UCD: PHYSICS 9B LAB

Tom Weideman
University of California, Davis

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University of California, Davis

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Read Me: About Labs in Physics 9

The Purpose of Labs

There are many reasons to include a mandatory lab component to the Physics 9-series. Among the benefits to a STEM education are:

- experiencing physical phenomena first-hand, to supplement the mathematically-abstract experience of lectures and problem-solving
- learning very broadly how one can go beyond what just intuitively seems right and actually *test an idea* by devising an experiment
- learning experimental skills, like minimizing errors and controlling for irrelevant factors
- learning data analysis skills, like using graphs and statistical examination
- learning to use uncertainty analysis to determine when a proposition is confirmed or refuted by the data

Some of the earliest labs in Physics 9A are somewhat less about physics, and more about developing some of these skills. At that point not a lot of physics has been learned yet, and these skills are needed throughout the 9-series.

Experiment Types

There are four basic varieties of experiments that will occur in these labs. Occasionally an experiment may have elements of more than one of these types.

- **Simple, repeatable, observations –** These are the most informal sorts of experiments. They typically do not involve a lot of mathematical modeling, and instead are focused on more general features. The most challenging aspect of these kinds of experiments is objectivity – the experimenter must come into them with an open mind, simply documenting what is observed without constructing elaborate explanations for what they are witnessing. One of the worst mistakes that can occur in these is to inadvertently "put your thumb on the scale" (introduce human error) because a certain result is expected. You should go to great lengths to avoid this critical error.
- **Confirmation of a Single Hypothesis** – A prediction is made regarding the outcome of a specific scenario. The result is never *exactly* what is predicted, but the amount of uncertainty measured and computed is used to determine if the experimental result is "close enough" to the predicted to result to be considered a confirmation.
- **Independent Confirmations –** Armed with the theoretical background to compute a physical quantity, the experimenter devises two separate, completely independent experiments to measure that value. Each experiment gives its own result and its own uncertainty range, and the goal is to check if the two experiments confirm the same number within these uncertainties.
- **Choose the Better Theory** – Two mathematical models are proposed to explain a single observed phenomenon. The experiment seeks to determine which of the two theories best describes the relationship between the variables present.

Typical Elements of Lab Meetings and Reports

Below is a list of common tasks performed in laboratory meetings, and items included in submitted lab reports:

- Short test runs of an apparatus are performed to "get a feel" for what is going to happen, and to assist in designing the setup in an optimal manner. These do not include actual data acquisition, and also should not be overused – some variation in results is expected, and variation is not an indication that the design needs to be tweaked indefinitely.
- Careful runs of the apparatus are performed, with multiple experimenters observing or playing a role in maintaining a smooth operation.
- Multiple runs are taken for each data point, to reduce statistical uncertainty. Sometimes the statistical uncertainty is computed and included in the analysis, other times just an average result of a few runs is used (because the statistical uncertainty only contributes a very small amount to the overall uncertainty). Doing this also helps weed-out weird anomalous runs where something unexpected and unnoticed happens (i.e. the removal of rogue data).
- Data tables are created (and included in the lab report). These include both raw data and values computed from that data, and are organized in a fashion that's easy for someone reading the lab report to review.
- Graphs (virtually always linearized – see here for more details) are produced, and best-fit curves (i.e. lines) are used to draw conclusions about the mathematical model used to explain the phenomenon tested in the experiment.
- Uncertainties of two types are computed:

- statistical – standard deviations of measurements with random errors introduced by the imperfect apparatus or by human involvement
    - estimated – educated guesses about how accurately one can expect a measuring device to function.
- Lab reports are written with contributions from all group members. The text does not need to be verbose or overly-details, but should get to the point and include most or all of the following points:
    - what you set out to test (explain the problem)
    - how you set up your apparatus to accomplish the test
    - what you expect to see (hypothesis)
    - your results (data tables, graphs, computations, general discussion, etc.)
    - checking to see if your results confirm the hypothesis to within the uncertainties (it is okay if this is not confirmed – staying agnostic about the final result is an important quality)
    - an accounting of the weaknesses in your apparatus or procedure, and suggestions for how these can be improved in future attempts

Organization of Reports

You are not required to follow a specific template for the format of your lab reports. However, it might be helpful to keep things organized in your head to follow something resembling this:

- **Goal** – Give a description of what you hope to accomplish or learn in this particular lab.
- **Hypothesis** – If the lab is one in which an hypothesis is tested, then expressing it explicitly is a good idea.
- **Procedure** – Give a details description of what you did in your experiment, from the preparation.calibration of the equipment, to the method of taking data. It is tempting here to sometimes give some numbers you recorded, but for the sake of organization it's a good idea to resist this. Also, while it is appropriate at times to give a short explanation of why you did something a certain way, this should be kept very brief, or this section will start treading heavily on the later section on analysis.
- **Data** – Display all the data you recorded, without including any discussion of what it means. This includes one-time measurements as well as tables. It's okay to include computed values (if, for example, every recorded number needs to be squared to be put into a graph), but save the main calculations toward a result for the next section.
- **Analysis and Conclusions** – This includes everything else:
    - physics that needs to be explained to get to your answer (free-body diagrams, algebra, etc.)
    - graphs and calculations of final results or uncertainties
    - a description of likely sources of error, and ways to improve the experiment (i.e. reducing errors/uncertainties)
    - final narrative that ties together the results of the experiment vis-a-vis the goal and/or hypothesis

A Final Word

These labs are intentionally not set up to be "cookbook" exercises. There will be some guiding questions to answer in the lab report, and some hints for how to proceed, but for the most part, the design of the experiment and the layout of the lab reports are up to you (your time is limited, so don't get too fancy with this). Keep in mind that you have two goals: The first is to convince yourself of the conclusion (i.e. perform a detail-oriented experiment), and the second is to write a clear lab report that conveys a convincing argument to the reader. Pro-tip for successful experimenters: Try to be more skeptical of your own work than the audience you seek to convince.

