

In this lab you will measure the density of an unknown liquid. You do this by forcing the liquid up a tube using a known amount of pressure (see figure).

Pressurize the bottle of liquid by squeezing the hand pump repeatedly. The liquid should be forced up the tube. Be sure that the silver air release valve is closed (twist it clockwise). Increase the pressure until the level of the liquid in the tube is almost 2 m above the floor. If you overshoot 2 m, you may lower the level of the liquid by opening the air release valve (twist it counter-clockwise).

Using the 2-meter stick, measure h_1 and h_2 (relative to the bottom of the bottle) and calculate $\Delta h = h_2 - h_1$. Record the results below. Record the pressure measured by the gauge. (Note that this is the pressure $P - P_0$ relative to the atmospheric pressure P_0 . Also note that the units of pressure measured by the gauge is oz/in². 16 oz = 1 lb.) Using $P = P_0 + \rho gh$, calculate the density ρ of the liquid and record the result below. Your result should be accurate to the nearest 0.01 g/cm³. Please release the air pressure when you are finished.

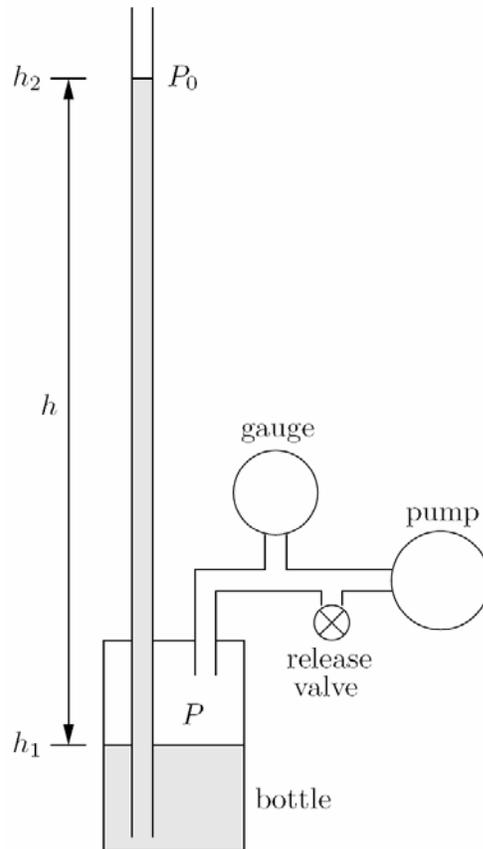
$h_1 =$ _____

$h_2 =$ _____

$h =$ _____

$P - P_0 =$ _____

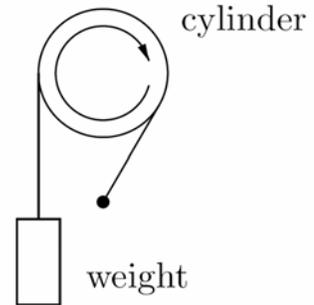
$\rho =$ _____



Lab #2

Heat Capacity of a Solid

In this lab, you will measure the specific heat of aluminum. A strap is wound around an aluminum cylinder of mass $m = 216$ g and radius $r = 1.00$ inch. One end of the strap is attached to a weight of mass $M = 1.00$ kg, and the other end is secured to a fixed support. As you turn the cylinder, the weight is lifted up slightly. The strap slips around the cylinder, and the weight is lifted due to a frictional force Mg between the strap and cylinder. When you turn the cylinder one revolution, the work done by the friction is equal to $W = (Mg)(2\pi r)$. This work becomes heat which causes the temperature of the cylinder to rise.



The temperature of the cylinder is measured using a thermocouple wire which is connected to a digital meter. Insert the wire into the shallow hole at the center of the red circle drawn on the end of the aluminum cylinder. Hold it there for 30 seconds. If you hold it with your fingers, then be sure to keep your fingers at least two inches away from the end of the wire so that the heat from your fingers does not influence the reading of the temperature.

In order to minimize the effect of the heat flow between the cylinder and the surrounding air, we first cool down the cylinder to a few degrees below room temperature. This is done by pressing a piece of cold aluminum supplied with the apparatus against the rotating cylinder for about two seconds. If the temperature is still not below room temperature (perhaps because someone else had just finished the lab and left the cylinder hot), press the piece of cold aluminum against the cylinder for another two seconds or so. Do not lower the temperature below about 18°C .

