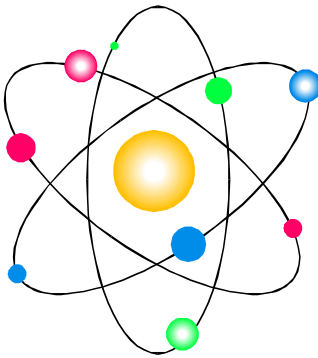


Physics 102 Laboratory Manual



Spring 2002

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1 General

Each student enrolled in Physics 102 must complete this course of labs concurrently. The structure will be pretty much like the Phy 101 labs.

There are a total of ten labs, roughly one per week. Lab classes are three hours long and all work should be completed during this time. Students may continue to use the same logbooks that they used in 101, and as in 101, these logbooks should *never* leave the lab without permission of the TA or lab manager.

2 Lab Reports

As before, the lab writeup requirements are not very demanding. There's no need to repeat what was said in the manual. Describe what was done, making appropriate sketches; present your data, results, and a brief discussion of errors. Also answer any questions that are asked in the manual.

3 Prelab Problem Sets

At the end of the lab manual, you will find a short set of questions for each lab, starting with lab II. These are to be completed before the lab each week and handed in at the beginning of your lab section. They should be trivial for anyone who has

read the lab write-up. TA's have the right to refuse to accept prelab problem sets if they see students working on them during lab time.

4 Grading

Lab writeups will be graded on a 5 point scale, with 4 being average. Anything below a 3 is considered a failed lab and must be re-done during reading week. The lab writeups will make up 2/3 of your lab grade, and the prelab problems sets 1/3. The lab grade will then count as 10% of your course grade.

5 Missed and Failed Labs

If for any reason you are unable to attend your assigned lab, you should attend one of the other lab sections during the week, if at all possible. You must inform the lab manager beforehand of the switch (E-mail will suffice). Whichever lab you attend, it's important that your lab notebook is graded by one of your usual TA's. It's *your* responsibility to see that your lab is graded, particularly if you attend a section which comes later in the week than your assigned section.

If you are unable to attend any of the lab sections on a particular week (or in the unlikely event that you fail a lab), there will be a make-up week during reading week.

If you feel that you will have some conflict that's impossible to resolve within this context, it's in your interest to inform the lab manager as soon as possible. As before, there will be a rather draconian policy about missed/failed labs:

- 1 missing lab = 1 letter grade drop in Phy 102.
- 2 or more missing labs = FAIL Phy 102.

6 Use of Computers

We will not make as much use of the computers this semester as last; however, they will remain set up at the lab stations. If students wish to use any of the programs for plotting or fitting, they may do so. Otherwise, most plots may also be made by hand.

Lab 1 - Introduction

1 Goal

The goal of this lab is to familiarize you with some of the concepts and equipment that you will use throughout the semester. In general, the labs will try to stay in step with the course material; however, in order to understand the use of some of the equipment, it will be necessary to introduce a few concepts in advance. Things which will be covered in this lab are

- Electric field, voltage, current, and resistance.
- The use of the digital multi-meter (DMM)
- Safety

2 Electric Field, Voltage, Current, and Resistance

Electric Field

As you have learned in class, the electric field (\vec{E}) is a measure of the force experienced by a test particle of unit charge, which results from the influence of all other charges in a system. The SI unit of electric field is N/C (Newton/Coulomb). In practice it is difficult to directly measure electric fields, because any sort of probe usually ends up influencing the field.

Voltage

Voltage (V) is a measure of potential energy. Like any potential energy, there is no such thing as “absolute” voltage; one can only speak of the voltage difference between two points. The voltage difference between two points is the amount of work needed to move one unit of charge from one point to the other. A *positive* voltage difference implies that one must do work to move positive charge, while one can extract work by allowing negative charge to move. A *negative* voltage difference implies the opposite. In other words, positive charge will tend to move from a higher voltage to a lower voltage, while negative charge will tend to move in the other direction. The SI unit

of potential is a “Volt” (V). It takes one Joule (J) of energy to change the potential of one Coulomb (C) by one Volt (V).

Current

Current (I) measures the rate at which charge moves. In these labs we will usually talk about current flowing through a wire. The SI unit of current is the “Ampere” (A). One Ampere is equal to one Coulomb/second (C/s).

Students are often confused about the sign of the current. The direction of the current is defined to be the direction of positive charge flow, *even though charge is usually transported by negative carriers (electrons)*; that is, if electrons are flowing from point A to point B, we say the current is flowing from point B to point A. With this definition, we can always say that current will tend to flow from a point of higher voltage to a point of lower voltage. For this reason, voltage is also called Electromotive Force (EMF).

Resistance and Ohm’s Law

The actual flow of current through matter is a complicated process, but it turns out that it can very often be characterized in terms of a linear relationship for a particular object (or electrical component). In other words, if one applies a certain voltage across the object and measures the current, then doubling the voltage will double the current. The constant of proportionality is called the “resistance” (R). The SI unit of resistance is called the “Ohm” (Ω), and it defined by “Ohm’s Law”

$$R = \frac{V}{I} \tag{1}$$

where R is the resistance in ohms, V is the voltage in volts, and I is the current in Amperes. A whole class of electrical components, called “resistors”, are designed to have a specific resistance. We’ll learn about these in more detail in lab III.

3 The Digital Multimeter (DMM)

One of our primary tools for the first few labs will be the Digital Multimeter (DMM). It’s often called a Digital Voltmeter (DVM), although it measures other things. The ones we will use have a display, a selector knob, and two wires, which are called “probes” or “leads”. You’ll see that the selector knob is divided into five regions, corresponding to the five functions of the DMM, with each region divided into several ranges, which define the full-scale reading (and therefore the precision) of the meter. The five things which the meter can measure are

- *DC Voltage* - in this mode, the meter will measure the average voltage difference between the red lead and the black lead. A positive reading means that the red lead is at a higher voltage than the black lead.
- *AC Voltage* - measures alternating voltage. Don't worry about this for now.
- *DC Current* - measures the average current flowing through the meter. A positive reading means that current is flowing in the red lead and out the black lead (remember, this really means that electrons are flowing in the opposite direction).
- *AC Current* - measures alternating current. Don't worry about this for now.
- *Resistance* - measures the resistance of an object placed between the two leads. There's no "direction" for resistance.

Measuring Voltage

In your lab setup, you will find a several batteries. A "battery" can be thought of as a source of voltage potential between its two contacts. Use the DMM to measure the different types of batteries. Establish what the voltage of each of them is and which terminal is positive (just pretend that this information *isn't* written on the side of the battery).

Now, connect the batteries, in series, in such a way as to make the following total voltages

- 3 volts
- 12 volts
- 6 volts

Use the voltmeter to verify that voltages are what you predict.

Measuring Resistance

You will find several resistors in your setup. Use the meter to measure their resistance, in ohms.

Measuring Current

Using ohms law, predict the current that will flow through each of the resistors if it is connected across the terminals of each type of battery. Use the meter to verify the

predicted value (hint, remember that the meter measures the current flowing through it).¹

4 Safety

In general, we will not be working with dangerous voltages in these labs. Still, it's good to understand some of the basic dangers of electricity.

The threat posed by electric power depends critically on the total current and the path it takes through your body. Very low currents (< 50 mA) pose little threat beyond a shock. It takes very high currents to actually damage the body (100's of Amperes or more); however, there can be an extreme danger posed by substantially lower currents. In particular, alternating currents of 100 to 150 mA passing through the heart can send the heart into "fibrillation" - a rapid, shallow, arrhythmic beating that is very quickly fatal. Higher currents will cause the heart to stop beating for the duration of the current, then resume normally. This is in fact how fibrillation is *stopped*.

The voltages needed to produce these lethal currents depend, of course, on the total resistance of the path. This depends on the condition of the skin and the area of contact.

Set the meter to measure resistance. Hold one lead between the thumb and forefinger of each hand and measure the approximate resistance. Based on this resistance, what voltage would it take to produce a lethal current of 100 mA?

Now connect the leads to the two brass bars. Hold one bar tightly in each hand and measure the resistance. How much voltage would it take to deliver a lethal current now?

Finally, soak your hands in the bowl of saltwater for about 30 seconds. Pat the excess water off of your hands, but do not dry them. Now repeat the measurement with the brass bars. What would be a lethal voltage now?

Why are water and electricity such a dangerous mixture?

Experienced electricians (ie, ones who have gotten a few shocks) will keep one hand in their pocket while working on a live panel. Why?

Skin resistance is one of the measurements made by a polygraph (lie detector). What do you think might happen to your skin resistance if you were lying and why?

¹It's very important that you do NOT connect the meter directly across the terminals in current mode. This could damage the meter.

Lab 2 - Electrostatic Fields

1 Goal

As we said, it's rather difficult to measure electric fields directly; however, in this lab, we'll learn to "model" electric fields using resistive paper and conductive paint.

This lab may seem kind of silly, but until the advent of modern computers, this was in fact how electric and magnetic fields were calculated for complicated geometries. This technique was used to design the cyclotron magnet in the Palmer basement, which you'll see in a couple of weeks. Very recently, a resistive model was made to double-check a computer calculation for a field within part of a micro-chip which was designed in the physics department.

2 Principle

Because the paper is resistive, voltage differences will cause current to flow. The current will follow the path that electric field lines would in free space. Because the paper is two-dimensional, it corresponds to a cross-section of an infinitely long three-dimensional body or bodies. Thus, a dot corresponds to a long line, a line to a plane, a circle to a cylinder, etc.

3 Lab Reports

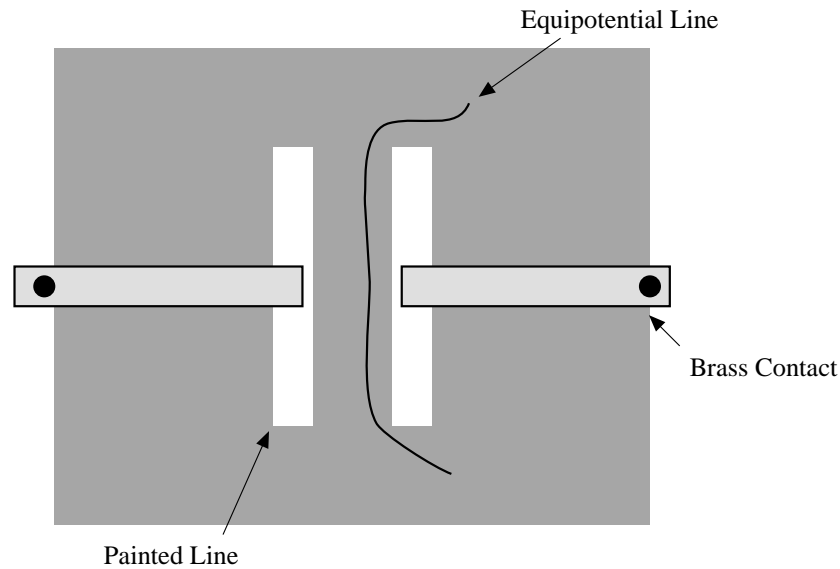
In this lab, you'll be making field maps on sheets of resistive paper. You only need to make one set of actual drawings per group, which should all be turned in with one member's lab notebook. All the lab notebooks should have reasonably accurate sketches of the field maps, and include the name of the person with the originals.

4 Geometries

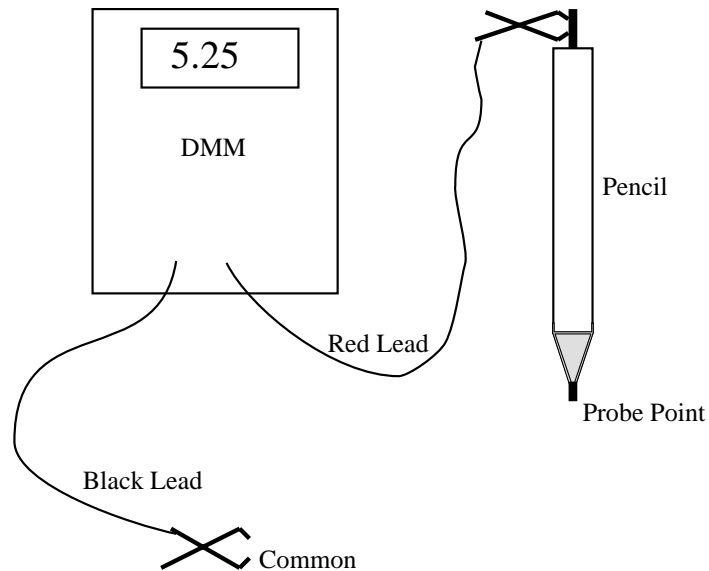
Note! For all the geometries you will draw, try to center the figures on the sheet as much as possible. While in most cases, exact measurements are not necessary, try to

be reasonably neat; ie, lines should be straight and of uniform width, circles should be round, etc.