CHAPTER OVERVIEW

Lab 1: One-Dimensional Waves

1.1: Background Material

Text References

- waves on strings
- wave reflection

A Reminder

This activity requires accurate measurement of time intervals of a phenomenon that is difficult to track. As we have done in Physics 9A labs, we can mitigate the tracking problem by using video capture of the action, with a timer included in the frame, followed by stop-motion study of what has been recorded.

But even with this, there is something more we can do, since what is important is the *percentage* uncertainty. To review what we have determined previously about this, see the "Improving Time Measurements" section of Background Material for Physics 9A, Lab 3. As for determining uncertainties in these time measurements, the last sentence of the Background Material for Physics 9A, Lab 1 spells it out.

1.2: Activities

Equipment

- slinky & "wave-pulse-starter"
- heavy chain
- string
- pulley assembly
- stretchy string
- hanging weights
- tape measure
- triple-beam balance

The General Idea

There are two parts to this lab:

Part 1

The first part is a bit unusual, as it is not an experiment in the usual sense. It is more of an exploration of phenomena in search of some enlightening speculation. The idea is this: From your pre-lab work (and from lecture or the textbook), you likely have a good idea of what happens to a reflected wave when it comes from a region where the medium is either fixed or free. The results of these two cases are complete opposites of each other, but what happens if we construct an "in-between" circumstance – one where the medium is neither held firmly in place, nor allowed to move completely freely? In particular, suppose the wave strikes a "barrier" that also will carry the wave? That is, what if the wave changes medium? The medium can be displaced, so it clearly isn't held fixed. But it also resists acceleration (it has mass), so it isn't exactly free like an empty end would be.

At your disposal to explore this, you have a slinky for your primary wave. Attach one end to a new medium and stretch it (don't ***over***-stretch it - it should have some sag in it). The opposite end of this new medium should be anchored to the lab table. Then rap it suddenly from the side at the end farthest from the new medium to create a wave pulse, and observe the pulse that reflects back. Available for the new medium are two objects that couldn't be more different: a light string and a heavy chain.

Feel free to video-record your tests, if it makes it easier to make out the relevant properties of the reflected wave.

Part 2

This part is a more traditional experiment. We start with a result from the textbook and lecture. We will call it the "theory of string wave speed," and our job is to confirm or refute it. This "theory" states that the speed of a string wave v is related to the tension force F on the string and the mass density of the string μ according to:

$$v=\sqrt{\frac{F}{\mu}} \tag{1.2.1}$$

In our experiment we will have a physical setup for which we can directly measure all of these quantities, to see if the theory holds, to within the uncertainty of our measurements. Normally we would do a graphical analysis to see if this mathematical relationship holds, but for reasons we will see later, all three of these variables will change in the course of the experiment. We will therefore only look for confirmation with a single tension in the string, using the time we save to do several runs for that one tension to get a measure of uncertainty in our result.

Some Things to Think About

Part 1

Some questions to answer with your observations (and include in your lab report):

- Presumably the wave carries forward into this new medium, but this question is about reflection. Does the pulse reflect off such a "barrier" at all?
- Does the pulse reflect the same off both barriers, or is there some property of the new medium that decides what happens to the reflected wave?

- If different barriers cause different reflections, when happens when the properties get closer together – is there a sudden transition point? You will have to speculate about what happens as the properties of the chain are morphed toward the string and those of the string toward the chain, as we don't have materials available for actually testing this directly.
- Assuming this phenomenon applies to all types of waves (even though we have only studied it specifically for mechanical waves), what generic wave property appears to be responsible for the reflection properties?

Part 2

One look at the apparatus should make clear how you are going to measure the tension that is applied to the stretchy string, but you may need to put some careful thought into how you will measure the other two quantities, and how you measure their uncertainties to apply the weakest link rule.

- Measuring the speed of the wave (as usual) comes down to measuring time intervals and distances. There are hints in the Background Materials about how best to measure the times and their uncertainties.
- The "obvious" way to measure the string density is to measure its length and its mass and calculate it from there. However, written in the last paragraph of The General Idea section is an obtuse hint, where it states that all three measurements – apparently including the string density – are changing from one experiment to the next. Figure out how the two experiments can involve different densities when the same string is used, and you will be on your way to devising a way to achieve a more accurate result.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

Every member of the group must upload a separate digital copy of the report to their lab assignment in Canvas *prior to leaving the lab classroom*. These reports are not to be written outside the lab setting.