Record the initial temperature T_i below. Turn the crank on the cylinder 100 times. Note that every revolution of the crank produces 12 revolutions of the cylinder, so the cylinder has actually gone through 1200 revolutions. Record the final temperature T_f . Calculate the change in temperature ΔT . Calculate the work W per revolution done. Calculate the total work W done. Calculate the specific heat c of the cylinder.

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

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

$$\Delta T = \underline{\hspace{2cm}}$$

$$W/\text{revolution} = \underline{\hspace{2cm}}$$

$$\text{total } W = \underline{\hspace{2cm}}$$

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

In this lab you will use a computer simulation to study how wave packets propagate in linear media. You will study both non-dispersive media in which sine-waves of all wavelengths travel at the same speed (like, for example, light traveling in a vacuum) as well as dispersive media (like light traveling through a piece of glass, electron quantum waves traveling through space, and just about every other real system).

The first step is to go to the class website and click the “Lab 3 - Dispersion” link. You can run the applet and get additional help there. Once the applet is running, you should see a screen with two graphs and some text. The next step is to click on the red “get help” button in the upper left-hand corner and read the instructions for the software. Before proceeding, you may want to play with the program for a bit to make sure that you understand how it works.

Uncertainty First let’s explore the uncertainty which is inherent in waves. To do this, first click on “Reset All.” In the upper graph you should see a depiction of a Gaussian wave packet (a little “burst” of a sine-wave with a Gaussian-shaped “envelope”). In the lower graph you can see the spectrum of the pulse (the amplitude of each of the sine waves which the computer added together to make the wave packet in the upper graph). On the far right-hand side of the program the computer displays Δx ; (the standard deviation of the pulse in space), Δk (the standard deviation of the pulse’s spectrum), and the product of the two.

We learned in class that in order to make pulses which were very narrow in space, we have to add a wide band of frequencies or wavenumbers together, making it difficult to state with certainty what the frequency of the pulse is. To make a wave packet with a very well defined frequency or wavenumber we have to let the packet extend over a large range in space such that it is difficult to assign a location to the packet with precision. Furthermore, we learned that if we defined uncertainty to be the RMS standard deviation, the uncertainties in x and k follow the uncertainty relation $\Delta x \Delta k \geq \frac{1}{2}$.

Notice that our wave satisfies the above uncertainty relation. Now type in a different value for the pulse width (w). Notice that as the pulse shrinks, its spectrum widens. The uncertainty relation should still hold. Now change the central wavenumber (k) and see what happens.

Now click “Reset All,” enter 150 for k , and enter `squarepulse(x/w)` for the “Envelope.” Now try different values for the pulse width and fill in the table below. Then answer the question below the table.

w	Δx	Δk	$\Delta x \Delta k$
0.02			
0.05			
0.08			
0.1			

- Do the values in this table satisfy the uncertainty relation above?

Note that the physical size of the pulse on the screen is about 4 times larger than Δx . This is just due to the fact that we have chosen to define uncertainty as the RMS standard deviation. This is the most commonly used but not always the most useful definition. So, you see, there is uncertainty in our definition of uncertainty! As a result, the uncertainty relation is often written in the less precise form: $\Delta x \Delta k \gtrsim 1$.

Non-dispersive media. In this part of the lab we will examine what happens when wave pulses travel in non-dispersive media. In non-dispersive media the angular frequency of a sine wave is simply proportional to the wavenumber of the wave: $\omega(k) = vk$, where v is the velocity that waves travel through the medium. Wait a minute... is that the phase or group velocity? Think about this for one minute, and then answer the following two questions in the space provided.

- The dispersion relation of light traveling through a vacuum is just $\omega(k) = ck$, where c is equal to 2.9979×10^8 m/s. What is the phase velocity for a pulse of light whose central wavelength is 657 nm?
- What is the group velocity for such a light pulse?

Now let's use the computer simulation to see what happens to a Gaussian-shaped pulse as it propagates through a non-dispersive medium. First click on the "Reset All" button. There should now be a pretty pulse displayed in the upper graph, with a nice spectrum centered around a wavenumber of 75 m^{-1} in the lower graph. Now click on the "Go!" button to let time run and see what happens. The dispersion relation, shown just below the "Reset All" button, is $\omega(k) = 0.1 \text{ m/s} \cdot k$. Use this dispersion relation to answer the following question.

- What is the group velocity for a pulse in this medium centered at 75 m^{-1} ?