Geometry 1



Use the conductive paint to paint two parallel lines on the page, each about 1 cm wide and 15 cm long, spaced 5 cm apart. Place one brass contact on each line. Set the power supply to 10V and verify it using the DMM. Attach one lead of the power supply to each bar. Attach one lead of the DMM to the negative bar and measure all voltages relative to that. Use the positive lead to “map” lines of equipotential. That is, find all the points on the sheet that are at a particular potential. The easiest way to do this is to attach the positive lead to the lead of a pencil and to make a mark at every point that has a particular potential, then go back and connect all points of the same potential. Trying to put the pencil on the sheet and “follow” lines of equipotential doesn’t work very well.



Map lines which are at the following potentials

- 5 V
- 1 V
- 7 V

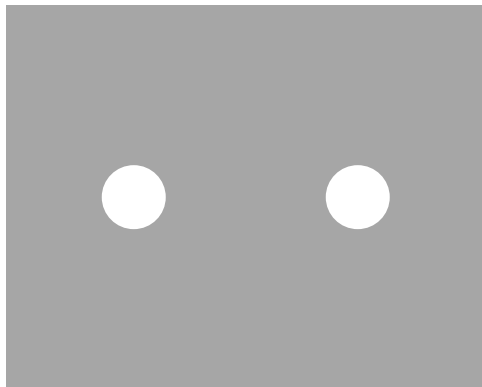
Carry the lines to the edge of the page. Be particularly careful once you get near the edge. What happens to the lines at the edge of the page? Why? (Hint: What is the orientation of the electric current relative to the lines of equipotential?)

If you have been careful to center your figure, then the lines you have drawn should allow you to predict the location of two other lines. What are they? Check a few points to verify that you are correct.

You'll notice that the lines look like the lines on a topographic map. What does it mean when the lines on a topographic map are close together? What does it mean when lines of equipotential are close together?

Make a plot of the potential versus distance along a line from the center of one line to the center of the other. What physical system are you modeling with these two lines? What can you say about the electric field in such a system based on the plot you have just made?

Geometry 2



Now paint two solid dots, about 2.5 cm in diameter and 15 cm apart. Place one brass contact on each one and map out several (at least 5) equipotential lines as before. Use these to sketch in (as dotted lines) approximate electric field lines.

Geometry 3



Paint one solid dot, about 2.5 cm in diameter, at the center of the page. Now paint a concentric circle with the same diameter as the brass ring. Place a brass contact on the dot and the brass ring on the circle. Put 10V across them. Map several equipotential lines. Make a plot of V versus R . Now calculate the electric field as a

function of radius using

$$E = -\frac{dV}{dR} \approx -\frac{\Delta V}{\Delta R} \quad (1)$$

where ΔV and ΔR are the finite differences between your lines. Take the position for each value of E to be the point halfway between the two lines you used to calculate it and make a plot of E versus R . Does it show the $1/R$ dependence that one expects for an infinite line of charge?

Lab 3 - DC Circuits

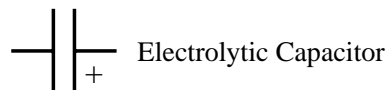
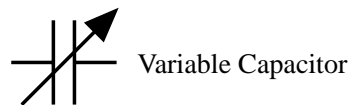
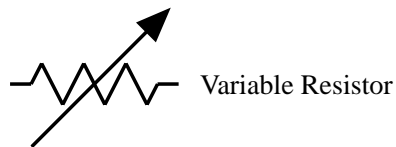
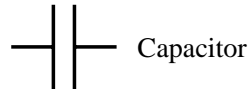
1 Goal

In this lab you will become familiar with basic DC (Direct Current) circuits.

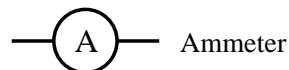
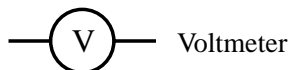
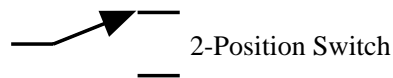
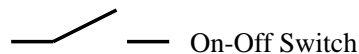
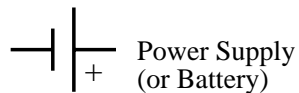
2 Introduction and Warm-up Questions

In this section you do not have to actually do any experiments. Just answer the questions.

You should familiarize with the following symbols:

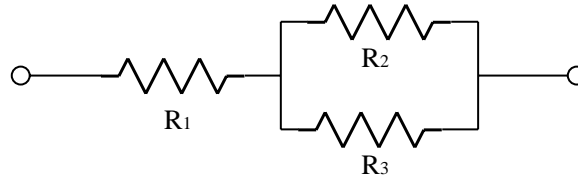


Warning!! Pay attention to the polarity!

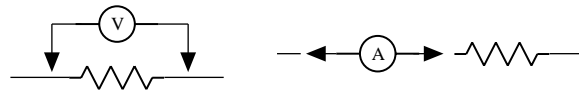


Problem 1

What is the effective resistance of two resistors R_1 and R_2 in series? in parallel? Answer the same questions for two capacitors C_1 and C_2 . What is the effective resistance of the following combination of resistors?



Problem 2



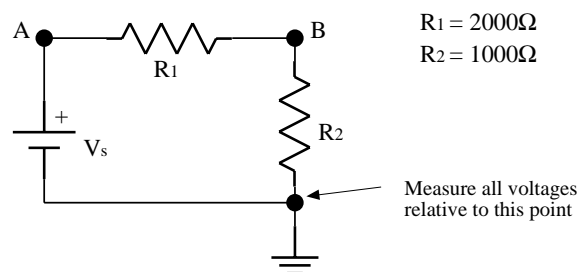
A voltmeter is placed in parallel with a resistor or a capacitor in a circuit. Why? An ammeter is placed in series with the components in a circuit. Why? What does this say about the internal resistance (resistance between the two probes) R_V and R_A of the two devices? What would be the ideal values of R_V and R_A ?

3 Circuits

Note! Realize that when you are constructing these circuits, it's not important that the circuit actually *look* like the schematic. Also, it's not really important what value the power supply is set to, as long as you know what it is. A nice round number like 10V is usually easiest to work with.

Resistors in Series

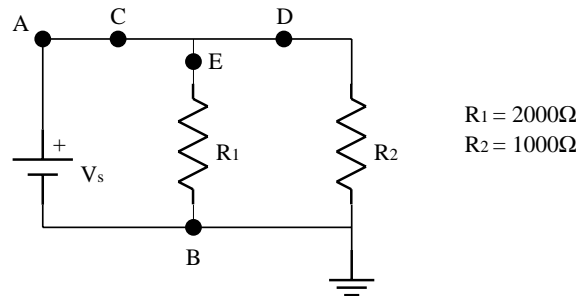
Construct the following circuit:



Measure the voltage at points A and B (relative to common). Measure the current passing through both points. Do these numbers agree with Ohm's Law? What size resistor could replace the two of them and give the same current at point A?

Resistors in Parallel

Construct the following circuit:

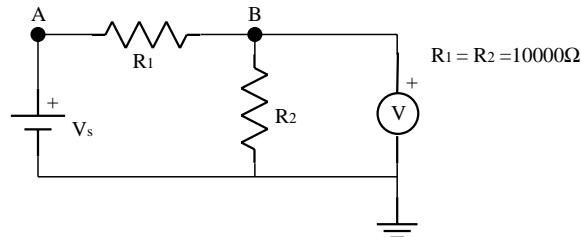


Measure the voltage at points A and B. Measure the current passing through points C, D, and E. Do your measurements agree with predictions? What value of resistor could replace R_1 and R_2 to give the same current passing through point C?

Meter Resistance

No measuring device is perfect. For example, every voltmeter allows some current to flow, which biases the measurement somewhat. Our digital meters are pretty good, so to investigate this we'll use the old analog meters that used to be used in these labs.

Set up the following circuit, using the old analog voltmeter:

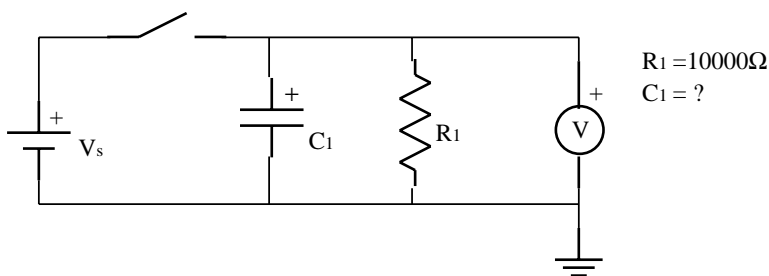


Verify the voltage at A using the DMM. Note that the two resistors have equal value. What voltage do you expect to read at B? What value does the analog voltmeter read? The reason is that some current is flowing through the voltmeter. It therefore acts like a resistor with a value R_V placed in parallel with R_2 . Based on the voltages you've measured, calculate the effective resistance of R_2 and R_V in parallel. Then use the fact that you know R_2 to calculate R_V .

(Try to) repeat this measurement using the digital voltmeter. What can you say about R_V for the digital voltmeter?

Capacitors

Wire the circuit as shown



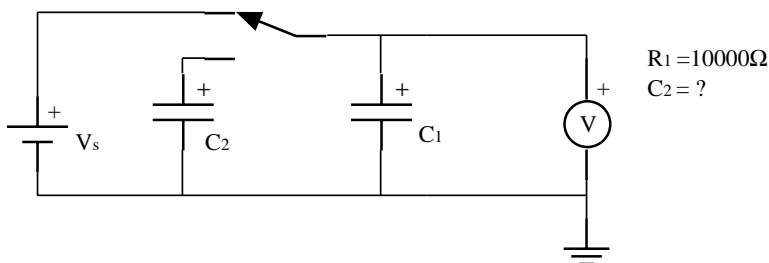
Close the switch to charge the capacitor. Now open the switch and measure voltage versus time, using the stopwatch. This goes pretty fast, so you should probably coordinate with your lab partners and take a couple of practice runs. Measure the voltage until it has dropped below 10% of its initial value.

Use the StatMost program on the computer to make a plot of V versus t . Fit the points to an exponential decay, ie

$$V = Ae^{-Bt} \quad (1)$$

and use this to calculate the value of C (with errors!).

Now that you have measured the value of one capacitor, you can use it to calibrate other capacitors. Wire up the following circuit:



C_1 is the capacitor that you have just measured and C_2 is a new, unknown capacitor. Place the switch in a position to charge C_1 . Measure the voltage across C_1 . Use an extra piece of wire to discharge (short) C_2 completely. Now move the switch into the other position so charge will flow from C_1 to C_2 . Measure the final voltage. What is the value of C_2 ?

Repeat the measurement, but this time do not discharge C_2 . What is the final

voltage measurement? Explain.

Lab 4 - Magnetic Force

1 Goal

The goal of this lab is to verify the magnetic force law and use it to measure the ratio of the charge of an electron to its mass (e/m). The lab is quite short to allow time for tours of the old Palmer Cyclotron (see next section).

2 Cyclotron Tours

During the lab, the class will be taken, in groups, to the Jadwin high bay to see the venerable Palmer Cyclotron magnet, originally located in the basement of Palmer Hall. As part of one of the first cyclotrons ever built, it was used for physics research from 1935 until the late 1960's. Since then, it has served as a valuable tool for instruction by creating a large area magnetic field of more than 1 Tesla. With a field this strong some very interesting effects can be demonstrated. The magnet was moved from Palmer Hall to Jadwin Hall in the fall of 1998.

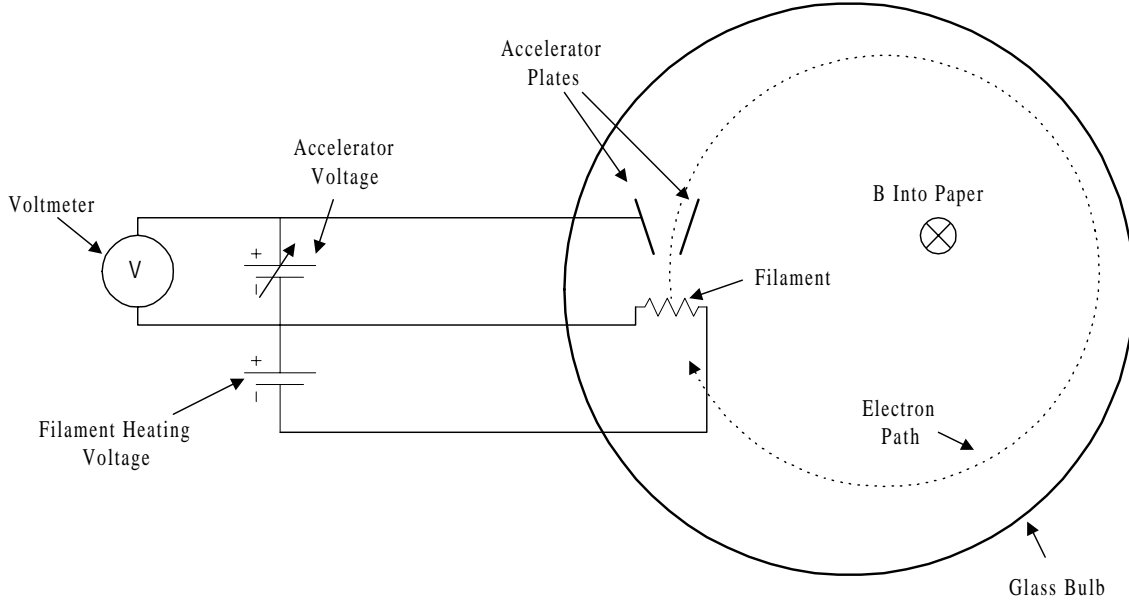
Warning!!