CHAPTER OVERVIEW

Lab 2: Standing Waves

2.1: Background Material

Text References

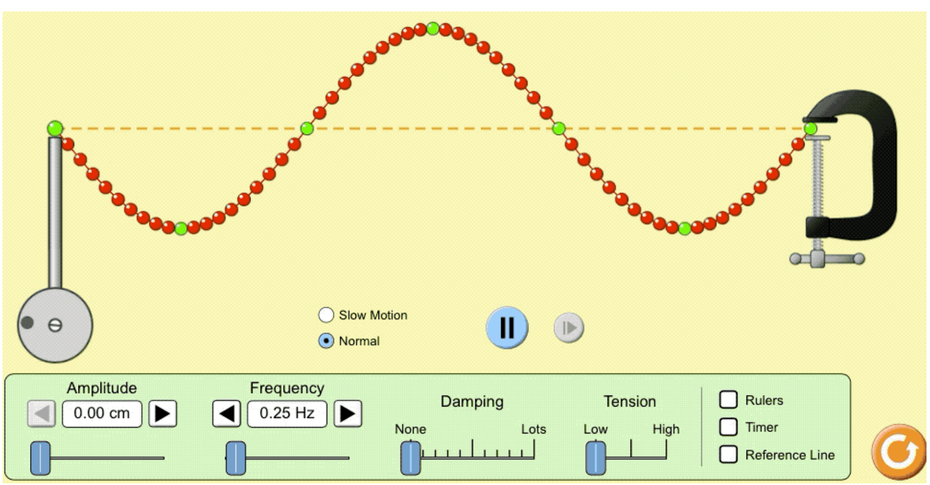
- standing wave harmonics

Creating a Standing Wave with the Simulator

For this lab, we will be using the same string wave simulator that we used in the previous lab. Our goal is to study standing waves, which requires a great deal more precision than existed in the previous lab. What follows is a careful step-by-step procedure for creating a standing wave. Start by running the simulator now in another window.

A standing wave requires two identical periodic waves traveling in opposite directions, generally achieved by reflections off two boundaries. In our simulator, we have one boundary (which we can choose to be fixed or loose), but the other end drives the wave (i.e. puts energy into the system). So the trick to forming a standing wave here is to drive a wave into the string for just the right amount of time, then stop the driver and hold it fixed (there is no way to make it loose, but that is fine). The waves will then bounce back-and-forth between the two ends, and a standing wave will be the result.

1. Configure the simulator as follows:
   - **click the pause simulation button**
   - **click the "Oscillate" radio button selected in the upper-left corner**
   - **leave the "Fixed End" radio button selected in the upper-right corner**
   - **set the "Amplitude" equal to 0.50cm**
   - **set the "Frequency" equal to 0.25Hz**
   - **set "Damping" to "None" (the minimum)**
   - **set "Tension" to "Low" (the minimum)**
2. Click the play simulation button, starting the driver. A wave will begin to propagate across the string. Allow this to continue until after it reflects, but click the pause simulation button before it gets all the way back to the driver.
3. We want to stop the driver at the moment the wave completes exactly one round-trip, so use the step simulator button to increment the return trip of the wave, and leave the simulation paused when the round-trip is complete. You will know this has occurred when the green bead at the top of the driver has returned to the dashed line from below it. Instead of watching the wave, you can just watch the driver – you want to freeze the simulation when it completes exactly three full cycles. [*Note: This "three cycle shortcut" only works for this specific case – you can't use this for more general cases.*] Besides looking at the green bead's position, you can also confirm that the cycle is complete when the black dot on the driver wheel is at exactly 9 o'clock.
4. With the simulator frozen in the perfect position, it's time to turn off the driver. Set the amplitude to zero, and click the play simulator button again... Voilà, a standing wave!



If you did not follow the above steps precisely, you may achieve something that *resembles* a standing wave – at least for awhile – but it will have a few small imperfections that will show up in the motion of the string.

2.2: Activities

Equipment

- string & pulley assembly
- weights
- wave generator driven with Pasco software
- tape measure
- spare length of string for direct density measurement
- triple beam balance

The General Idea

In this lab, we will use standing waves to measure the density of the string in which those waves vibrate. We will do this by noting that every string tension has its own fundamental harmonic (as any guitar player knows). The relationship between the tension and the fundamental harmonic involves the mass density of the string and the distance between its two fixed ends, and this comes from the role that tension and mass density play in the traveling wave velocity.

We have the tools to drive a standing wave at whatever frequency we like, and at the same time we can hang whatever weight we like from the string. If we tune the frequency to the hanging weight, we can create a standing wave in the string. The standing wave doesn't have to actually be vibrating at the fundamental frequency to determine what it is, because we can easily count the number of antinodes, and $f_1=\frac{f_n}{n}$. By changing the weight several times and recording the corresponding fundamental frequencies, we have data that we can use for a best-fit line (linear regression) to find the string density. The formula for this line comes directly from equations we are already familiar with; the wavelength of the fundamental harmonic for a string wave with both ends fixed is $2L$, where L is the distance between the endpoints, so:

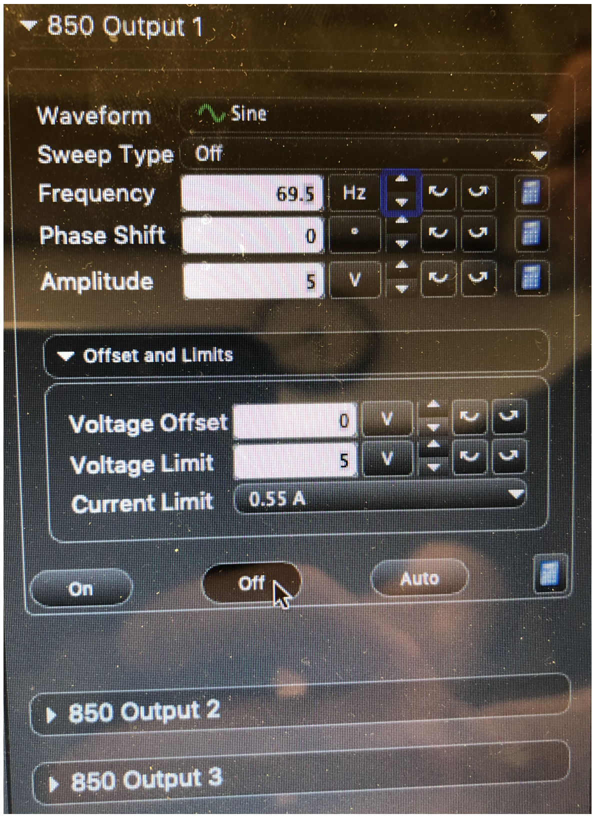
$$\sqrt{\frac{T}{\mu}}=v=\lambda f=(2L)\,f_1 \quad\Rightarrow\quad T=\left(4L^2\mu\right)\; f_1^2 \tag{2.2.1}$$