Now click on the “Stop” button to stop the simulation if it hasn’t already stopped, and click on the “Reset $t=0$ ” button to set time back to zero. Now plug the group velocity you calculated above into the “x-Axis Velocity” box to make our “view window” move with the pulse. Click on “Go!”. If you did your calculation correctly, the pulse should stand still in the window.

Based on what you have seen, answer the following question.

- What happens to the spatial size of a pulse and the spread of frequencies or wavenumbers in a pulse as it travels in a non-dispersive medium?

Dispersive Media. Now let’s pick a dispersion relation which is a little more interesting. Click on “Reset All,” and then enter the dispersion relation $0.001 * k^2$. Before you do anything else, use this dispersion relation to calculate the group and phase velocities for a pulse centered around $k = 75 \text{ m}^{-1}$.

- Group Velocity
- Phase Velocity

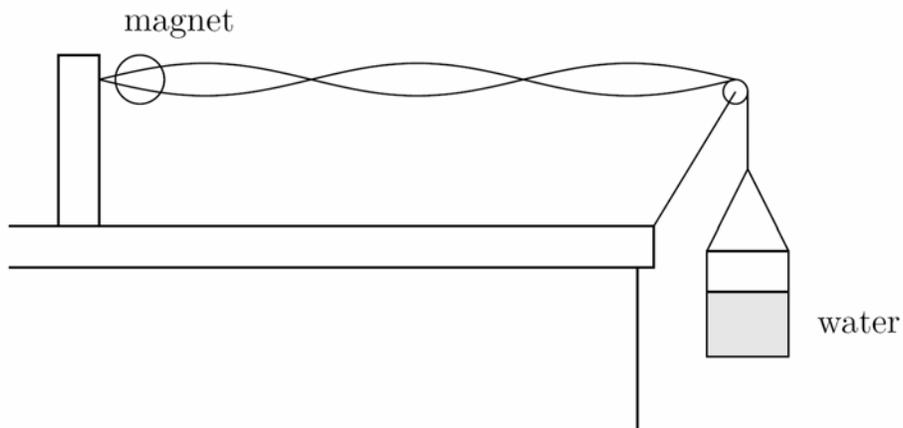
Now click on “Go!” and see what happens. Now stop the simulation, set time to $t = -10$, and set the “x-Axis Velocity” equal to the group velocity you calculated above. Press “Go!” again and watch what happens. Now stop the simulation, set time to $t = -2.5$, and set the “x-Axis Velocity” equal to the phase velocity calculated above. Press “Go!” and see what happens (hint: this is the part of the lab where the vertical blue line in the center of the graph is useful). Finally, based on what you saw and in your own words explain what phase and group velocity represent:

- Group velocity is...

Lab #4

Standing Waves in a Wire

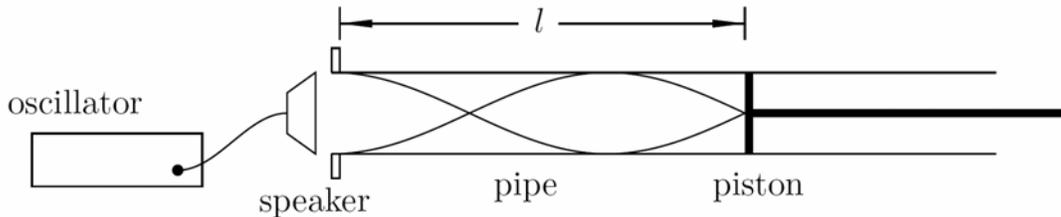
In this lab, you will produce standing waves in a wire. This is done by placing the wire through the poles of a magnet and passing an alternating current (60.00 Hz) through the wire. The resulting force of the magnetic field on the current drives the wire into a vertical oscillation at 60.00 Hz. The tension in the wire is equal to the weight hanging at the end. At certain tensions, the wire will resonate and produce visible standing waves.



Produce a standing wave by adjusting the amount of water in the container and thus changing the tension in the wire. (Don't add any additional weight beside water. You may break the wire.) Adjust the tension until the amplitude of the antinodes is as large as possible (even though the nodes may not be as well defined). Using a meter stick, measure the wavelength λ of the standing wave. Calculate the velocity v of the waves in the wire. Weigh the container of water to obtain its mass m . Calculate the tension F in the wire. From F and v , calculate the linear mass density μ of the wire. Repeat this for a different standing wave.