A 1 Tesla field is very powerful. Please observe the following rules:

- Remove all magnetic objects (iron or common steel) from above the waist. At some points you'll be leaning into the field and they could be pulled from you. Precious metals are OK, as is surgical steel (eg bone pins). If you wear wire frame glasses, just pay attention to them if you start to feel any tugging.
- Remove all magnetically encoded cards: credit cards, meal cards, MAC cards, etc. before entering the cyclotron enclosure. They will be erased by the magnetic field. Also it's a good idea to remove watches, as they could be damaged. There'll be a box outside the cyclotron enclosure for this purpose.
- At some point you will be allowed to "play" with the magnetic field. DO NOT, under any circumstances, put anything into the field other than the objects indicated by the tour guide. In particular, there are plenty of metal pieces lying around large enough to *cut through your hand* if you get them too close to the pole pieces. In general, don't put anything larger than, say, 1/4" in diameter by a few inches long into the field.

3 e/m Measurement

You see at your stations a rather complicated-looking device...



The principle of the device is quite simple. Within the large glass bulb is a filament, which can be heated by passing current through it. The hot filament ejects electrons from its surface. This filament is kept at a negative voltage relative the the nearby accelerating plates, so the electrons accelerate toward them, acquiring a kinetic energy given by

$$\frac{1}{2}mv^2 = eV \quad (1)$$

where m is the electron mass, v is the electron velocity, and V is a the voltage difference between the plates and the filament. The plates themselves are kept at more-or-less the potential of the rest of the device, so once the electrons pass through them, there is no electrostatic acceleration.

The external “Helmholtz” coils provide a fairly uniform magnetic field B within the globe. It is straightforward to show that the field at the center of the coils is

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 I N}{R} \quad (2)$$

Where R (=15 cm) is the radius of the coil, N (=130) is the number of turns, and I

is the (adjustable) current. This magnetic field bends the accelerated electrons into a circular trajectory. The radius is derived by equating the magnetic force with the centripetal force, that is

$$Bev = m \frac{v^2}{r} \quad (3)$$

Combining equations (1) and (3), one finds an expression for the ratio of the electron charge to its mass

$$\frac{e}{m} = \frac{2V}{B^2 r^2} \quad (4)$$

You will be able to see the electrons because the bulbs are filled with low pressure hydrogen. Some of the energetic electrons strike the hydrogen atoms and knock the atoms into excited states. When they return to their ground states, they emit visible light. You'll learn about this in a few weeks.

Of course, e/m is a constant. In this experiment, we can keep the accelerating voltage fixed and study the relationship between r and B by varying the current in the coil. According to (4), if we keep V constant, we expect

$$\frac{1}{r} = \alpha B \quad (5)$$

where

$$\alpha \equiv \sqrt{\frac{(e/m)}{2V}} \quad (6)$$

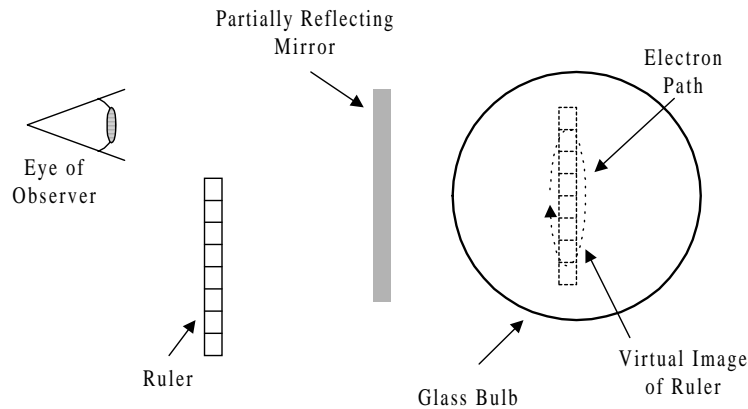
Alternatively, we can keep B constant, and vary V . According to equation (4), There should be a linear relationship between r^2 and V , what is it?

4 The Measurement

First, play with the apparatus a little. Set V to about 150 V with no current in the coils. You should see a faint beam of electrons coming from the filament. Bring the small bar magnet near the beam and see if you can deflect it. Be very careful as the bulb is quite fragile.

Next, increase the current in the coil until the the beam of electrons is bent into a circle, completely contained within th bulb. Again see what effect the small bar magnet has on the trajectory. Now it's time to make some measurements.

This measurement would be very straightforward if we could reach in and put a ruler in the bulb, but unfortunately we can't, so we use a very clever trick.



Position the partially reflecting mirror near the bulb so you are looking through it at the circular electron path. Now position the lighted ruler on your side of the mirror, so that its image in the mirror lies on top of the electron trajectory. Use “parallax” to fine tune the position. That is, move your head back and forth a bit and see if the ruler moves relative to the electron beam. Adjust the distance between the ruler and the mirror until there is no visible difference in the position of the image of the ruler and the electron beam. At this point the mirror will be exactly half way between the ruler and the electron beam, and you can use the apparent image of the ruler to measure the diameter of the electron path. This is known as a “virtual image” and you’ll learn more about them in a couple of weeks.

First, keeping V fixed, measure the radius for a range of I values (say 5), for which the electron beam is completely contained in the bulb. For each value of I , measure and record the radius of the electron path. Make a plot of $1/r$ vs. B . Is it linear as expected? If so, use its slope to calculate e/m (including error!) based on (5) and (6). How does it compare to the accepted value?

Next fix I at one of the middle values and vary the accelerating voltage V . Again measure about five points and make a plot of r^2 vs. V . Again, use this to calculate e/m . How does it compare to the accepted value? to your previous measurement?

Lab 5 - AC Circuits I

1 Goals

Many interesting uses of electricity involve “AC” circuits - those in which currents and voltages are changing with time. In this lab we’ll try to investigate some simple concepts in this area.

2 The Oscilloscope

Your primary tool for this lab will be the oscilloscope, or just “scope”. Oscilloscopes look a little intimidating, but their basic principle of operation is quite simple. They are used to make a very fast plot of voltage versus time for one or more sources. For those of you thinking about medical careers, this is similar to a chart recorder (used for EKG’s, EEG’s, polygraphs, etc), only much faster.

These scopes can plot one or two inputs (or “channels”) at frequencies up to 60 MHz. You’ll be supplied with detailed instructions for the scope, but you really only need to worry about a few things:

- *Time Base* - This is the scale of the horizontal axis. In other words, how much time each division corresponds to. This is common to both channels.
- *Sensitivity* - This is the scale of the vertical axis, in volts per division. It can be set separately for each channel.
- *Trigger* or *Sync* - This is the condition which will start the plot. In the simplest case it is set by
 - *Source* - Which input controls the start of the plot.
 - *Level* - What level (in Volts) will start the plot.
 - *Slope* - Directs whether to start the plot when the input crosses the specified “level” with a positive or negative slope.

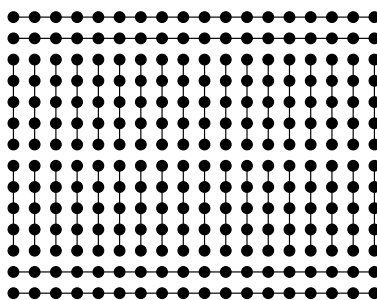
For example, Source=“Chan. 2”, Level=“.2V”, Slope=“Negative” would start the plot when the signal on input 2 crossed from greater than .2V to less than .2V.

The scopes also have “cursors”, which allow you to measure the amplitude of signals and the distance between peaks (used for calculating frequency).

These modern scopes also have a magic “Autoset” button which will usually pick reasonable settings for a particular set of inputs. It’s often a good way to begin.

3 Bread Board

You’ll build the circuits for this lab using a “bread board”, also known as a “proto board” or “perf board”.



The holes of the bread board are designed to firmly hold the leads of electronic components or the ends of wires. The holes are connected to one another approximately as shown. Components are connected together by pushing the leads into connected holes.

4 Signal Generator

You’ll generate inputs to your circuits using the “signal generator” at your station. This device can generate square, triangle or sine waves of adjustable amplitude and frequency. The “function” knob on the right is actually a double knob. The outer knob controls the type of waveform; set it to the sine wave shape. The inner knob controls the amplitude; set it to maximum (all the way clockwise). You can then control the frequency with two knobs. The knob on the left sets the full scale frequency. This is then multiplied by the number set on the two concentric knobs in the center. That is, if the knob on the left is set to 1K, the outer center knob is set to .5 and the inner center knob is set to 7, frequency will be $1000 \times .57$ or 570 Hz. Note that this setting is only approximate and you should rely on the frequency read out by the oscilloscope when actually taking data.

5 Transducers

Electric circuits are used to process many things - sound for example. For this to happen, signals must be converted to and from voltage or current levels. A device which does this is known as a “transducer”.

As an example, a speaker can convert electrical signals into sound, but it can also be used the other way around to convert sound into voltage levels. Connect the earphone to channel 1 of the scope. Set the scale to about 10 mV/div and the time scale to about 100 ms/div. Set the trigger to “auto” and talk into the earphone. Observe the trace it makes on the screen. See if you can identify the individual words.

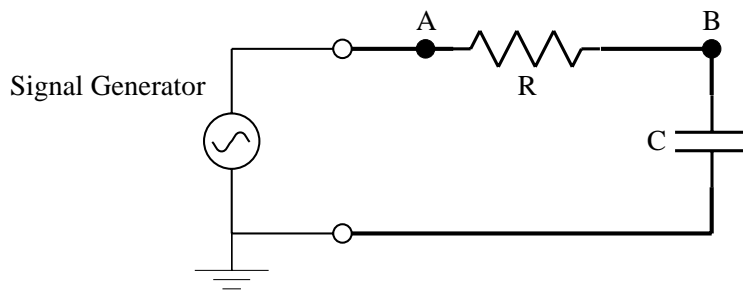
Set the time scale a bit faster, say 5 ms/div, and try to whistle or hum to generate tones. See if you can generate a sine wave.

6 Filters

As you saw in the previous section, sound is in general a complicated function. Mathematically, we can represent any sound as a combination of many different frequencies. One of the most basic operations we could do on sound (or any other sort of signal) would be to construct a circuit which would transmit some frequencies while blocking others. Such a circuit is known as a “filter”.

Low Pass Filter

Construct the following circuit using the bread board



Use $R = 10 \text{ k}\Omega$ (brown-black-orange) and $C = .05 \mu\text{F}$ (.05M) Using the grounded line as a reference, connect probe A to point A and probe B to point B.

This circuit is called a “low pass filter” because it allows low frequency signals to pass from point A to point B, but not high frequency signals. The terms “low” and

“high” mean slow or fast compared to the characteristic RC time of the circuit. The “characteristic frequency” of the system is

$$f_0 \equiv \frac{1}{2\pi RC} \quad (1)$$

You’ll be using the scope to measure the ratio of the voltage at point B to that at point A as a function of the signal generator frequency. You’ll have to adjust the time scale throughout your measurements. A good place to start is to set the signal generator to approximately f_0 . Then, on the oscilloscope, set the sensitivities to 2 V/div and the time base to 1 ms/div. You can go faster or slower as you change the frequency.

To measure the amplitude of a signal, set the scope cursors to “ ΔV mode” and position the horizontal cursors to the highest and lowest point on particular trace. The peak-to-peak difference will display on the screen.

To measure frequency, set the scope cursors to “ $\frac{1}{\Delta t}$ mode”, then position the two cursors at two consecutive peaks. Try to be as precise as possible. The frequency will display on the screen.

