Laboratory Manual

General Physics Laboratory II
PHYS 118B

Spring 2015
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Nashville, TN

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Introduction

The Sermon

The charge of an electron is $1.602176656(35) \times 10^{-19}$ Coulombs. This is not science.

The Wikipedia entry on Newton’s 2nd 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.* 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!† More than any other science, physics is about fundamental principles, and those few principles‡ 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 get through each lab just fine. The problem is that the following week 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 the results of your experiments to the underlying principles. 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.

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* To get through organic chemistry, sometimes you just have to memorize all those formulas.
† . . . but not less.
‡ $F=ma$, conservation of energy and momentum, oscillations and waves. You will learn a few more in the second semester.
The Lab

Before coming to lab§, read over the lab write-up and do the Pre-Lab. Occasionally you will find links to online media files in the Pre-Lab; watch and/or listen to them.

Bring to each lab:
- This lab manual
- Your completed pre-lab
- A scientific calculator (A graphing calculator is not necessary.)
- A pen/pencil and extra paper
Occasionally, you will find a laptop useful for spreadsheet calculations, but it is not required.

The topics covered in lab are usually also covered in the lecture. As best as possible the labs are arranged to correlate with the lecture, but not always. If you find unfamiliar material while completing the pre-lab, you may find your text book a valuable reference. To maintain synchrony with the lectures, we may deviate for the arrangement of labs in this manual. If so, you will be notified no later than Friday of the previous week. Check your email.

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).

More information, (Grading scheme, make-up policy, etc.) including official syllabus for the lab and a FAQ is available on the physics labs web page.

my.vanderbilt.edu/physicslabs/

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§ . . . as in the night before, or the morning before your lab. NOT 5 minutes before your lab!
**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.

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Lab 1: Electrostatics

“\textit{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.}”

\textit{--Benjamin Franklin, 1747}

Objective:
To understand electrostatic phenomena in terms of the basic principles of electric charges.
Distinguishing 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. \textit{Insulators}: electrical charges are frozen in place in the material.
   b. \textit{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 (-). \textit{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*.**

1. Vigorously rub an inflated balloon with your hair.††

![Fig 1](image)

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 electroscopes 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.‡‡ 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.

![The Triboelectric Series](image)

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

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**Tribo** is from the Greek term for rubbing.

†† If you are follicly challenged, use the fur.

‡‡ 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.
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.  

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?

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$^{99}$ 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***. 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?

*** 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‡‡‡ 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](image)
2. What are the final net charges on the electroscope and the metal plate?

3. Illustrate the cartoons in Fig. 6 with + and – symbols to indicate the distribution of charge at each step.

The Faraday Cage

1. Touch the Faraday cage to verify that it is discharged.
2. Recharge the electrophorus
3. Transfer three doses of charge from the electrophorus to the Faraday cage. Describe the effect on each of the foil leaves.
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.

§§§

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.
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?
Pre-Lab Preparation Sheet for Lab 4: Introduction to Capacitors
( Due at the beginning of Lab)

Directions:
Read over the lab and then answer the following questions.

1. Capacitance represents the relationship between accumulated charge induced between a set of conductors and the applied potential difference. How would you expect the capacitance for a parallel plate capacitor to change as the area of the plates is increased? Explain your answer.

2. Given Equation (4.5) and the definition of capacitance, write an expression for the voltage across a charging capacitor.
3. Given Equation (4.5) and definition of current \( I \equiv \frac{dQ}{dt} \), derive an expression for the current across a charging capacitor.
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 Jars 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 develop a detailed understanding of capacitors and their relation to current and voltage

**Equipment:**
- Multimeter
- Textbook
- 2 20 cm x 40 cm sheets of aluminum foil
- Caliper
- 22000 μf 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.