Some Things to Think About

There are two sections of advice here. The first consists of pointers on the actual process of taking data. There are many nuances of the software and the apparatus that are useful to know so that you don't waste a lot of time. The second is advice in doing the analysis.

Equipment

With the laptop powered off, turn on the Pasco box. Then power-up the laptop. You will find the application in the 9B folder on the desktop of the laptop. It is called "Standing_Waves." Below is a picture of the control panel in the software.



- Only "Output 1" is involved here (it comes from the ports into which the wires are connected).
- "Waveform" should be left in the default setting of "sine".
- "Sweep Type" should be left in the default setting of "off".
- The "Phase Shift" and "Voltage Offset" numbers are unimportant and should be left at the default setting of zero.
- The default "Amplitude" is 1V, but it will likely need to be made higher. It will only go to 2 unless you increase the "Voltage Limit" value. You may make this increase (only if you need to!), *but under no circumstances should it go above 5V*. If you can't seem to generate a standing wave with the amplitude set at 5, call over your TA for assistance.
- "Current Limit" should not be changed.
- You can turn the oscillator on and off with the buttons conveniently labeled with those very names. Always turn off the oscillator when changing weights.
- The simplest method for searching for harmonics is as follows:
  - Estimate a frequency for the new weight.
  - Make sure that the digit *in the one's place* of the "Frequency" field is selected, and use the up/down arrows on the keyboard for increase or decrease the frequency by units of $1Hz$ (if the ten's place is highlighted, those arrows will make changes in units of $10Hz$).
  - When you hit a frequency that gets the string to start to jiggle, click inside the Frequency field after the one's place, and the first decimal place will appear. Now toggling the up and down arrow keys will change the frequency by tenths of hertz. When you find the standing wave that has steady nodes and has the largest possible antinodes (which remain consistent and don't periodically dissolve and re-form), you have found a harmonic.
  - When you have found one harmonic with a given weight and are ready to search for another, do a quick computation to make an *educated guess* at what one should be, and type-in that frequency to start your search, so that you don't spend a lot of time searching blindly. Even if your guess is very good, you should fine-tune it.
- A node (other than those at the endpoints) is useful for pinpointing an harmonic, and higher frequencies have lower percentage uncertainties, so you should not use the standing wave in its fundamental harmonic useless absolutely necessary. Don't use harmonics higher than 4th.
- The best results seem to be achieved for weights between $200g$ and $1000g$, with higher harmonics working well for smaller masses and lower harmonics for higher masses.

- Take data for at least 5 different weights (with two harmonics for each), or your graph's usefulness will be marginal.

Analysis

- As mentioned above, the fundamental frequency does not need to be measured directly, because we know how to extract this value from the measured frequency and number of antinodes. What is more, being able to measure the same quantity more than one way is valuable in experimentation as a way of reducing uncertainty. So for each tension in the string, you should make two separate measurements of the fundamental frequency (which you can then average).
- The relationship between the tension and the fundamental frequency isn't linear, but a graph of tension versus some appropriate function of the fundamental frequency will still result in a line, allowing us to carryout our plan. You can review this Background material from an old 9A lab for a refresher of how this works.
- As usual, for your plots you should use the usual online graphing calculator to plot your data points. Here is a reminder of how to get the best-fit line (do the linear regression) on Desmos: Create the data table by clicking on the "+" in the upper-left corner, and selecting "table". You will see that the variables "x_1" and "y_1" are used in the table. In the next box, put in the equation for a line with these two variables, but instead of using an equal sign, use "~". So it should look like "$y_1 \sim mx_1 + b$". A best-fit line will be drawn for you, and the values of m and b for this line will be displayed.
- From the best fit line, we can extract the slope (actually Desmos does this for us), but this is not exactly the mass density we are looking for, so you will have to calculate it from the slope, with the help of another measurement.
- After computing the mass density, you can check your answer by measuring the length and mass of a string similar to the one in your apparatus. ***Do not detach the string from your apparatus for this purpose.*** Every group in the class does not need to make this measurement once one group has done it and another group has confirmed it – everyone can use their findings.
- While we could do so, we will continue to eschew extracting a measure of the uncertainty of our answer from the linear regression results, but we can still nevertheless compute the uncertainty of the direct measurement (use the weakest link rule for this), and the experimental result can be compared using this uncertainty. Be sure to elaborate other possible sources of uncertainty not accounted-for.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

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CHAPTER OVERVIEW

Lab 3: Compression Waves in Solids

3.1: Background Material

Text References

- speed of compression waves in solids
- standing wave harmonics

Sound Waves in Solids

Unlike through fluids, when compression waves move through solids, the particles in the medium that is vibrating are *not* free to roam, and therefore really do oscillate. Our previous study of standing waves involved strings, which necessitated creating fixed endpoints. For compression waves in a solid metal bar, as we will study in this lab, the endpoints are free to move, so our standing waves in this case have different boundary conditions.