Make a plot of square of the ratio of V_{pp} at point B to that at A as a function of frequency; that is, plot

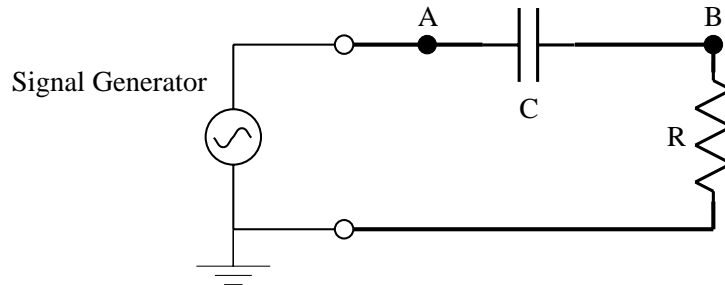
$$\left(\frac{V_{pp}^B}{V_{pp}^A} \right)^2 \quad \text{vs} \quad f \quad (2)$$

for frequencies from 20 Hz to 3000 Hz. We plot the square because we are usually interested in the fraction of transmitted *power*, which will depend on the square of the voltage. Use the special log paper provided. (Question: why is acoustic response almost always plotted on a logarithmic scale?) Take enough points to get an accurate picture of the function, say about 10. Don’t try to space the points evenly in frequency. You’ll want to take lots of points where the function seems to be changing quickly as a function of frequency. It’s probably easiest to plot data as you go, rather than to wait until the end. Indicate f_0 on your plot.

In your log book, explain qualitatively the general shape of the plot, in terms of the things you know about resistors and capacitors.

High Pass Filter

Construct the following circuit



Use the same component values as before. This is called a “high pass filter” because it allows only high frequencies to pass from point A to point B.

Make the same plot that you made for the low pass filter. If you wish, you can even make the two plots on the same piece of paper. Again, indicate f_0 on the plot and explain qualitatively the behavior you’ve observed.

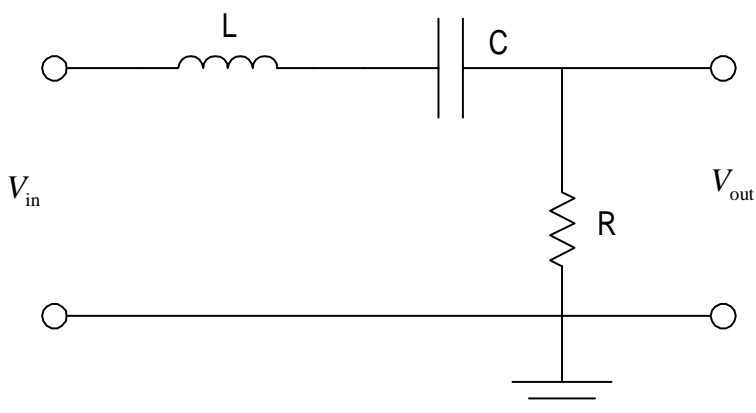
Lab 6 - AC Circuits II

1 Goals

The goal of this lab is to learn something about electrical resonances, which are fundamental to such things as television tuners, radio receivers, etc...

2 Bandpass Filter

Last week you learned to make a high-pass and a low pass filter; however, as anyone who's ever used a graphic equalizer knows, one sometimes wants to select a narrow range of frequencies. Construct the following circuit using the breadboard, with the component values $C = .1 \mu\text{F}$, $L = 85 \text{ mH}$, and $R = 50 \Omega$



Connect the circuit to the signal generator and the scope, as you did last week. Using the special log paper, make a plot of

$$\frac{V_{out}}{V_{in}} \text{ vs } f$$

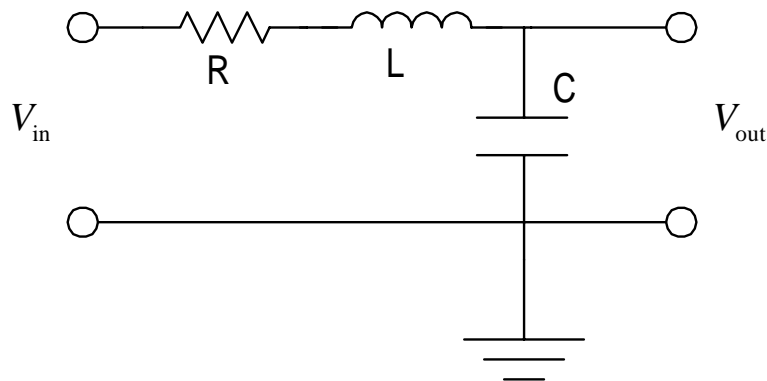
What is the peak amplitude? at what frequency? Explain the shape in terms of total impedance of the circuit

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \quad (1)$$

where $\omega (= 2\pi f)$ is the angular frequency. Based on this, calculate the expected frequency of the peak to be at. How close is your measured peak?

3 Resonant Behavior

Now move the circuit around, as follows



As you can see, you've really constructed the same circuit, you're just looking at a different part of it (If we had more sophisticated scopes, you wouldn't have to redo the circuit). Again make a plot of

$$\frac{V_{out}}{V_{in}} \text{ vs } f$$

Only this time, you'll have to adjust the vertical scale of the paper, because you'll see it get much bigger than one.

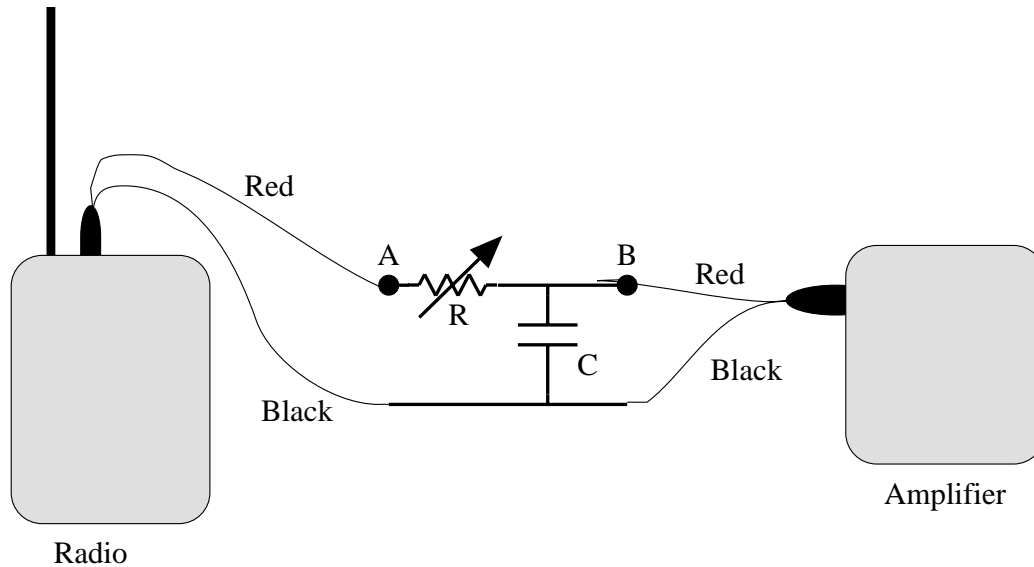
What you're seeing is an electrical resonance. You've already learned a little about resonant behavior in mechanical systems, involving springs, masses, and damping forces. If we make the correspondence between electrical charge in a circuit and mechanical displacement in a physics system, then which electrical component (L , R , or C) corresponds to mass? to the spring constant? to a dissipative damping force?

4 Example Application - Tone Control

Some of the most common uses of filters involve the processing of sound. A variable low-pass filter can serve as a simple tone control.

For this section, you'll use a small AM/FM radio. You'll take the signal from the earphone jack, filter it, then use the small amplifier to hear the result.

Using the bread board, wire the circuit as follows



Use the $1\text{ k}\Omega$ variable resistor and the $1\text{ }\mu\text{F}$ capacitor (105). Connect probe A to point A and probe B to point B. Turn on both the radio and the amplifier. Set the radio to FM and select a station that comes in clearly (which won't necessarily be your favorite station). Describe what happens to the sound as you increase the resistance of the variable resistor.

Try to describe in words any visual differences between the signals measured at points A and B, when the resistance is a maximum.

Now interchange the capacitor and resistor to make a high-pass filter and answer the same questions, only now observe what happens as the resistance *decreases*.

Note: please remember to turn off both the radio and the amplifier when you are done using them, to conserve the batteries.

Lab 7 - Geometric Optics I

1 Introduction

Geometric optics is a practical subject, leading directly as it does, to the understanding of very practical optical instruments: eyes; eyeglasses, cameras, magnifiers, microscopes, telescopes, projectors, medical endoscopes. Geometric optics rests on three simple assumptions:

- (1) Light travels in straight lines, called rays;
- (2) Light rays cross each other with no interference between them;
- (3) Whenever the rays strike the interface between two media in which the speed of light is different (e.g., air-glass; glass-air; air-water, etc.) the rays bend (change direction), by an amount which depends on the two speeds (Snell's Law)

The purpose of these laboratories is fourfold:

- (1) to verify and thus become familiar with the most important law in geometric optics, the law that governs the bending of light at the interface between two transparent media, Snell's Law, and to measure an index of refraction;
- (2) to measure the critical angle of total internal reflection (the basis of fiber optic light pipes and cystoscopes);
- (3) to use and thus become familiar with the lens equation for thin lenses and the formula for magnification of the images; as well as the method of ray tracing;
- (4) to understand, build and use, several optical instruments (based on the three principles of geometric optics) which extend the power of your sight, and let you see things which you could otherwise not see.

2 Pinhole Camera

The pinhole camera is a simple device which depends for its operation, solely on the first two assumptions of geometric optics: light travels in straight lines called rays; the rays cross each other without affecting each other. Construct and use a pinhole camera as described below.

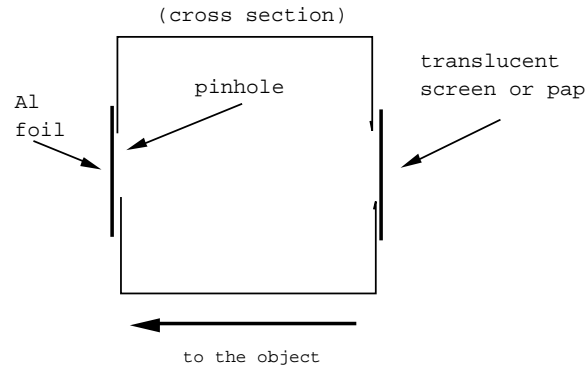


Figure 1

- (1) Unfold the folded up box with which you were provided, and use the knife to cut an approximately square hole (approximately 5 cm. on a side) in each of face of a pair of opposite faces.
- (2) Cover one of the holes with a piece of aluminum foil, and the other hole with a sheet of translucent paper or plastic — non-shiny side to the outside. Use adhesive tape to hold them in place.
- (3) Make a pinhole in the aluminum foil, using a pin or needle. Your pinhole camera is now complete.

Use the pinhole camera to view (form a picture of) the filament of a clear glass light bulb, or the array of colored light bulbs, by pointing the pinhole side toward the bulb(s) and looking at the plastic covered hole, keeping it at a comfortable distance from your eye. Watch the image as you move toward or back away from the light bulb, or the array of colored bulbs.

Now see if you can get a picture of the outdoors, though the window. You may have to put a black cloth over your head and the camera to get rid off extraneous light, and you may even want to enlarge the pinhole slightly with a sewing needle, to get a bit more light. Explore. Q: Were the pictures erect or inverted? Q: Did you have to be at any particular distance for the image to be in focus?

Now write your name on the pinhole camera and put it aside — we shall be using it later to make a lens camera. (You may take it with you after the next week's lab, if you like).

3 Snell's Law

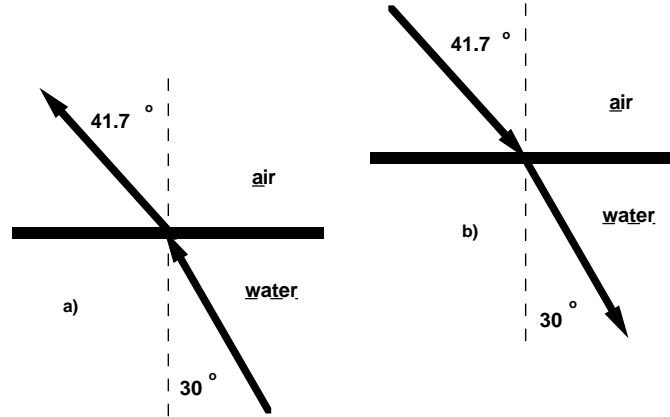


Figure 2

We now examine the bending of light at an interface (between glass and air), (Snell's Law).