	1st Standing Wave	2nd Standing Wave
$\lambda =$	_____	_____
$v =$	_____	_____
$m =$	_____	_____
$F =$	_____	_____
$\mu =$	_____	_____

In this lab, you will produce standing waves in a pipe. This is done by placing a speaker at an open end of the pipe and driving the speaker with an oscillator as shown below:



A piston is inserted into the other end of the pipe. At certain positions of the piston, the speaker will cause the pipe to resonate, thus producing standing waves.

Set the frequency f of the oscillator at approximately 700 Hz. Read the frequency shown on the counter and record it below. Starting with the piston at the end of the pipe, push it in slowly. You will notice that at certain positions, the sound of the speaker is enhanced. This is caused by standing waves in the pipe. Use the sound meter to accurately determine the position of the piston where the enhanced sound is loudest. Measure the distance l between the piston and the open end of the pipe at all positions of the piston for which this occurs and record it below. You ought to find 5 of them.

For each standing wave, the piston is at a position of a displacement node. From the data, you can thus obtain the distance between nodes and consequently the wavelength λ . Using the wavelength and frequency, calculate the velocity of sound to the nearest m/s (three significant figures). Record these results below.

$f =$ _____

$l =$ _____

$\lambda =$ _____

$v = f \lambda =$ _____

In this lab you will study the relationship between time dependent signals and their frequency spectrum (i.e., their Fourier transform). You will do this using a computer program which can generate or record waveforms or read-in pre-recorded waveforms. This program will display the waveform along with its Fourier transform.

The first step is to go to the class website and click the “Lab 6 - Fourier transforms” link. You can run the applet and get additional help there. The next thing to do is to play with the program and make sure that you understand how to use it. In particular, make sure you understand how to zoom in and out on the graphs, and how to find the exact value of a point by right-clicking on it.

Musical Octaves. Click on “RESET ALL”. This will set up the program to work with a “user defined” waveform and set the waveform equal to $\sin(2\pi \cdot 440 \cdot t)$. This will generate a sine wave at 440 Hz (the A above middle C). Now, adjust the frequency (the 440) until you hear a tone which is one octave higher. Note the frequency below. Adjust the frequency again until the tone is another octave higher. Note the frequency below. Now think to yourself— does this agree with what we studied in class?

$f_{\text{One Octave Up}} =$

$f_{\text{Two Octaves Up}} =$

Generating a Square Wave. Now enter $\text{squarewave}(2\pi \cdot 440 \cdot t)$ as the user defined waveform to generate a 440 Hz square wave. Zoom in on the wave until you can see that it is, indeed, a square wave. Play the wave and hear what it sounds like. Now, using the “Its spectrum” graph, find the frequency and amplitude of the four lowest-frequency Fourier components and record them in the table below. Also record the frequency divided by the fundamental frequency (440 Hz). (Hint, $f/440\text{Hz}$ should be an integer for all of the components, and should equal 1 for the lowest frequency component.)

	f	A	$f/440 \text{ Hz}$
1.			
2.			
3.			
4.			

Now let's see what happens when we add together four sine waves with the above frequencies and amplitudes. Type

$$A*\sin(2*\pi*f_a*t) + B*\sin(2*\pi*f_b*t) + C*\sin(2*\pi*f_c*t) + D*\sin(2*\pi*f_d*t)$$

in as the user defined waveform, where A, B, C and D are the amplitudes you measured above, and $f_a, f_b, f_c,$ and f_d are the frequencies which go with each amplitude. Click on "Recalc/Record" and then zoom in on the graph of the wave to see if it looks like a square wave. Sketch what you see below:

For kicks, you might want to see what the wave looks like as you add more and more sine terms together. You can get a pretty decent looking square wave!

Uncertainty Relations. Now let's make a short pulse of sound and explore the topic of "wave uncertainty". Enter $\sin(2*\pi*440*t)*\exp(-10000*(t-0.5)^2)$ as the user defined waveform and click on "Recalc/Record." Click on "Zoom to fit," and take a look at the wave and its spectrum. Then play the wave. Now zoom in on the wave and on its spectrum and estimate Δt and Δf . Now calculate $\Delta\omega$ from Δf , and calculate the uncertainty product $\Delta\omega \Delta t$ and record everything below.

Δt :

Δf :

$\Delta\omega$:

$\Delta\omega \Delta t$:

Now make the pulse shorter and longer in time by changing the 10000 in the waveform to other numbers. Change it by at least a factor of 20 in both directions (smaller and larger). Describe below what happens to the width of the spectrum when you change the duration of the pulse in time. Why does this happen?

