m}{s}$
Elementary charge	$e$	$1.602176565(35) \times 10^{-19} C$
Electron volt	1 eV	$1.602176565(35) \times 10^{-19} J$
Plank's constant	$h$	$6.62606957(29) \times 10^{-34} Js$
	$\hbar = h/2\pi$	$1.054571726(47) \times 10^{-34} Js$
Permeability of free space (exact)	$\mu_0$	$4\pi \times 10^{-7} \frac{Wb}{Am}$
Permittivity of free space (exact)	$\epsilon_0 = \frac{1}{\mu_0 c^2}$	$8.854187187187... \times 10^{-12} \frac{C^2}{Nm^2}$

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\* Values are from NIST ([physics.nist.gov/cuu](http://physics.nist.gov/cuu)). The number in parentheses is the standard uncertainty of the final digits of the main number. For example,  $1.602\,176\,565 \pm 0.000\,000\,035 = 1.602\,176\,565(35)$