It is customary to describe the bending (refraction) by giving two angles: the angle between the incident ray and the perpendicular to the boundary; and the angle between the bent (refracted) ray and the perpendicular to the boundary. As an example, in the figures at the right, 2a shows a ray traveling through water at an angle of 30° with the perpendicular to the boundary is bent as it crosses the interface into air, and now makes an angle of 41.7° with the perpendicular. It does not make any difference which way the light is going — if from water to air (2a) and the angle in water is 30°, then the angle in air will be 41.7°; if from air to water (2b) and the angle in air is 41.7°, the angle in water will be 30°. That is, for an air/water interface, the angle 30° in water is permanently paired with the angle 41.7° in air. The same is true for other pairs of angles. This pairing was first documented by Claudius Ptolemy (140 A.D) for air and water. It is the anatomy of this pairing that the ancients could not find, but Mr. Snell, fifteen centuries later, did.

It was not until 1621 that Snell found the rule:

$$n_{air} \sin \phi_{air} = n_{water} \sin \phi_{water} \quad (1)$$

Where n is the “index of refraction”. Every transparent material has its own index of refraction. The values of the index of refraction for a variety of such materials are given in the table below:

Vacuum (by definition)	1	Crown Glass	1.52
Air	1.0003	Crystalline Quartz	1.54
Water	1.33	Heavy Flint Glass	1.65
Ethyl Alcohol	1.36	Sapphire	1.77
Fused Quartz	1.46	Diamond	2.42

Note that the index of refraction of air is so close to 1.00 that we take it to be 1 in all that follows.

More generally, when light is refracted at an interface between two media of refractive index n_1 and n_2 ,

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \quad (2)$$

Although Snell just assigned n as a property of a material, we now know it is simply a measure of how much greater is the speed of light in a vacuum (c , the fastest speed known) than it is in the particular material (v). Thus:

$$n \equiv \frac{c}{v} \quad (3)$$

or stated another way, for any two media, 1, 2

$$n_1 v_1 = n_2 v_2 = c \quad \text{or} \quad \frac{n_1}{n_2} = \frac{v_2}{v_1} \quad (4)$$

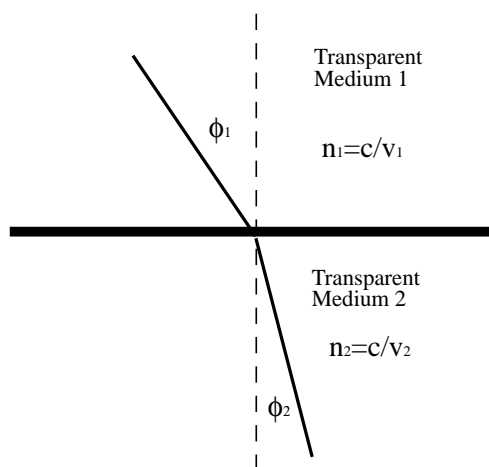


Figure 3

4 Snell's Law Measurements

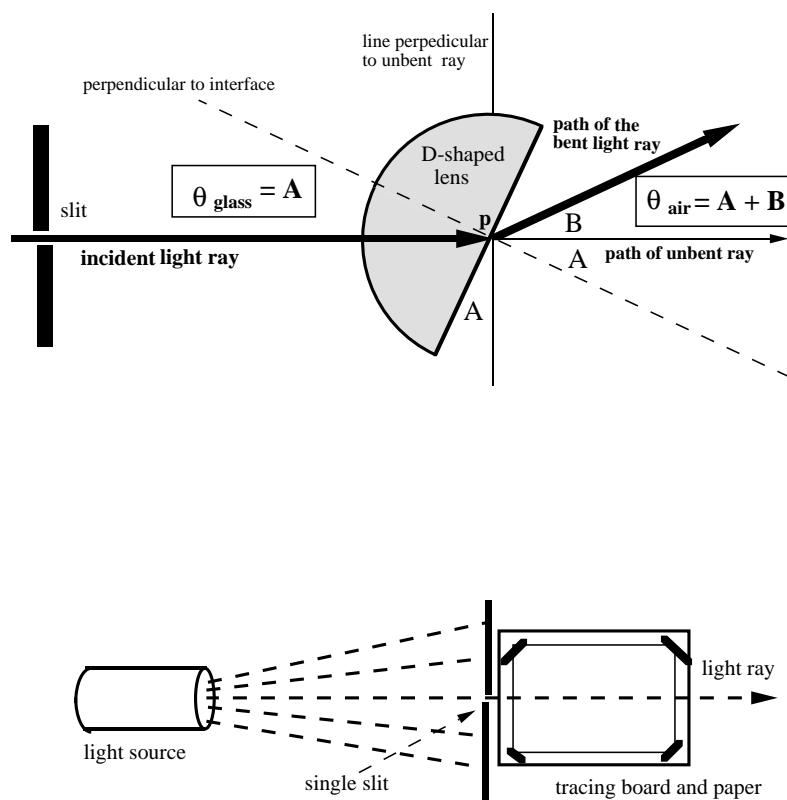


Figure 4

To produce one sharp non-diverging light ray, block off all but one slit. Position the light source, as shown in the diagram, and rotate the housing and light bulb until the filament of the bulb is vertical (as evidenced by sharp shadows).

Tape down the tracing paper, and using a straight edge, draw a long, straight line along the light ray.

Using the protractor, carefully draw a line perpendicular to the ray about 10 cm from the slit.

Now place the D-shaped lens on the board, with its straight edge along your perpendicular line and the curved face *toward the light source*. Slide the lens along the line until the ray leaving the lens follows the line you drew along the original ray. This guarantees that the center of curvature (P) of the circular side of the lens lies on the original ray and that the incident ray suffers no angular deviation at the curved surface. Using a sharp pencil, trace around the circular side of the lens. Before you

move the lens, note the spacing of this line from the glass due to the finite size of the pencil line (note: If you rotate the lens around P so that P remains in its original position then the incident ray through the curved surface will always be perpendicular to the curved surface and no bending of the ray occurs there. All the bending you are measuring takes place when the ray passes from glass to air through the straight side).

Rotate the lens about 5° , (angle A on the diagram), carefully centering the lens by fitting the circular edge to your traced line. Draw a line along the straight edge of the lens, and label it (1); also make a mark and write an (1) on the paper in the center of the outgoing, bent ray about 10 - 15 cm from the lens.

Rotate the lens approximately another 5° and repeat the last step, this time labeling with a (2)

Continue turning the lens through 5° angles, labeling with successive numbers until you find that there is no emerging ray.

Draw lines along the paths of the outgoing rays (through your marks and the center of curvature, (P). Measure the angle B between the outgoing ray and the incident ray's direction, and the angle A between the line drawn along the straight edge of the lens and your perpendicular line. Do this for each of the positions of the lens.

Make a table showing the the measured angles A , B , and the pair of computed angles $\phi_{glass} = A$, and $\phi_{air} = A + B$. Then compute the index of refraction (n) of the glass for each pair of angles $(\phi_{glass}, \phi_{air})$.

Plot the computed indices of refraction as a function of (ϕ_{air}) . Draw a best fit horizontal line through the points.

Q: Do they lie approximately on the line? Q: What is your best estimate of the index of refraction of the glass in the lens?

Ptolemy recorded the following data for water in the second century AD:

Angle in air (deg.)	Angle in water (deg.)
10	8
20	15 1/2
30	22 1/2
40	28
50	35
60	40 1/2
70	45
80	50

Plot Ptolemy's data in the same way you plotted your own. Q: Did you have more or less spread than Ptolemy? Q: From Ptolemy's data, what is your best estimate of the index of refraction of water? In each case compute a mean and take the spread between the maximum and minimum values of n and state the value of n as: mean \pm half the spread.

5 Total Internal Reflection

As a check on your Snell's Law results, using your measurement of the glass' index of refraction, compute the critical angle ϕ_c for total internal reflection within the glass. Then measure ϕ_c it is the value of ϕ_{glass} for which ϕ_{air} is exactly 90° . Q: Do experiment and prediction agree? Q: What happens when the angle of incidence ϕ_{glass} is greater than ϕ_c ?

Lab 8 - Geometric Optics II

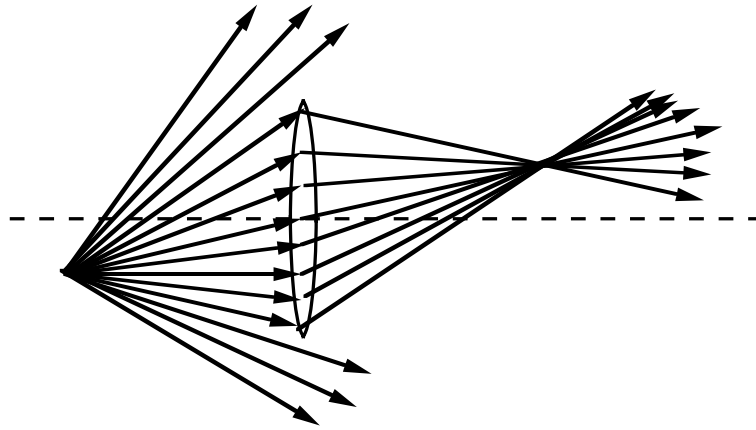


Figure 1

1 The Lens Equation

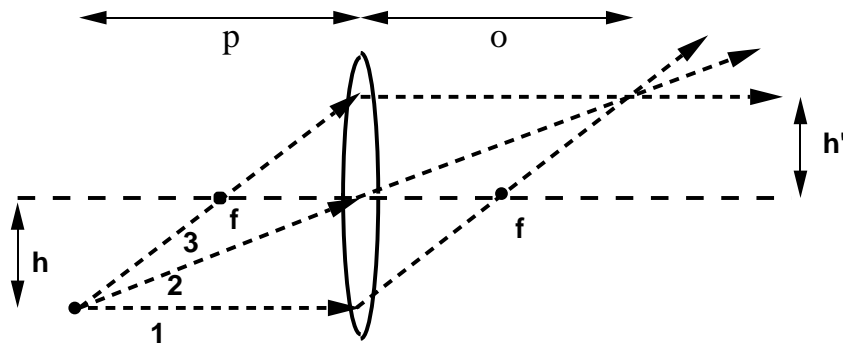


Figure 2

First, we'll define some terms

- *Object* — anything which emits rays of light, either because it is self-luminous, or because it is illuminated;
- *Real Image* — when all the rays from a point of the object after passing through the lens, converge to a second point, that second point is called the real image;
- *Virtual Image* — when all the rays from a point of the object diverge after passing through the lens, and the continuation in a straight line of the rays (behind the lens) converge to a second point, that second point is called the virtual image;

- *Object Distance* (p) — distance from object to lens;
- *Image Distance* (i) — distance from lens to image;
- *Focal Length* (f) — the distance of the (special) image point made by parallel rays, i.e. from rays coming from an object at infinity. The focal length is positive for a converging lens, negative for a diverging lens. Converging strength goes as $1/f$;
- *Height of object/image* (h/h') — length of the object/image perpendicular to the principal or optic axis.

Then there are only two equations you need know

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

and the lateral magnification given by

$$m \equiv \frac{h'}{h} = -\frac{i}{p} \quad (2)$$

(later we will want the angular magnification)

With the following convention for signs:

- (1) Focal length (f) is positive for converging lenses (fatter in the middle than at the edge) and negative for diverging lenses (thinner in the middle).
- (2) Object distance (p) is positive on the side of the lens from which the light is coming (normally the case but not necessarily when combination of lenses is used), negative if on the side of the lens to which the light is going.
- (3) Image distance (i) is positive on the side to which the light is going, negative if on the side from which light is coming. (Equivalently, i is positive for a real image, negative for a virtual image).
- (4) Object and image heights (h and h') are positive for points above the axis, negative for points below the axis.

2 Ray Tracing

Ray tracing is another way to solve the lens equation and to get the magnifications. As a visualization of the action of a lens on light rays, it is, of course, more graphic than the algebra of the lens equation. It is useful to know, and often very instructive.

Given a luminous object and a lens, all the rays which leave the object and strike the lens, are brought back to a focus after passing through the lens — either to a real focus where all the rays actually cross, or to a virtual focus, a point from which all the rays seem to diverge. All the rays that miss the lens are, of course unaffected and contribute nothing to the image. You can see how the diameter of the lens enters — not with any effect on the focusing properties, but rather on how much light is gathered, and thus, how bright the image will be.

As far as ray tracing, of all the rays that enter the lens, there are three which are particularly useful (refer to figure 2):

- (1) The ray parallel to the optic axis — is bent by the lens so that it goes through the focal point on the far side of the lens for diverging lens the ray parallel to the axis is bent so that it seems to have come from the focal point on the side from which the light is coming.
- (2) The ray that hits the lens right in the middle — is not bent at all (because the faces of the thin lens are parallel at that point, so no net bending occurs) same for diverging lens.
- (3) The ray that goes through the focal point on the side from which the light is coming — is bent so as to leave the lens parallel to the optic axis for diverging lens, the ray that is heading toward the focal point on the far side is bent so that it is parallel to the axis.

Any two of these rays is sufficient to give the position of the image and its height — the undeviated ray is particularly useful in establishing the linear and the angular magnification.