Squelching Harmonics

Most of the energy in a standing wave is contained near the antinodes, because that is where the medium is moving the fastest. Near the nodes there is very little of the standing wave's energy. If we damp the motion of a single position in a standing wave (like pinching a small segment of a string) then the harmonics that have an antinode near that position will lose their energy, while harmonics that have a node at that position will hardly be affected. We can't make the metal bar in this experiment float in mid-air for us – we have to hold it somewhere as we create the standing wave. Wherever we decide to hold it will have a dampening effect on the standing wave, so depending on what harmonics we want to observe, the bar will need to be held differently.

3.2: Activities

Equipment

- sound sensor with Pasco software
- metal bar & "bang weight"
- hanging string
- tape measure

The General Idea

We are given a bar made of an unknown metal, and are tasked with determining is composition. It is silver in color, which doesn't narrow things down a lot, but let's just say we have whittled the possibilities down to aluminum and titanium. Titanium is significantly more dense than aluminum, which suggests a quick way to answer this question, but we can't be certain that the bar isn't hollow. A hollow bar of titanium could have the same average density of a solid bar of aluminum. So our (perhaps convoluted) approach will instead be to measure the speed of sound through the bar, and match it to the proper metal (within uncertainty).

To determine the theoretical speed of sound in these metals, we need to know a couple of their properties. A short Google search reveals the following about these metals:

	Young's modulus	mass density
aluminum	$7.80\times 10^{10}\pm 13\%\frac{N}{m^2}$	$2.70\times 10^{3}\pm 0.1\%\frac{kg}{m^3}$
titanium	$1.03\times 10^{11}\pm 2\%\frac{N}{m^2}$	$4.51\times 10^{3}\pm 0.1\%\frac{kg}{m^3}$

To measure the speed of sound in our lab, we can employ a method similar to Lab #1: Create standing waves and use the length of the bar and the measured frequencies of the harmonics excited to compute the speed of the traveling wave that comprises that standing wave. What is different from the previous lab is that we will just dump energy into the system haphazardly, exciting several harmonics at once, and use a sound-sensing device to sort out the harmonics (which, due to constructive interference, get almost all the energy).

Some Things to Think About

We use the Pasco equipment in both parts of this experiment, so advice for each part is includes pointers for using the software as well as hints about methods for data acquisition and analysis. In terms of the software, the startup is the same for both parts. As with the previous lab, the Pasco box laptop have to be started from scratch (with the power off, and with the Pasco box turned on before the laptop).

The application to run from the 9B folder on the laptop is called "Sound_1". The sensor will start displaying data as soon as you click the "Monitor" button. Clicking the same button to stop very nicely freezes the screen in place for you to analyze at your leisure.

This program displays the the sound detected by the sound sensor, organized according to energy detected (technically, it is voltage coming from the sensor) as a function of frequency. So each little vertical bar indicates how much energy from the sound entering the detector comes from a thin range of frequencies. So for example, a monotone, having only one frequency, is represented in the display by a single thin monolith. Ambient sound has no particular preference for a single frequency, which is why you see a whole wide spectrum of vertical bars when the detector is just picking up noise.

When struck by the metal weight (this should be done by striking the bar end-wise – we are creating compression waves along the length of the bar), at first the bar vibrates with more-or-less random frequencies, but thanks to the constructive interference inherent in standing waves, it doesn't take long for the harmonic frequencies to account for most of the vibrational energy in the bar (the wave bounces back-and-forth between the ends thousands of times in the first second, so you won't even notice a lag time for the peaks to occur).

- As always, you want as much data as you can get, for the most accurate result possible, so you should measure the frequencies of at least 4 different harmonics, and not all of them can be odd-numbered.

- The bar has to be held somewhere, but doing so squelches some of the vibrations, so we want to grip it as little as possible. One thing that will help is use of the string provided, which maintains far less contact than human fingers.
- Useful as the string is, it still has its limitations, and in fact *where* the string holds the bar will be critical. No single placement will allow you to see all the harmonic resonances (peaks in the vertical bars) that you want – you will need to support the bar in two different manners to get clear views of both odd and even harmonics. Thinking about what the standing waves look like in this bar (in terms of its nodes and antinodes) should help you determine where the support points should be.
- When you adjust your string and begin measuring the frequencies of some even harmonics, you may observe a couple of odd occurrences. First, the fundamental may not squelch-out as fast as you expect. Be sure to wait long enough for this to happen, so that you get the correct resonance peaks. And second, you may not be able to find the fourth harmonic at all. To answer this puzzle, you may want to sketch the standing wave of the fourth harmonic. Unlike the odd harmonics, which are all manifest with a single string placement, the same is not true of the even harmonics.
- You can most easily read the value of the frequency for a given peak by using the coordinate tool. To activate this, click the button that looks like this: . Then just drag the cursor over the peak, and the horizontal component shown is the value of the frequency. You can print/screen-capture/photo the output for your lab report.
- Armed with the frequencies of several harmonics, and your knowledge of the wavelengths of these standing waves in terms of the length of the metal bar, you have many separate measurements of the speed of the traveling sound wave in the bar, and you can average them for your official measurement of the speed of sound in the metal bar.
- All that remains is to determine which metal the bar is made from. We are given uncertainties in the measurements of Young's modulus and mass density to use as our bounds. There is one thing to keep in mind here, however. The speed calculation uses the *square root* of these values, and the uncertainty of the square root of a quantity is not the same as the uncertainty of the quantity itself. You can review this (as well as the "weakest link rule", which you should also use here) in the Background Material of Lab #4 from Physics 9A.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

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CHAPTER OVERVIEW

Lab 4: Two-Source Interference

4.1: Background Material

Text References

- double-slit interference

Play with this Simulator!