§§§§§ Cue sound effect.
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:

\[ C \equiv \frac{Q}{V} \]  

(4.1)

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

\[ C = \frac{\kappa \varepsilon_0 A}{d} \]  

(4.2)

where \( \kappa \): the dielectric constant of the insulating material; \( \varepsilon_0 \): 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.

a. 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.

b. 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.
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

\[ C_{1\text{ pages}} = \] 

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

\[ C_{2\text{ pages}} = \] 

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

\[ C_{3\text{ pages}} = \] 

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†††††† 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.

\[ C_{1\text{page}} = \text{______________} \]

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

\[ C_{2\text{pages}} = \text{______________} \]
\[ C_{3\text{pages}} = \text{______________} \]

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.

\[ C = \text{______________} \]

†††††† 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.

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.

\[ V_0 = V_R + V_C \]  

(4.3)

Applying the definitions of resistance, capacitance, and current:

\[ V_0 = IR + \frac{Q}{C} \]

\[ = R \frac{dQ}{dt} + \frac{Q}{C} \]

(4.4)

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

The solution to this differential equation for \( Q(t) \) is

\[ Q(t) = Q_0 \left( 1 - e^{-t/\tau} \right) \]

(4.5)

where

\[ Q_0 \equiv CV_0 \quad \text{and} \quad \tau \equiv RC \]

\( \tau \) is known as the time constant 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.

---

†††††††††††††††† 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.
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:

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\*, so it is worth your time to get familiar with them. These functions are illustrated below.

\* They are found in applications as divergent as bank accounts, bacterial growth, and radioactive decay.
Discharging a Capacitor: Theory

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

![Circuit Diagram](image)

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:

$Q_C(t) =$

$V_C(t) =$

$I_C(t) =$

Write an expression for the voltage across the resistor:

$V_R(t) =$

Verify these expressions with your TA.

††††††††††† I’m not looking for a rigorous proof here. Just apply the Stephen Colbert method and use your gut.
Charging and Discharging a Capacitor: Experiment

Carefully construct the following circuit using the Vernier circuit board and the large 22000 µF 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.

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 51Ω 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?

\[ \tau_{\text{avg}} = \___________________________ \]

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

\[ C(\text{from } \tau) = \___________________________ \quad \% \text{ diff} = \___________________________ \]

‡‡‡‡‡‡‡‡‡‡ Electrolytic capacitors, like the one you are using, are notorious for varying from their nominal values.
Consider the charging phase of capacitor. From the definition of current

\[ I = \frac{dQ}{dt} \]

\[ dQ = I \, dt \]

\[ \int_{0}^{Q_{0}} dQ = \int_{0}^{\infty} I \, dt \]  \hspace{2cm} (4.6)

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 \( C \).

\[ Q_{0} = \underline{_________________________} \hspace{2cm} C(\text{from } Q) = \underline{_________________________} \]

**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.

\[ \tau(\text{expected}) = \underline{_________________________} \hspace{2cm} \tau \text{ (from fit)} = \underline{_________________________} \]
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?
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*

**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*§§§§§:

\[
\oint \mathbf{B} \cdot d\mathbf{S} = 0
\]

---

§§§§§ *In the modern convention,* \( \mathbf{B} \) *is the standard algebraic symbol for magnetic field because that makes perfect sense. We used to use* \( \mathbf{H} \) *for magnetic field, but not anymore ‘cause that’s just silly.*
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 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?

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

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 ?? A)
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 sound. With the connectors facing up, place the 800 turn coil in the center of Figure ??
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

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

\[ F_B = q \vec{v} \times \vec{B} \]  

(1.8)

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.
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.

The electrons are both:

   a) . . . moving **down** due to the motion of the wire
and

b) . . . moving **laterally** along the length of the wire due to the induced current. Again, consider the wire being pushed **down** into the magnet, but this time consider the force on the electrons due to the current moving along the length of the wire.

13. Applying the right hand rule and equation (1.8), what is the direction of the force on the electrons due to their **lateral** motion along the wire?

14. Pull the wire **up** out of the magnet. Applying the right hand rule and equation (1.8), what is the direction of the force on the electrons due to their **lateral** motion along the wire?