3 Measuring Focal Length

In this part we use an apparatus consisting of: two converging lenses each with a different focal length; a screen on which to focus, observe and measure the images; two light bulbs — one blacked over except for a small region at the top (the bulb's power

rating and the numerals “15” – printed in the unblackened region and illuminated from within will be an object whose image you focus and measure on the screen), and one bulb, mounted across the room in various locations (to be used when a bright, distant object is needed). You are also provided with a long metal bar (optical bench) on which to mount and align the lenses, screen and markers.

The object of this part is for you to find the focal length of each of the two lenses by arranging for each lens in turn to form an image of a luminous object, making appropriate measurements, and applying the lens equation.

Using a Distant Object

Mount the screen and the weaker of the two lenses provided, on the optical bench.

Choose the most distant of the bright light bulbs which are along the walls of the lab, and using that bulb as the object, focus its image on the screen. Measure (i) the distance between the lens and the image on the screen.

Find the distance from the lens to the object (p) (the distant light bulb), using a long tape measure, or even by pacing it off. Use this object distance (p) and your measurement of the lens-screen distance, i.e., the image distance (i) to compute the focal length (f) of the lens, using the lens formula.

Q: Why is a crude measurement of the object distance adequate? Q: How close does the image distance come to being equal to the focal length?

Using a Near Object

Mount the blacked-over bulb on the table-edge clamp, with its top facing down the optical bench. The bulb should be about 15 cm beyond the end of the bench.

Place the screen at the other end and the lens in between.

Slide the lens along the bench until it focuses an enlarged image of the “15” on the screen. (You may have to adjust the height of the components to have the light through the lens fall on the screen.)

Calculate the actual measured magnification ($m = h'/h$), and also compute the magnification from the bulb- lens distance (p) and the lens-screen distance (i), ($m = i/p$); compute the focal lengths (f) from the bulb-lens distances and the lens-screen distances.

Q: Is the image upright or inverted? Is it real or virtual? Now measure: lens-bulb distance (p), lens-screen distance (i), height of numerals on the screen (h), height of numerals on the bulb itself (h'). Repeat the measurements for the other location of the lens which yields a focus on the screen. Q: There are two locations of the lens

which yield a focused “15” — why? (Hint: Look at the lens equation.) Q: Is this second image enlarged or reduced?

Repeat the focal length measurements for the other lens (the stronger) lens.

4 The Camera

The simple camera consists of a converging lens and a box. The lens in one side of a box brings a real image of the objects in front of the camera to a focus on the opposite side of the box, where the film is. Since we want the real image exactly in the plane of the film, focusing is important, and thus, so is the focal length of the lens and a lens which can be moved toward or away from the film. The amount of light gathered, and thus the brightness of the image, depends, of course, on the diameter of the lens.

Look once more at the scene outside through your pinhole camera. Then make a hole in the aluminum foil about the diameter of one of the two lenses. Put one of the two lenses (trial and error), in front of the hole, and move the lens toward and away from the hole in the aluminum foil until you get a picture of the great outdoors on your translucent plastic. Now you have a camera. Q: What is the difference in the image between what you remember of the pinhole camera and what you see now?

5 The Eye as a Camera

The eye is a camera with a fixed image distance (i), but in which the focal length of the (converging) lens can be changed by muscular action. Thus the normal eye lens can have its shape changed. The change in shape changes the focal length and therefore its converging power (the process is called accommodation). When a normal eye is relaxed (longest focal length, least converging power) it can bring parallel rays (from an object at infinity, i.e., far, far away) to a focus on the retina. For nearer objects it can “accommodate” (i.e., decrease its focal length, and increase its converging power) so that it can continue to bring the nearer objects (rays more divergent) to a focus on the retina. The normal eye can accommodate and produce an image on the retina for something as close as 15 centimeters (for younger people). The normal eye can thus “accommodate” for objects anywhere between 15 centimeters (called the “near point”) and far, far away (called the “far point”).

Measure your own near point without glasses: bring a book to where it is comfortable to read; now bring it even closer to your eyes so that it becomes uncomfortable

to read, and somewhat blurry; Now move it back away from your eyes until it just becomes clear and comfortable to read. Have your partner measure the distance from the book to your eyes — that is your “near” point distance. ..

The eye that is not “normal” may have:

- (a) the far point too close (nearsightedness or myopia) so that it cannot focus distant objects, this relaxed eye is too convergent; or,
- (b) the near point too far (farsightedness or hyperopia), when the eye cannot become convergent enough to focus on close objects.

Note that a nearsighted eye was given a divergent (negative) eyeglass because its convergent power had to be reduced , and a farsighted eye which does not have sufficient converging power has its converging power added to by the addition of a converging (positive) lens.

For those of you who wear glasses to read, a pinhole held at your eye will serve in lieu of your glasses lens or even as magnifier, if there is enough light. Try it with a a pinhole in a 3X5 card. Q: Since it is a simple and seemingly universal corrector of vision defects, why doesn’t everyone use a pinhole instead of eye glasses? Q: Suppose you lost your reading glasses, and had neither a pin nor a 3x5 card, but that you had desperately to look up a number in a phone book, what would you do?

6 The Simple Magnifier (or Eyepiece)

When you wish to examine something in detail with the naked eye, you bring it closer and closer to your eye, so that it will subtend a larger and larger angle at the eye, and thus be spread larger and larger on the retina so that it can be seen in greater and greater detail.

The normal relaxed human eye has a focal length such that in its relaxed state it brings to a focus on the retina the almost parallel rays from an object at far away. If you bring the object closer (or get closer to the object) the eye must “accommodate”, that is squeeze up its lens to make its focal length shorter and shorter in order for it to bring the image of the object to a focus on the retina. There is however a limit to the accommodation of the human eye, a limit to its converging power, so that there is a smallest distance from the eye to which one can bring the object and still have it focused on the retina, (a point that doctors call the “near point”). For the young, normal eye this is often taken to be 15 centimeters from the eye’s lens.

The simple magnifier is then a converging lens, placed immediately in front of the eye's lens, where it adds to the converging power of the eye lens so that the object can be brought even closer and still be in focus on the retina. At this point the concept of an angular magnification is useful. When something is brought closer it subtends a larger angle at the eye, and using the undeviated ray to indicate where the image will fall on the retina, you can see from the diagram above that closer means larger angle. When the simple magnifier is used as an eyepiece of a telescope or a microscope, it functions in precisely the same way except that it is now helping the eye to look at and magnify a real image rather than a real object. The magnifying power of a simple magnifier, for a relaxed eye, is taken to be

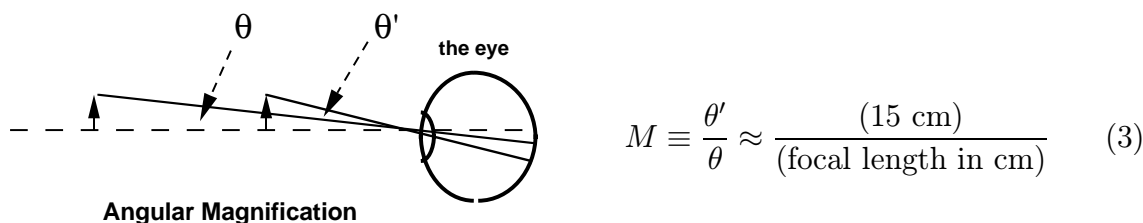


Figure 3

Place one short piece of plastic ruler in in a spring clip, and get as close to it as you can and still see it distinctly and comfortably (nominally 15 cm).

Now hold the shorter focal length lens in front of and close to one eye and bring up the second short piece of plastic ruler as close to the lens as you can and still see its enlarged image through the lens distinctly and comfortably. Looking through the lens with one eye, and at the plastic ruler in the clip with the other, you should see the magnified image superimposed on the non-magnified original ruler in the clip. This is a bit tricky, as the two images tend to wander around, but with perseverance, it can be made to work.

Observe how many millimeters (cm) on the scale seen through the lens corresponds to the millimeters (cm) on the scale seen without the lens. This is the magnification. This cannot easily be done with high precision - just try to get a good approximation, and compare it with the result gotten from the formula for magnification above, i.e., Q: What magnification did you expect? What magnification did you get?

Each of you should adjust the focus and make the, albeit crude, measurement of the magnification.

Standard microscope eyepieces are marked with a magnification (e.g., 10X) which is calculated by the ratio of 25 cm (the nominal value of the near point distance) to the focal length. A 10X eyepiece therefore has a focal length of 2.5 cm.

7 The Keplerian Astronomical Telescope

When you wish to examine a distant object, such as the moon, or Jupiter and its moons, or Saturn and its rings, in more detail from earth, you do not have the option of moving it closer to your eye. You can however use a converging lens to form a real image in front of your eyes. If you choose a lens of suitable focal length, the real image can, be examined in more detail than you can the original object, i.e., even with just an objective lens you can already have an angular magnification at the eye. But then of course you have one additional advantage, you can now examine the real image even better, by using a simple magnifier (called the eyepiece lens). For reasons that you will have read about, the total magnification of the telescope is:

$$M \equiv \frac{f_o}{f_e} \quad (4)$$

where f_o is the focal length of the objective and f_e is focal length of the eyepiece.

Each of you should now get a telescope kit. It should contain:

- Two cardboard tubes, one of which can slide inside the other;
- A 400 mm focal length converging lens (objective);
- A 15 mm focal length lens (eyepiece);
- A foam holder for the eyepiece lens;
- Cardboard spacers for the eyepiece lens;
- A cardboard field stop.

Assemble the telescope as shown below

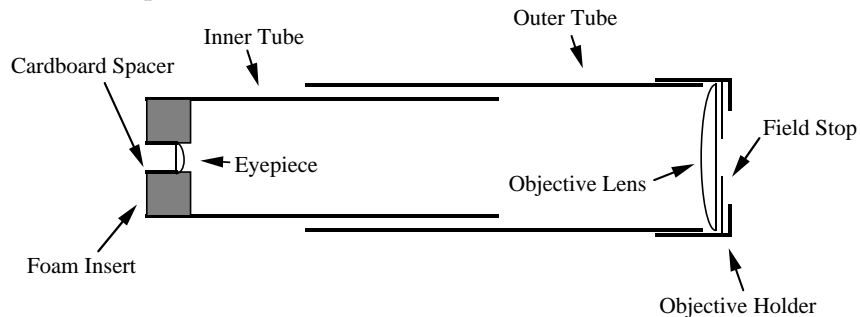


Figure 4

Estimate the magnification you expect with your telescope.

Use your telescope to sight a distant object (outside if you can), focusing by sliding the inner tube in or out of the outer tube, as appropriate. A good place to start is with the inner tube slid out so that the distance between objective and eyepiece lens is approximately the sum of the focal lengths. Q: When you get it focused, do you find that what you see is right side up or inverted? Can you tell why?

NOTE: NEVER, REPEAT NEVER, LOOK DIRECTLY AT THE SUN WITH A TELESCOPE, OR FOR THAT MATTER, NEVER LOOK DIRECTLY AT THE SUN WITH THE NAKED EYE.

Note: the telescope is your to keep.

Lab 9 - Wave Nature of Light

1 Goals

In this lab, you will investigate Fraunhofer diffraction by one or several slits. This is Fraunhofer diffraction instead of Fresnel diffraction because the patterns are observed on a screen very far from the slits, compared with their widths. When several slits are involved, the phenomena are sometimes referred to as interference, e.g. the Young's interference pattern of a pair of slits, but a thorough treatment uses the techniques of Fraunhofer diffraction analysis.

2 Young's Double Slit Interference

In this section, you will make a double slit and use it to measure the wavelength of the light from a laser.

In order to better understand the phenomenon of double slit interference, it might help you to take a look at the wave tank at the back of the room, which simulates the effect using waves in water.

You have a small piece of exposed photographic plate. Look at reflections from it to find the side which has the black emulsion on it; that is, the dull side. You also have a pair of razor blades taped together, and a steel straight-edge with sticky tape on one side.

Place the sticky side of the straight-edge on the emulsion side of the glass plate. Holding the double razor blade between your middle finger and thumb, with your forefinger pressing down on the top (dull) side, draw a line on the photographic plate about .5 cm from one edge. Be sure to hold the two blades tightly together insure uniform line separation. Look at it with a lens to see if there is a clean double line scratched in the emulsion. If it is less than ideal, try again near the other edge. A third try can be made near the middle of the plate, if needed.

The spacing between the lines can be easily checked by measured by measuring the thickness of the two razor blades with the micrometer caliper. Assuming that the tapers ground on razor blades are alike, the spacing of the lines is the thickness of one blade (half the thickness of two).

Mount your double slit in a spring clip in front of the laser, with the slit vertical.