Go ahead and run this PhET simulator in another window. This software simulates wave interference of various types. In the lab, we will be focusing on interference of EM waves passing through a double slit. To prepare for this, you should therefore configure the simulator as follows:

- **select the window "Slits"**
- **click the light source button** 
- **select the "Screen" check box, and the "Intensity" sub check box**
- **select "Two Slits" in the drop-down menu**
- **leave the "Amplitude" slider at its "max" setting**
- **use the "Frequency" slider to adjust the frequency (wavelength) of the light**
- **use the "Slit Separation" slider to change the double slit**

The green button on the Light Generator starts a plane wave, represented by alternating bright and dark regions that represent the crests and troughs of the waves, respectively. [*Note that these do not represent bright and dark regions! That is, if you were in the simulator, and you looked at the Light Generator, you would see constant, uniformly-bright red light coming from it. If you run the simulator, this is in fact what you see on the screen.*]

In particular, you want to explore the effect of changing the wavelength of the light and changing the slit separation for a fixed wavelength, as these are things we will be doing in the lab.

4.2: Activities

Equipment

- microwave emitter & detector
- goniometer assembly
- aluminum double slit barrier
- laser & optical bench
- laser slit collection
- tape measure
- masking tape & paper

The General Idea

There are two parts to this lab, both of them involving the same phenomenon of two-source interference.

Part 1

We are given a microwave emitter and microwave detector, which are mounted on opposite arms of a goniometer (a device for measuring angles), with an aluminum barrier that includes two slits between them. The angle at which one or more "bright fringes" are deflected by the double slit interference can be measured by rotating the detector's goniometer arm until the gauge reads a local maximum. From this angle and measurements made on the apparatus, the frequency of the microwaves coming from the emitter are to be calculated.

Part 2

In this part we are given the wavelength of the laser light used ($633nm$), and use the interference pattern on a wall far away to compute the slit separation for a couple of different cases.

Some Things to Think About

These two experiments look very different, but involve exactly the same phenomenon. Each of them has a few features that are distinct from each other, however.

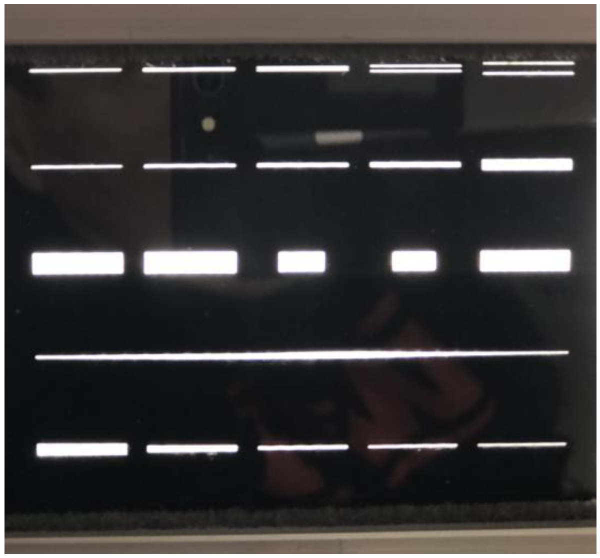
Part 1

- The amount of energy removed from the microwaves by the double slit barrier is substantial. When the emitter and detector are used together without a barrier, the detector does not need to be in a sensitive setting for the needle to move enough to get a good reading, but the sensitivity may have to be increased substantially to get an adequate reading through the double slit. Keep in mind that if you remove the barrier while the detector is in a sensitive setting, the sudden flood of microwaves can spike the needle in the detector, and over-ranging it like this is not good for it.
- The official "bright fringe" location is the point where the needle in the gauge makes its maximum deflection. The "play" you have in changing the angle while still measuring a max deflection is the uncertainty in the angle.
- As always, more data is better! If there are multiple bright fringes (there are at least two – one on each side of the center), you should seek to locate as many as you can. Each one give you an independent calculation of the same value, which you can then average for your best guess at the correct number.
- When you have a solid number for the frequency of the microwaves (with an uncertainty range), check to make sure it lies in the microwave part of the spectrum, and if it does, ask your TA how well you did in determining the frequency, and see if it comes out within the estimated uncertainty.

Part 2

- ***Safety first! Do not look directly into the laser beam, as it can damage your retina. All viewing of the laser should involve seeing it reflected from a dull, diffuse surface, like a piece of paper. It therefore goes without saying that it should not be pointed at anyone, either.***
- The laser is a delicate device, so handle it as little as possible. It is set up on the optical bench for you, and shouldn't need to be moved from there. To alter the vertical position where the laser strikes the plate, try to avoid raising or lowering the laser, and raise or lower the plate instead.
- The glass slide includes several transparent holes that include various combinations of slits. The 5 holes at the top of the slide are the ones we will use for this lab. In the picture below, it is clear that the right two holes are double slits, but all 5 of the

holes across the top feature double-slits, and you can use any two of them for your experiment. Find the separations of the slits for both cases, and provide uncertainty ranges.