Describe below what happens to the tone of the note as you change the duration of the pulse in time. Why does this happen?

Playing Around. You have now finished the lab. But for your own learning experience I recommend that you play around with the program. In particular, you should do the following things.

(1) Record the sound of your hands clapping (or use the pre-recorded sound of my hands clapping, available under the “Waveform” drop-down box) and see if the uncertainty product $\Delta\omega\Delta t$ makes sense.

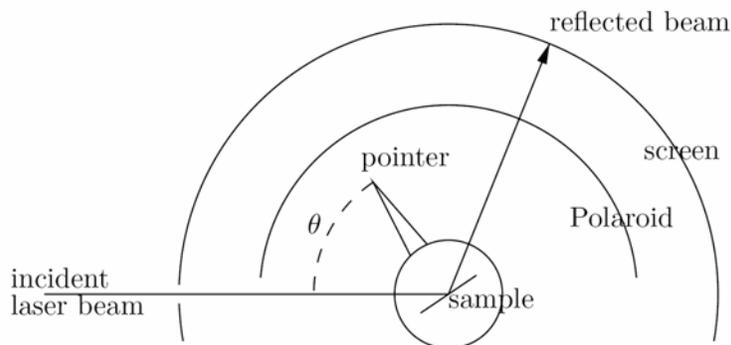
(2) Listen to the various pre-recorded waveforms and note their spectral properties. Notice that most of the instruments have a spectrum which looks like a harmonic series and ask yourself why that is the case. Also notice that the percussive instruments do not have a spectrum which looks like a harmonic series. Not even the timpani which seems to generate a specific tone! Ask yourself why a timpani’s waveform does not consist of a harmonic series of frequencies.

(3) Try to generate different waveforms by adding sine waves together. You might want to actually calculate the Fourier transform of some waveform, and then plug the results in and see what you get.

In this lab, you will measure the Brewster angle for two different materials. From these measurements, you will then calculate the index of refraction for each material.

As shown in the figure below, a laser beam is directed towards the surface of a sample. The sample is mounted on a platform which can be rotated. The pointer attached to the platform points in a direction perpendicular to the surface of the sample. The incident angle θ of the beam can be read from a scale on the apparatus.

The reflected beam passes through a sheet of Polaroid and hits a white screen. The transmission axis of the Polaroid is horizontal. When the angle of the incident beam is equal to the Brewster angle, the reflected beam is polarized vertically and thus will not pass through the Polaroid. At this angle, the illuminated spot on the screen will disappear. (Actually, since the sample and the Polaroid are not ideal, the spot will not disappear completely, but will have a minimum intensity.)



There are two samples. One is ordinary glass, and the other is zirconium oxide (ZrO_2). First insert the glass into the sample holder. Rotate the sample platform and find the orientation where the reflected beam has a minimum intensity. Be sure that the Polaroid sheet is in place so that the reflected beam passes through it. Read the incident angle from the scale and record it below. This is the Brewster's angle θ_p . Determine the index of refraction from $n = \tan \theta_p$ and record it below. Repeat this for the ZrO_2 sample.

Warning: Do not touch the sample surfaces. Fingerprints on the samples will affect your measurements. Wipe off any fingerprints with the tissues provided.

Glass sample: $\theta_p =$ _____ $n =$ _____

ZrO₂ sample: $\theta_p =$ _____ $n =$ _____

When you are finished, remove the Polaroid sheet and notice how intense the reflected beam is. Then place a small circular Polaroid sheet in the path of the reflected beam and observe how its intensity changes as you rotate the sheet.

In this lab, you will construct a simple telescope using two lenses. Mount the source (illuminated arrow) and the screen on the optical bench, and mount one of the lenses between them. Adjust their positions until a real image of the arrow is focused on the screen. For best results, adjust the positions so that the lens is about half-way between the object and the image. Measure p and q . Calculate f from the thin lens equation,

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}.$$

Repeat for the other lens. Record your results below.