Mount a screen with a scale at the other end of the optical bench. Carefully adjust the alignment until the laser beam is centered on the pattern, and produces a Young's pattern on the screen. You can measure the spacing of the maxima with the scale. You should have a large number of interference maxima, so that you can measure the distance between widely spaced maxima and divide by the number of periods to get good accuracy. Measure the distance from the slits to the screen.

As you learned in class, the angles of the maxima are given by

$$\sin \theta_m = \frac{m\lambda}{d} \quad (1)$$

where λ is the wavelength of the light, d is the slit spacing, and m is the “order” of the maximum. For the small angles here

$$\sin \theta_m \approx \theta_m \approx \frac{x_m}{l} \quad (2)$$

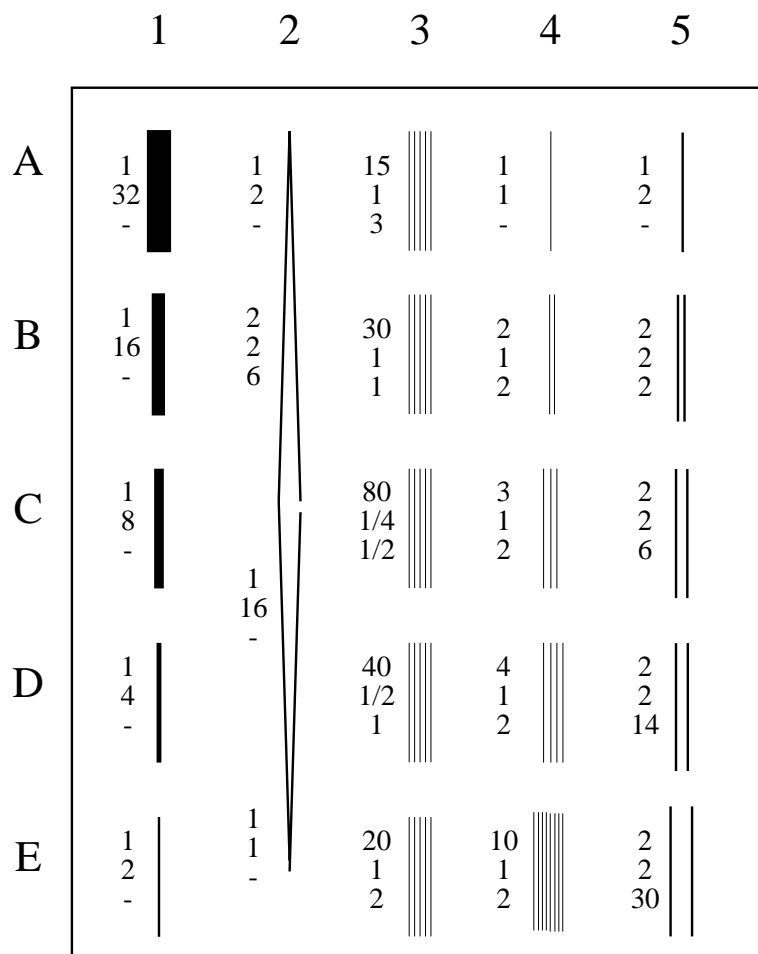
where x is the position on the screen and l is the distance to the screen. Thus the maxima should be more or less uniformly spaced at a distance

$$\Delta x \approx l\theta \approx \frac{l\lambda}{d} \quad (3)$$

Use this formula and your measurements to calculate the wavelength of the light. How does it compare to the accepted value of 632.8 nm?

3 Single Slit Diffraction

For this part, you will use the Slitfilm slide shown (schematically) below



Slit Drawings Only Approximate

The film has a variety of slit patterns, each one identified by its coordinates on the slide (e.g. C-3). The patterns are described by the three numbers at the left. Their meaning is as follows:

- The top number gives the total number of slits in the pattern.
- The middle number gives the width of the slits in units of $44 \mu\text{m}^2$.
- The bottom number gives the width of the dark spaces between the slits (not the distance between the slit centers!!), again in units of $44 \mu\text{m}$.

You will probably find these widths only approximate.

²If anyone knows the origin of this unit, I'd like to hear it.

The Fraunhofer diffraction pattern from a single slit shows a prominent central maximum, and then minima at angles given by

$$\sin \theta_m = \frac{m\lambda}{D} \quad (4)$$

where D is the width of the slit. Again, for small angles, the approximation

$$\theta_m \approx \frac{m\lambda}{D} \quad (5)$$

is valid.

Position the glass slide in a spring clip in front of the laser so that the narrowest single slit, A-4, is illuminated by the laser beam. Measure the separation between the central maximum and the successive minima of the resulting diffraction pattern on the screen. Use this measurement to calculate the slit width. How close is it to the nominal value?

Repeat with a wider slit, say A-5 or D-1.

4 Multiple Slit Diffraction

Because the patterns on the slide have slit widths comparable to their spacing, the diffraction patterns show an interesting modulation of the Young's pattern convoluted with a single slit pattern. The minima of the Fraunhofer single-slit pattern can fall on the maxima of the Young's interference pattern, causing "missing orders". You can observe these best by holding the slide in front of your eye and looking at the spot formed by your laser beam on the screen, from about 10 feet away. Try this for patterns B-3, E-3, and A-3. Try to explain the observed missing orders. Note that because the slit widths and spacings are not exact, this may work better for some of the patterns than others.

5 Diffraction by a Round Aperture

Diffraction of light going through a round aperture (ie, hole) is similar to that of light going through a slit, but the math gets slightly more complicated. Careful calculation shows that the first minimum for light coming through a small aperture will occur at

$$\sin \theta = 1.22 \frac{\lambda}{D} \quad (6)$$

where θ is the angle from the center of the image to the middle of the first dark ring, D is the diameter of the aperture and 1.22 is a numerical factor coming from the integration. It is precisely this formula that, among other things, limits the angular resolution of cameras with a particular aperture (“F-stop”).

Make a small hole in a piece of foil by smoothing the foil over a piece of lucite and pressing firmly (but not too hard) with a sewing needle. Remove the needle before lifting the foil off the lucite.

Place this piece of foil in front of the laser and make a sketch in your logbook of the diffraction pattern you observe on the screen. Measure the radius of the first dark ring to determine the diameter of the hole which you made in the foil.

6 Polarization

As you’ve learned, the waves that make up light consist of alternating electric and magnetic fields. In ordinary “unpolarized” light, these fields point in random directions. A polarizing filter allows only those waves to pass whose electric fields point in a particular direction.

Take one of the polarizing filters at your station (the grey semi-transparent pieces of plastic). Look at one of the overhead lights through it. Rotate the filter; that is, continue to look straight through it, but change its orientation. Does the light intensity appear to change? What does this tell you about the lights in the room?

Now take a second filter. Look at the room light through both of them and rotate one relative to the other. Describe and explain what happens as you change the relative orientation of the two filters.

Whenever light is incident on a transparent medium with a different index of refraction, some of the light is reflected and some is transmitted (refracted). At any non-zero incident angle, the reflected light is partially polarized with the E field parallel to the surface. At the “Brewster Angle” (θ_b), the light is completely polarized. This angle is given by

$$\tan \theta_b = \frac{n_2}{n_1} \quad (7)$$

For light in air incident on water ($n=1.33$), this angle is about 53° . Try to verify this phenomenon, at least qualitatively, using the flat water tank in the back of the room and one of the polarizing filters. Look through the filter at a reflection coming off the water at approximately the Brewster angle. See how its intensity varies as you change the orientation of the filter.

Lab 10 - Atomic Spectra

1 Goals

In this lab you will measure the discrete wavelengths of light emitted by excited mercury (Hg) and hydrogen (H) atoms. In the case of hydrogen, you will attempt to verify whether your data are consistent with the simple model developed by Balmer, and thus with the later “Bohr Atom”, the first quantum model of the hydrogen atom.

2 Introduction

Around the turn of the century, several experimental results appeared to be completely inconsistent with a “Newtonian” picture of the atomic and subatomic world. The three most important observations were:

- The fact that the spectrum of radiation from a hot body (so-called “black body” radiation) was inconsistent with calculations in which oscillating molecules could take on arbitrary energies, but was consistent with a model in which these energies could only have certain discrete values.
- The “photoelectric effect”; that is the fact that in using light to eject electrons from a metal surface, it was found that it was the wavelength of the light that was most important, not its intensity, prompting Einstein to postulate that light was made of discrete “quanta”, each of which carried an energy proportional to its frequency³.
- The fact that the light emitted from excited atoms comes in discrete frequencies.

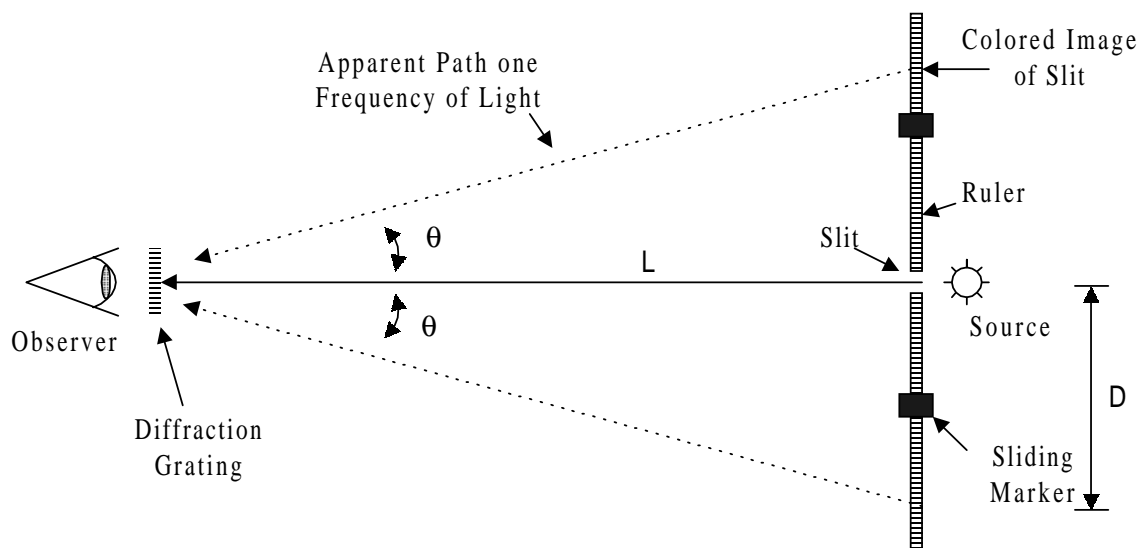
All of these observations could be explained in terms of energy and energy transfer being “quantized” rather than continuous. Surprisingly, in these three very different experiments, this quantization was found to be related to the same constant, the so-called “Planck Constant”. This precipitated the development of a revolutionary new model of physics at atomic and subatomic scales known as “quantum mechanics”.

³It is this, and not the theory of relativity, for which Einstein won the Nobel Prize. It’s ironic that Einstein himself never believed all the implications of quantum mechanics, although his work was seminal in its formulation.

In this lab, we'll recreate the measurement of some atomic spectra. The atoms in gases are excited by passing an electric arc through them. We then study subsequent frequencies of light that are emitted.

3 The Spectrometer

In this lab, you'll be using the "crossbow" spectrometer



Light through a slit in the ruler is incident on a diffraction grating, which is held near the eye. The various frequencies of the light will form interference maxima at angles given by the usual

$$d \sin \theta = m\lambda \quad (1)$$

where d is the slit spacing, λ is the wavelength of the light, and m is the integer order.

Because this light enters the eye at an angle, it will *appear* to come from a different point than the slit. You will therefore see the individual frequency components of the light as colored images of the slit along the ruler in either direction.

To measure the angles, have one person look through the grating at the slit. This person should direct another member to move one of the sliding markers until it is at the apparent position of the slit corresponding to a particular frequency component. The angle can then be calculated with

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

where L is the length of the beam and D is the distance between the apparent slit and the real slit. A more accurate measurement is obtained by measuring the position on each side and taking the average.

4 Experimental Data

First measure the spectral lines for the mercury (Hg) lamp. To start the mercury lamp, hold the button until you see the bluish white light begin to appear, then release the button. Unplug the lamp to turn it off.

You should clearly see a purple line, a green line and two very close yellow lines (you might not be able to resolve them). Use the crossbow spectrometer to measure their wavelengths and compare them to the accepted values:

color	wavelength (nm)
purple	435.8
green	546.1
yellow (1)	577.0
yellow (2)	579.1

Next measure as many of the spectral lines as you can for hydrogen lamp. The hydrogen lamp is only on while the button is pressed, so one person will have to hold the button while the other makes the measurement. These hydrogen lamps have a limited lifespan, so try to expedite the measurement.