- The interference pattern will include *lots* of bright fringes that are, to the extent of our measurements, equally-spaced. If you want to minimize percentage uncertainty, is it a good strategy to base your results on two *adjacent* fringes?
- When doing measurements with bright fringes, please do not write on the wall or on the blackboard (unless you use chalk, but chalk is very imprecise). There is paper and masking tape available for you to use for the purpose of marking fringe positions.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

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CHAPTER OVERVIEW

Lab 5: Diffraction

5.1: Background Material

Text References

- single slit diffraction
- Babinet's principle
- interference of many sources in phase

Interference After Reflection

In the previous lab, we explored interference of light waves coming through two slits. The two waves emerged from the slits in phase, so difference in distances they traveled accounted for the interference pattern observed. In the reading above, we see that if we use many more slits (a diffraction grating), then we get a much more sharply-defined pattern, with very intense bright fringes separated with the same $d\sin\theta = m\lambda$ relationship as for the double-slit, but separated by broad regions of darkness.

We are going to explore this phenomenon in this lab, but rather than pass the laser light through the many slits of a diffraction grating, we are going to *reflect it* off a surface with many grooves – a compact disk. The light that strikes the raised ridges of the disk are reflected diffusely (i.e. not in phase), which effectively means that these ridges act like the spaces between slits in a diffraction grating. Meanwhile, the interior of the grooves are highly reflective, so the light reflected from them remains in phase, and the grooves behave like the slits of a diffraction grating.

5.2: Activities

Equipment

- laser & optical bench
- microscope comparator
- compact disk
- tape measure
- masking tape & paper

The General Idea

There are two parts to this lab, both of them seeking to answer a question. The first question is, "What is the approximate width of a human hair?", and we will do it in two ways. The first is to look at it directly through a special microscope called a comparator. The second way, which we hope to confirm the first measurement, is to use laser light and the diffraction pattern the hair produces thanks to Babinet's principle. In the second part of the lab, the question we seek to answer is, "What is the approximate spacing of the grooves on a compact disk?" For this we'll again use laser light, and observe the reflective interference pattern.

Some Things to Think About

Here is a repeat of the safety warning given in the previous lab regarding the use of the laser:

Do not look directly into the laser beam, as it can damage your retina. All viewing of the laser should involve seeing it reflected from a dull, diffuse surface, like a piece of paper. It therefore goes without saying that it should not be pointed at anyone, either.

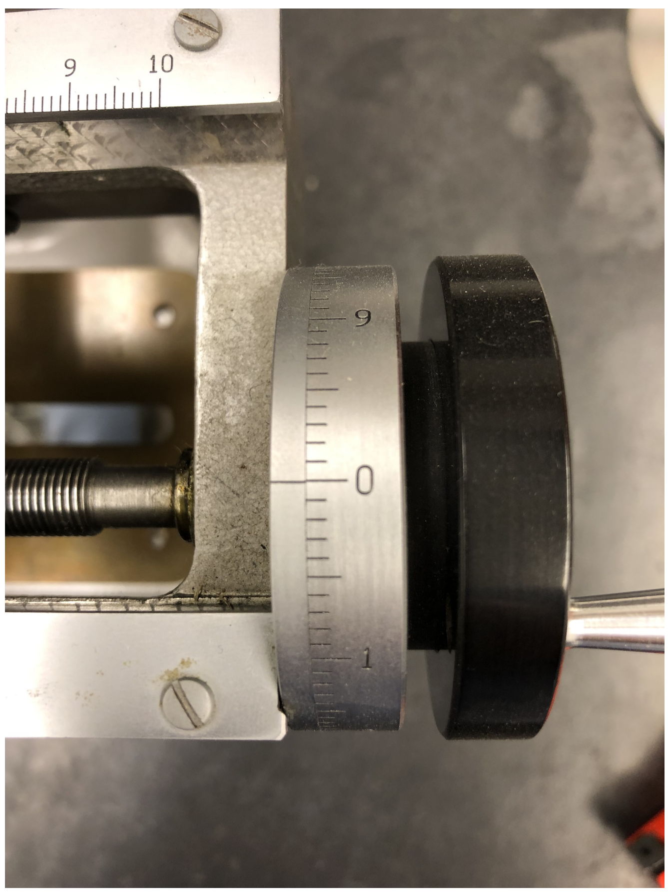
As with the previous lab, if you need to make any marks to indicate positions in your interference patterns, please use paper & masking tape – please don't write on the walls or blackboard.

We are using the same $633nm$ wavelength laser that we used in the previous lab.

Part 1

- The use of the comparator is not immediately obvious, though you'll understand it better with a bit of trial-and-error. The idea is this: This device is a microscope with cross-hairs (or perhaps just a vertical line), which can move side-to-side, achieved by turning a crank. The amount it moves can be measured to a very small dimension. Measurements come from two scales on this device that are used in tandem. The first is on the horizontal bar, and this is a typical ruler – the markings show centimeters and are subdivided into millimeters. There are also markings on the dial around the crank, dividing it into 10 numbered sections, with 10 subdivisions each (so a total of 100 measurable positions per crank revolution). You should play with this crank to see how the dial divisions are related to the horizontal bar distances, so that you can use both scales together to get an accurate measurement of the distance that the microscope moves laterally when the crank is turned.