15. 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.

**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

\[ \Phi_B \equiv \oint_{\text{area of loop}} \vec{B} \cdot d\vec{A} \]  

(1.9)

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†††††††† \( V_{\text{coil}} \) across the coil of wire

\[ V_{\text{coil}} = -N \frac{d\Phi_B}{dt} , \]

(1.10)

where, \( N \) is the number of turns in the coil.

Applying Faraday’s law is equivalent to applying Equation (1.8); however, it involves an important change in perspective. Equation (1.8) makes your 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 (1.8) 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.

16. Connect the 800 turn coil to the current sensor. (See the figure below.)
17. 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!
18. 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?

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

Exercise 5: Measuring magnetic fields

20. Open the page Voltage Pulse.
21. Coil a wire two or three times. Quickly pull the coil in (or out) of the large magnet (as illustrated in figure ??), and observe the voltage pulse on the screen.
   
   Note: The program will start recording data when the voltage exceeds +0.02 V. Hence, it will only record positive voltage pulses. Getting the program to record a pulse can be a bit tricky. Try it several times until you get a clean pulse.

22. From the width of the pulse, estimate the speed of the wire as it moved through the magnet.

23. Calculate $\frac{d\Phi}{dt}$. (Assume the magnetic field is constant in the region between the poles and zero elsewhere.)
24. Applying equation (1.10), estimate the magnitude of the magnetic field between the poles. Show all of your calculations below.
Pre-Lab Preparation Sheet for Lab 6:
Inductors and RL Circuits
(DUE AT THE BEGINNING OF LAB)

1. In the mechanical analogy, to what is inductance analogous?

2. How would the inductance of a coil change if the number of turns were doubled but other parameters remained the same?

3. Consider the circuit shown in Exercise 3. When the circuit is opened, why does the current not smoothly fall to zero?
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

**Equipment**

- 800 turn coil
- 1600 turn coil
- steel bar
- current probe
- voltage probe
- multimeter
- Vernier circuit board
- knife switch
- gaggle of wires
- 33 Ohm resistor
- ~40 μF cap

**Introduction**

Cast your mind back to your first semester of physics.

Newton’s 1st 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 2nd Law of motion: To change the velocity \( \left( v = \frac{dx}{dt} \right) \) 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,

$$0 = V - V_R - V_L = V - IR - L \frac{dI}{dt}$$

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

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

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.

![Circuit Diagram]

**A mechanical analogy: Newton’s Laws of Circuits.**

1\(^{\text{st}}\) 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\(^{\text{nd}}\) 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 Lens’ 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.

\[ \text{RL, L} \]

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.

\[ \text{V, RL, A, 3V} \]

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 33Ω 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 (Lens’ 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††††††††, 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.

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

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?
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?
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”

Objective: To develop a basic understanding of Resistance, Reactance, and Impedance

Equipment:
- 800 and 1600 turn coils
- ~40 μF 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:

\[ V(t) = V_0 \cos(\omega t) \]  

(5.1)

where \( \omega \) is the angular frequency,

\[ \omega = 2\pi f \]  

(5.2)

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

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

\[ I = I_0 \cos(\omega t + \phi) \]  

(5.3)
The instantaneous power drawn by a circuit element is the instantaneous voltage across the device times the instantaneous current

$$P = IV$$ \hspace{2cm} (5.4)

**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.

![Circuit Diagram](image)

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.

   ![Trace Plot](image)

   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 1V.
   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 $X_C$.

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

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?

§§§§§§§§§§§§§§§ 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 that for the time being.
14. With the amplitude of the voltage set at 1V, 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

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

(5.6)

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.