5 Interpreting the Hydrogen Data

As you saw, the data from the mercury lamp is rather complicated, particularly the yellow “doublet” line; however, hydrogen is a simple atom consisting of a single proton and an electron. In 1885, Balmer discovered that the observed visible spectral lines of hydrogen obeyed the following relationship:

$$\frac{1}{\lambda} = R \left(\frac{1}{2^2} - \frac{1}{n^2} \right); \quad n = 3, 4, 5, \text{etc.} \quad (3)$$

where R is the so-called “Rydberg Constant”. See if your data fit this model. Make an assumption about which lines correspond to which n values (hint: will a longer wavelength (redder line) correspond to a lower or higher value for n ?). Make a plot

of $1/\lambda$ vs. $(1/2^2 - 1/n^2)$ and measure the slope to determine the Rydberg constant. How close is it to the accepted value of $1.097 \times 10^7 \text{m}^{-1}$?

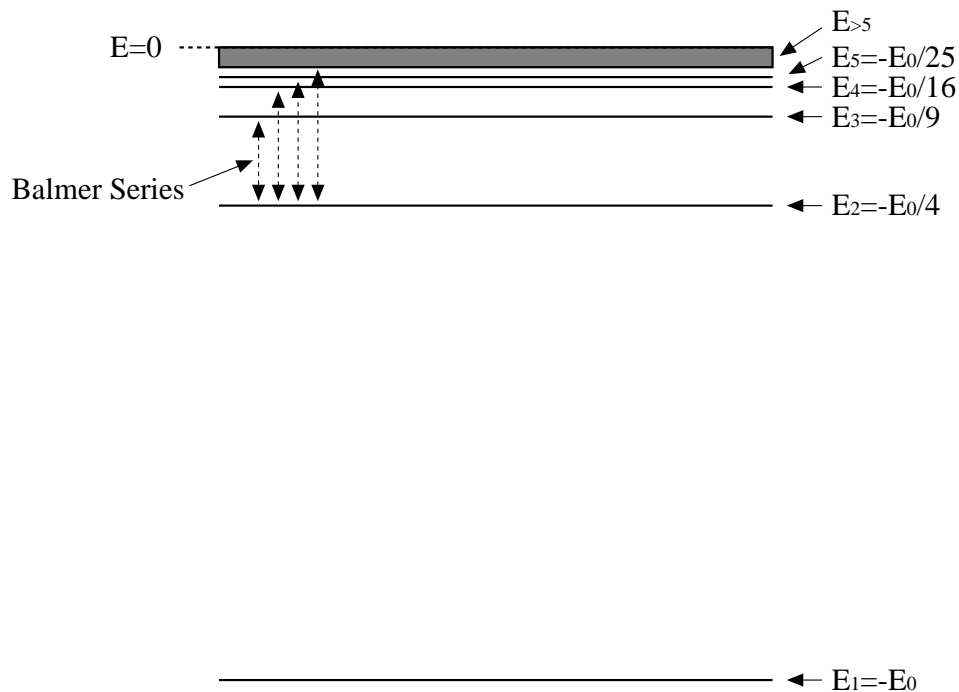
The quantum mechanical interpretation of these lines is that the electron orbiting the hydrogen atom can only exist at discrete energy levels given by

$$E_n = -\frac{E_0}{n^2}; \quad n = 1, 2, 3, \text{etc.} \quad (4)$$

(The exact derivation of this expression can be found in the book.). When an electron makes a transition from a higher energy (n) state to a lower energy ($n' < n$) state it emits a photon with an energy given by

$$E_\gamma = h\nu = \frac{hc}{\lambda} = E_n - E_{n'} = \left(-\frac{E_0}{n^2}\right) - \left(-\frac{E_0}{n'^2}\right) \quad (5)$$

$$= E_0 \left(\frac{1}{n'^2} - \frac{1}{n^2} \right) \quad (6)$$



In this experiment, the atoms are excited to a high energy state by the electric discharge, then gradually transition back down to their ground state.

In this context, the Balmer series is interpreted as transitions to the $n = 2$ state from higher initial states. Why don't we see transitions to the $n = 1$ state? What is

the exact relationship between E_0 and the Rydberg constant (R)? Use your measured value for R to get a value for E_0 . Express your answer in electron-volts. How close is it to the accepted value of 13.6 eV?

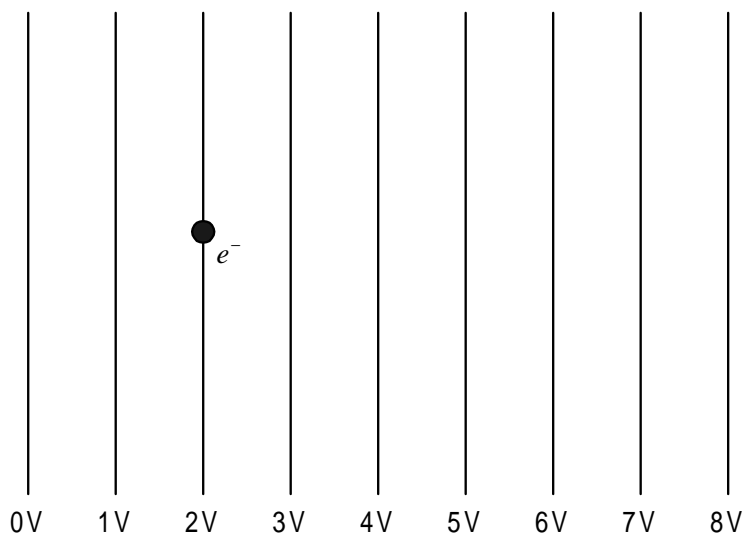
Prelab Problems Sets

Following are the prelab problem sets, one for each lab starting with lab 2. The problems sets are due *at the beginning of each lab* and make up 1/3 of your lab grade. Each week you should tear out the appropriate problems set, do all work in the space provided (continuing on the back if need be), and place the sheet in the box near the door as you come into the lab. Remember to put your name on each sheet!!!

Lab 2 Problem Set

Name: _____

The following lines represent infinite planes of uniform voltage, each with the voltage indicated, spaced 1 cm apart.



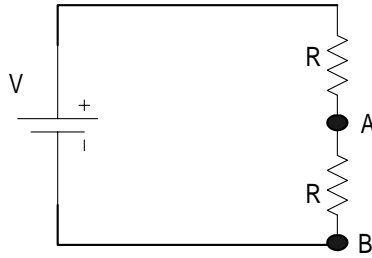
The dot represents an electron ($q = -1.6 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg)

- (a) On the figure, draw an arrow indicating the direction which the electron will go when it is released.
- (b) What will be its acceleration, assuming there are no other forces?

Lab 3 Problem Set

Name: _____

The following circuit is made with a $V = 3$ Volt battery and two identical resistors of $R = 100\ \Omega$ each.



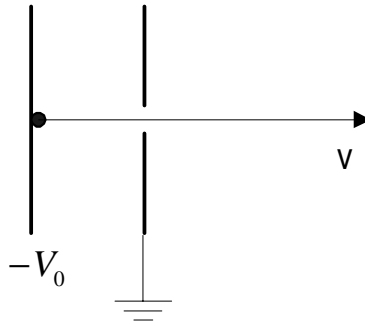
(a) What is the magnitude of the current in the circuit (in amps)? Draw an arrow on the figure to indicate the direction.

(b) What is the voltage difference (magnitude) between A and B?

Lab 4 Problem Set

Name: _____

An electron is accelerated by the plate capacitor device shown below. The accelerating voltage is $V_0 = 1000$ V.

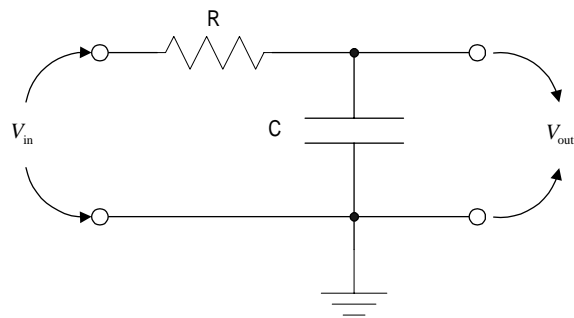


- (a) What is the magnitude of its velocity v as it leaves the second plate?

- (b) If someone turns on a uniform magnetic field of .1 T, pointing out of the page, will the electron travel in a clockwise or counterclockwise circle?

- (c) What will be the radius of the circle?

The following circuit represents a type of filter.



The input is a sinusoidally oscillating voltage V_{in} . The output is V_{out} . The component values are $R = 10 \text{ k}\Omega$ and $C = 1 \text{ }\mu\text{F}$.

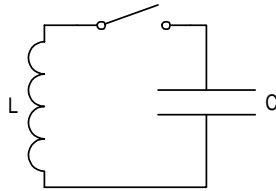
(a) Is this a high-pass or a low-pass filter?

(b) What is the cutoff frequency, in Hz?

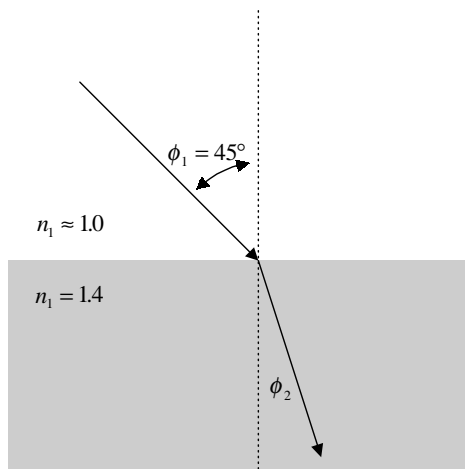
Lab 6 Problem Set

Name: _____

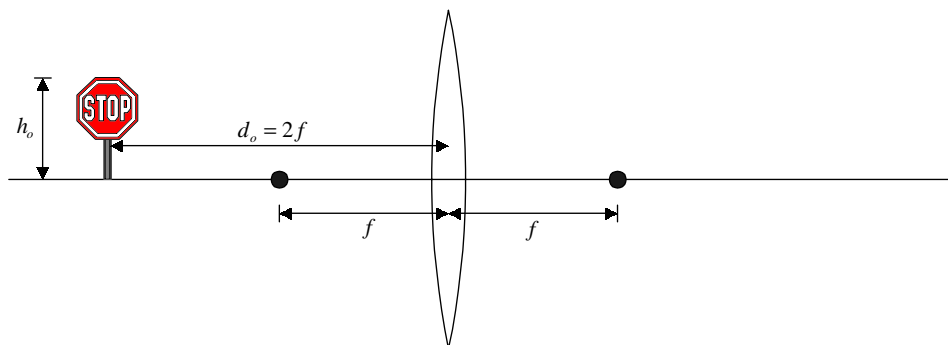
The following circuit has $C = 1\ \mu\text{F}$ and $L = 1\ \text{mH}$. The switch is closed when there is a small amount of charge on the capacitor.



At what frequency, in Hz, will the circuit oscillate?

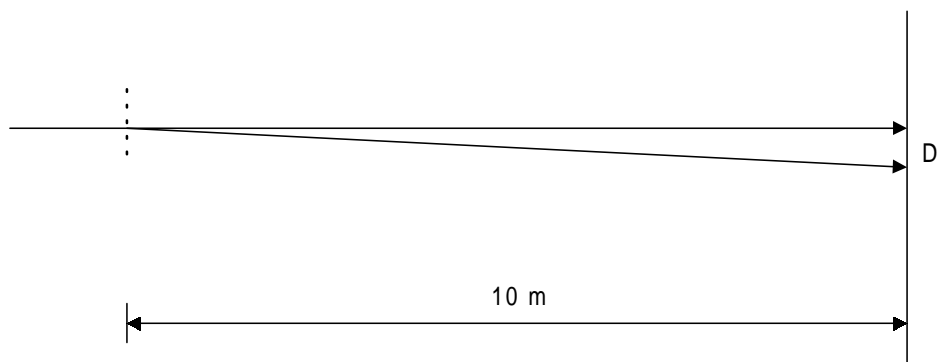


A ray of light crosses a boundary between air ($n_1 \approx 1$) and a material with an index $n_2 = 1.4$. The angle of incidence is $\phi_1 = 45^\circ$. What is the angle of refraction, ϕ_2 ?



An object is placed in front of a converging lens at a distance d_o , which is twice the focal length f , as shown.

- (a) Will the resulting image be real or virtual?
- (b) How far from the lens will it form, in terms of f and d_o ? Indicate the position and orientation of the image on the figure.



Monochromatic light of wavelength $\lambda = 500 \text{ nm}$ passes through two narrow slits $10 \text{ }\mu\text{m}$ apart and is incident on a wall 10 m away. How far apart are the interference maxima at the wall D ?

Lab 10 Problem Set

Name: _____

Atomic hydrogen makes a transition from the $n=4$ state to to the $n=2$ state.

(a) What is the energy of the resulting photon, in eV?

(b) What is the wavelength of this photon, in nm?