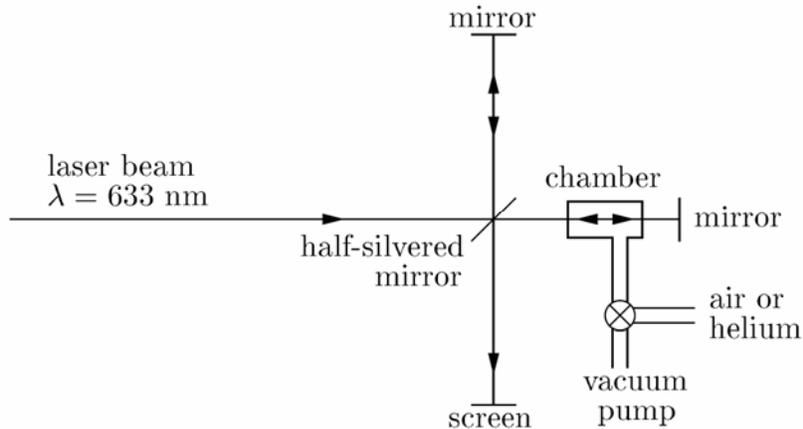
Construct a telescope by mounting the two lenses a distance $f_1 + f_2$ apart. Use the lens with the smaller focal length for the eyepiece. View the large scale mounted on the wall across the room. The distance between the two lenses may be adjusted to bring the image into better focus.

Measure the angular magnification m of the telescope by viewing the scale through the telescope with one eye and looking directly at the scale with the other eye. In this way, you ought to be able to see both the magnified and unmagnified scale superimposed on each other.

Finally, calculate m from the measured focal lengths.

	lens 1	lens 2
$p =$	_____	_____
$q =$	_____	_____
$f =$	_____	_____
$m =$	_____	measured
$m =$	_____	calculated

In this lab, you will use a Michelson interferometer to measure the index of refraction of a gas. A chamber which can be evacuated is placed in one arm of the interferometer. All of the air is first evacuated from the chamber. As the gas to be studied is slowly allowed to enter the chamber, the number of fringes passing by the center of the screen is counted.



The index of refraction n of the gas is given by

$$n = 1 + \frac{N\lambda}{2L},$$

where N is the number of fringes counted, λ is the wavelength of the laser in vacuum, and L is the length of the chamber. See the Supplement on the next page for the derivation.

Turn on the vacuum pump and evacuate the chamber. Pump for at least a couple of minutes to obtain a good vacuum. Valve off the vacuum pump and *slowly* open the chamber to air and count the fringes. (You will probably open the valve too fast the first time you try, and the fringes will go by too quickly to count. If this happens, evacuate the chamber again and start over.) Repeat using helium gas instead of air. Measure L and calculate n for each gas.

	Air	Helium
$L =$	_____	_____
$N =$	_____	_____
$n =$	_____	_____

Supplement to Michelson Interferometer

When the chamber is evacuated, the number of wavelengths along its length L is given by

$$N_{vac} = \frac{L}{\lambda_{vac}},$$

where λ_{vac} is the wavelength of the laser light in vacuum. When the chamber is filled with some gas, the number of wavelengths along its length is now given by

$$N_{gas} = \frac{L}{\lambda_{gas}},$$

where λ_{gas} is the wavelength of the laser light in the gas.

Each time one arm of the interferometer gets behind (or ahead) by one wavelength, one fringe passes by the screens. As we fill the chamber with gas, that arm of the interferometer will get behind by $N = 2(N_{gas} - N_{vac})$ wavelengths. (The factor 2 is included since the light passes through the chamber twice, once going and once coming back.) From the two above equations, we thus obtain

$$N = 2 \left(\frac{L}{\lambda_{gas}} - \frac{L}{\lambda_{vac}} \right).$$

We also know that

$$\lambda_{gas} = \frac{\lambda_{vac}}{n},$$

where n is the index of refraction of the gas. Using this to solve for n , we obtain

$$n = 1 + \frac{N\lambda_{vac}}{2L}.$$

In this lab, you will observe the interference pattern produced by shining a laser beam through a diffraction grating. From the distance between peaks in the pattern, you will determine the distance between the slits in the grating.

The He-Ne laser used in this lab produces red light of wavelength 633 nm. Turn on the laser. Its beam should pass through the diffraction grating. You should observe the interference pattern on the wall.

Use a meter stick to measure the distance Δx between peaks in the interference pattern. Average this distance over several adjacent peaks so that your measurement will be as accurate as possible. Record your result below.

Use the tape measure to determine the distance L between the diffraction grating and the interference pattern on the wall and record your result below.

Calculate the angle θ between adjacent bright spots in the interference pattern and record your result below.

Using $d \sin \theta = \lambda = 633 \text{ nm}$, calculate the distance d between the slits in the grating and record your result below.

$\Delta x =$ _____

$L =$ _____

$\theta =$ _____

$d =$ _____