   $\quad R = \underline{\text{__________________________}}$

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. (5.6) and your plot on Page #3.

   \[ f_0 \text{ (800 turns, capacitor) } = \text{_________________________} \]

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

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}} \quad (5.7)$$

1. Replace the capacitor with the 10 µF capacitor (C1) on the Vernier board. With the oscilloscope on Page #1, measure the resonant frequency and the inductance.

   \[ f_0 \text{ (800 turns, 10 } \mu \text{F)} = \underline{\text{__________________________}} \quad L \text{(800 turns)} = \underline{\text{__________________________}} \]

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

   \[ f_0 \text{ (1600 turns, 10 } \mu \text{F)} = \underline{\text{__________________________}} \quad L \text{(1600 turns)} = \underline{\text{__________________________}} \]

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 nob of an antique Zenith set, what are you mechanically doing?********

******** “Be sure to drink your Ovaltine™!”
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 TiO₂?

2. What is the critical angle for TiO₂?

3. Define dispersion.
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

Equipment

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

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.
   \[ \theta_i = \theta_r \]  \hspace{1cm} (1.8)

2. Part of the wave will transmit into the 2nd medium, but its direction of travel will be bent or refracted. The angle of the transmitted wave is given by Snell’s Law
   \[ \frac{\sin \theta_i}{\sin \theta_t} = \frac{v_t}{v_i} \],  \hspace{1cm} (1.9)

where \( v_t \) and \( v_i \) 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:

\[ n \equiv \frac{c}{v} \],  \hspace{1cm} (1.10)
Where \( v \) is the velocity of light in a particular material, and \( c \) is the velocity of light in a vacuum 
\[
(2.998 \times 10^8 \text{ m/s})
\]. Hence, we can write Snell’s Law as

\[
\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_r}{n_i}
\]  

(1.11)

**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.

3. Using Excel, plot the refracted angle as a function of the transmitted angle.

**Figure 2**
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](image)

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 \( \theta_c \).
<table>
<thead>
<tr>
<th>( \theta_i )</th>
<th>( \theta_r )</th>
<th>( \theta_t )</th>
<th>( \frac{\sin(\theta_r)}{\sin(\theta_i)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
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</tr>
<tr>
<td>80°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1A: Air to Acrylic

<table>
<thead>
<tr>
<th>( \theta_i )</th>
<th>( \theta_r )</th>
<th>( \theta_t )</th>
<th>( \frac{\sin(\theta_r)}{\sin(\theta_i)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

13. Arrange the 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° mirror?

![Figure 5](image)

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](image)

15. Look at the prism as shown below. Slightly rotate the prim. Describe and explain your observation.

![Figure 7](image)

16. Repeat the step above with the acrylic prism, but this time submerge it into the water as you are looking at the reflection. Describe and explain your observation.

††††††††† This is called a retro-reflector. (The taillights covers of your car use this principle.)
Exercise 4: Dispersion

17. 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?

18. What does this imply about the speed of light and the index of refraction of the different colors in glass?

‡‡‡‡‡‡‡‡‡ This is best done while humming *The Great Gig in the Sky*. 
19. Using a 2nd prism, can you recombine the colors? Can you separate them more? Using colored pencils, diagram your results.
20. Position the aluminum block after the 1st prism so that only red light can pass. Then send the single color through the 2nd prism. Does the 2nd prism have any effect on the color or dispersion of the red beam? How about blue light? Again, with colored pencils, diagram the result.
21. Before Newton, it was generally believed that glass could transform *pure* white light into colored light. What do your observations indicate about the nature of colored and white light? Explain?

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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?
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

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 . . .

a. reflect off a surface (angle of reflection = angle of incidence), or
b. refract at an interface (Snell’s Law).

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

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.

§§§§§§§§ §§§§§§§§
In principle, you could design a telescope with nothing but a straight edge, a protractor, and a really sharp pencil.

An aperture is the opening through which light can pass.
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.

Consider Figure 2 below. If we curved the surface of the glass *just right*, all of the parallel rays will be bent toward a single *focal point*. This is a *convex* or *positive lens*.

![Fig. 1](image1.png) ![Fig. 2](image2.png)

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.

\[
\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad (9.1)
\]

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 \( M \equiv \frac{\text{image height}}{\text{object height}} \) 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

<table>
<thead>
<tr>
<th></th>
<th>$p$</th>
<th>$i$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th></th>
<th>Near focus</th>
<th>Far focus</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>No masking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large aperture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle aperture</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Small aperture</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
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 your 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:

$$\frac{1}{f_{\text{effective}}} = \frac{1}{f_a} + \frac{1}{f_b} \quad (9.2)$$

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=Iuv6hY6zsd0

... 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.
   \[ \Delta L = BC - AC \]
Lab 10: Wave Optics

"And God said . . .
\[ \oint E \cdot dA = \frac{q}{\varepsilon_0} \]
\[ \oint E \cdot dS = \frac{-d\Phi_B}{dt} \]
\[ \oint B \cdot dA = 0 \]
\[ \oint B \cdot dS = \mu_0 \varepsilon_0 \frac{-d\Phi_E}{dt} + \mu_0 i \]

. . . and there was light."

--Genesis 1:4

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

Equipment:
- Optics track
- Single slit set
- Laser
- 10 cm lens
- Metal bead glued to a slide
- Multiple slit set
- Steel/magnetic optics holder
- Ruler
- Corkboard & pins
- Phosphorescent calipers
- 100 and 300 lines/mm gratings
- Desk lamp
- One CD and one DVD
- Lab jack

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 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!!!
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, 2π, 4π, 6π, . . . , (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 \( \frac{\pi}{2} \), \( \frac{3\pi}{2} \), \( \frac{5\pi}{2} \), . . . , (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.

![Phase Diagram](image)

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.

![Opposite Phase](image)

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‡‡‡‡‡‡‡‡‡‡ 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§§§§§§§§§§ 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.

‡‡‡‡‡‡‡‡‡‡ Only native Dutch speakers can pronounce his name, but it is something like HOW-gkens. That is HOW as in *house*, and the *gk* is just as unpronounceable as it looks.

§§§§§§§§§§ That is, the width of the slit is close to the wavelength.
3. Describe the pattern on the screen. How does the pattern respond to changes in the width of the slit?

4. How does the orientation of the slit (vertical or horizontal) compare to the orientation of the pattern on the screen?

5. Suppose the slit were replaced with a circular aperture. What do you think the screen pattern would look like? Make a sketch of your guess.

6. Rotate the aperture device to select the circular apertures: first the large one, then the small one. Sketch the two patterns.

You will investigate the details of the single slit diffraction pattern (the position of the dark spots) in a later exercise. First, let’s deal with something conceptually simpler.
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: \( a = 0.04 \text{ mm}, \ d = 0.25 \text{ mm}. \)

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

\[
\Delta L = d \sin \theta
\]  

(10.1)

A similar triangle relates \( D \) and \( y \).

\[
\tan(\theta) = \frac{y}{D}
\]  

(10.2)
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.

$$\Delta L = d \sin \theta = m\lambda, \quad \text{where } m = 0, 1, 2, \ldots$$

(10.3)

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 5th 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 $a = 0.04 \text{ mm}, d = 0.50 \text{ mm}$ slit. Complete the table below.

<table>
<thead>
<tr>
<th>Separation</th>
<th>Measured $y$</th>
<th>Calculated $\lambda$</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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, $a = 0.02$ 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.

$$\Delta L = \frac{a}{2} \sin(\theta) = \frac{\lambda}{2} \quad (10.4)$$

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.

$$\sin(\theta) = \frac{\lambda}{a} \quad (10.5)$$

If we break up the slit in to 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.

\[ \Delta \ell = \frac{a}{4} \sin(\theta) = \frac{\lambda}{2} \]  

(10.6)

\[ \sin(\theta) = \frac{2\lambda}{a} \]  

(10.7)

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

\[ \sin(\theta) = \frac{m\lambda}{a} , \ m = 1, 2, 3, \ldots \]  

(10.8)

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 (10.8), calculate the laser wavelength (and corresponding uncertainty) for each spacing and the corresponding percent difference from 650 nm.

\[ D = \text{________________________} \]

<table>
<thead>
<tr>
<th></th>
<th>first order</th>
<th>second order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured ( y )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured ( \lambda )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% diff</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
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: \( d = \) ________________

<table>
<thead>
<tr>
<th>( m )</th>
<th>( y )</th>
<th>( \theta )</th>
<th>( \lambda )</th>
<th>( % \text{ diff} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

300 lines/mm grating: \( d = \) ________________

<table>
<thead>
<tr>
<th>( m )</th>
<th>( y )</th>
<th>( \theta )</th>
<th>( \lambda )</th>
<th>( % \text{ diff} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

\[
\sin(\theta_m) = \frac{m \lambda}{d}
\]  

(10.9)

29. Using equation (10.9), 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.
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**********:
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?
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 ¼ wave plates
- Magnetic optic rail
- Three magnetic optic mount
- One steel optic mount
- White screen with magnetic mount
- White light source
- Blackened microscope slide

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 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° 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 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?

*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.

3. 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.

4. 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 = ____________________

5. 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.
6. Adjust the analyzer to 90°. Note the effect on the transmitted light.
7. 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.
8. Perform the experiment. Insert P2 as shown. Rotate P2 from 270° to 90° (-90° to +90°) 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).

1. Looking through a polarizer, observe the reflection of randomly polarized light off the blackened glass slide. Which orientation of light is preferentially reflected? Light oriented parallel to the plane of the glass, or its compliment?

2. How does the angle of incidence θ 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 is different for light parallel 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° 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 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 ¼ wavelength behind the y component (phase shift of -90°). Such a device is called a ¼ wave plate. Now, the amplitude is constant as it rotates and the light is left circularly polarized (lcp). If we rotate the wave plate by 90°, the x component would be advanced by ¼ wavelength (+90° 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.
† That is, the electric field vector would trace out a left handed helix through space. This is best seen in the animation.
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 ¼ wave plate oriented at 45°.

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 ¼ wave plate for 560 nm (green) light. But it is not quite a ¼ 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°) 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‡ 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.

‡ Polycarbonate, in this case.
½ Wave Plate
If we add a 2nd ¼ wave plate oriented in the same direction as the first, you will create a ½ wave plate. Study the diagram below.

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

9. Combine both ¼ wave plates to create a ½ wave plate. Place this on the optical bench at 45° relative to P1. Is the light linear or circular? If linear, what is the direction of the polarization?

10. Orient the 2nd wave plate so that its fast axis is parallel to the slow axis of the 1st 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 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\(^\ddag\). 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.

\(^\ddag\) 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**††. 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.
†† Do not make a mess! Let’s keep the syrup in the flask.
7. Which way does the polarization rotate?

8. Explain how this could be used to monitor the sugar content of a solution (for example, fermenting wine)?
Useful Physical Constants*

<table>
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<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Speed of Light (exact)</td>
<td>$c$</td>
<td>$2.99792458 \times 10^8 \frac{m}{s}$</td>
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<tr>
<td>Elementary charge</td>
<td>$e$</td>
<td>$1.602176565(35) \times 10^{-19} C$</td>
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<tr>
<td>Electron volt</td>
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<td>$1.602176565(35) \times 10^{-19} J$</td>
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<tr>
<td>Plank’s constant</td>
<td>$h$</td>
<td>$6.62606957(29) \times 10^{-34} Js$</td>
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<tr>
<td></td>
<td></td>
<td>$h = h/2\pi$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.054571726(47) \times 10^{-34} Js$</td>
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<tr>
<td>Permeability of free space</td>
<td>$\mu_0$</td>
<td>$4\pi \times 10^{-7} \frac{Wb}{Am}$</td>
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<tr>
<td>Permittivity of free space</td>
<td>$\varepsilon_0 = \frac{1}{\mu_0 c^2}$</td>
<td>$8.854187187187... \times 10^{-12} \frac{C^2}{Nm^2}$</td>
</tr>
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</table>

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