3 4 5 6 7 8 9


9 10
9
0
1

- You are using this comparator to measure the width of a hair, so once the hair is aligned with the line (which of course can only be done after you bring the hair into focus), then moving the line from one side to the other should give you what you need.
- The interference pattern create when you shine the laser through the hair is not quite the same as the one you saw with the double slit in the previous lab. The equations of the two cases look similar, but they are subtly different, and understanding the difference is important.
- Because of the broad area covered by bright fringes and narrow regions, it is better to use separations of dark fringes rather than separations of bright fringes. [Also, it is mathematically more challenging to determine the formula for the spacing of brightest points.]
- As always, the percentage uncertainty is reduced when you use larger dimensions for a given absolute uncertainty. The dark fringes are equally-spaced, so this should give you an idea about how to determine these separations more accurately.
- How will you compute the $\sin\theta$ (found in the formula) from what you can measure?
- What do you estimate to be the percentage uncertainty in comparator measurements of the hair width, and how does this compare with estimated percentage uncertainty of hair width using the laser, i.e. which is the weakest link?

[*Not part of lab report: Do you recall seeing a pattern similar to this within the double-slit pattern from the previous lab (i.e. shown in the brightness of the many fringes)? Any idea why it would be there? Check with your TA to see if you have the answer.*]

Part 2

- Remember that in this case, the laser light is reflecting off the grooved (shiny) side of the compact disk.
- In order to make the distance between bright fringes as easy as possible to measure, you will want them to deflect from the central bright fringe *horizontally*. Think about how you should position the compact disk in the laser beam to achieve this.
- How will you compute the $\sin\theta$ (found in the formula) from what you can measure?
- How many bright fringes can you see? How many can you use to make measurements?
- Once you have determined the spacing of the grooves, convert this into a groove *density*. Approximately how many grooves are there on the entire CD?
- If the distances to the bright fringe(s) on the right are a different distance from the cental fringe than those to the left, what does this tell you about the alignment of your apparatus?
- We don't really have numbers to compare in this case, but you should still make an estimate of percentage uncertainty in your measurement of the groove spacing.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

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CHAPTER OVERVIEW

Lab 6: Geometrical Optics

6.1: Background Material

Text References

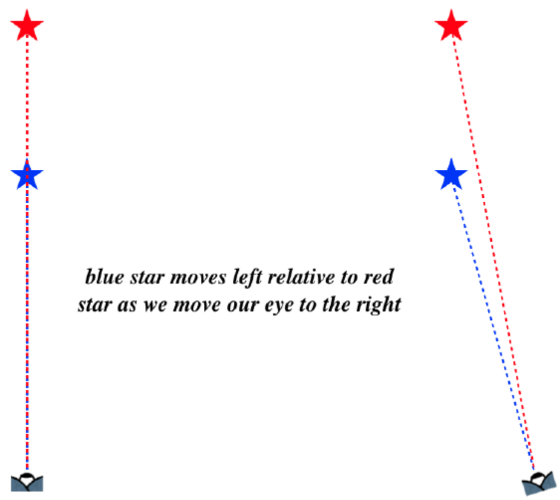
- Snell's law
- locating an image from a plane refractor

Using Parallax

One of the challenges for today's lab is determining how far away an image is from the viewer. We already know that things look larger when they are closer, and smaller when they are far away. But when light is reflected or refracted on its way from the object to the viewer, the size of the image seen is affected, so we can't rely on this.

While there is no way to determine an image's distance from us without knowing its actual and apparent size, and the path that the light had to follow to get to us, there is nevertheless a way to compare the relative distances of two images, using something called *parallax*. Consider viewing two images aligned with one another, with one being farther away than the other. We can determine which one is closer simply by changing the angle of perspective so that they are no longer aligned.

Figure 6.1.1 Changing Perspective to Exploit Parallax



As we change our eye position, the change in relative positions of the images reveals which is closer – it moves in the opposite direction as our eye relative to the other object. So how can we use this to locate an image when the light follows a reflected or refracted path? We compare position of an image from the altered path with a "reference" image that comes from an unaltered path. Let's look at a simple example with a plane mirror.

Start by placing a vertical rod in front of a vertical plane mirror, such that when we look in the mirror, the top of the rod's reflection reaches the upper edge of the mirror. Next place another rod *behind* the mirror so that its top extends beyond the top of the mirror. If the two rods are placed such that the line joining them is perpendicular to the plane of the mirror, then looking straight into the mirror (along the line joining the rods) will give the appearance that the image of the rod in the mirror is continued by the image of the rod above the mirror.

Now what do we we see if we move our eye right or left? If the rod placed behind the mirror happens to be at the same place as the image of the rod in front of the mirror, then they remain aligned at the top of the mirror – parallax does not cause one to move side-to-side differently from the other. But if the rod we see above the mirror and the image in the mirror move relative to each other, then we know that the rod behind the mirror is not the same distance away as the image in the mirror, and we can tell which one is closer by the relative directions that they move (the closer one moves the opposite direction as our eye motion).

Figure 6.1.2 Reflection and Rod Behind Mirror the Same Distance Away

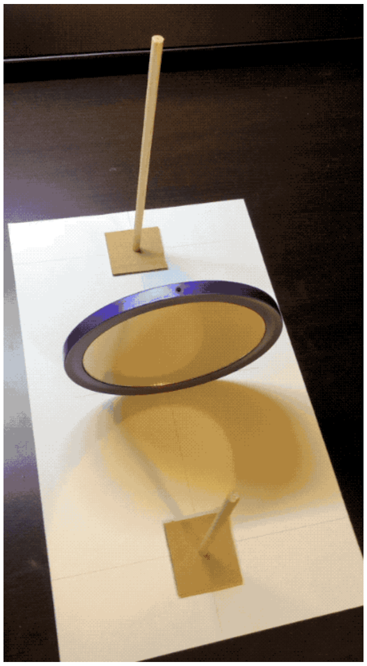


Figure 6.1.3 Reflection Closer than Rod Behind Mirror

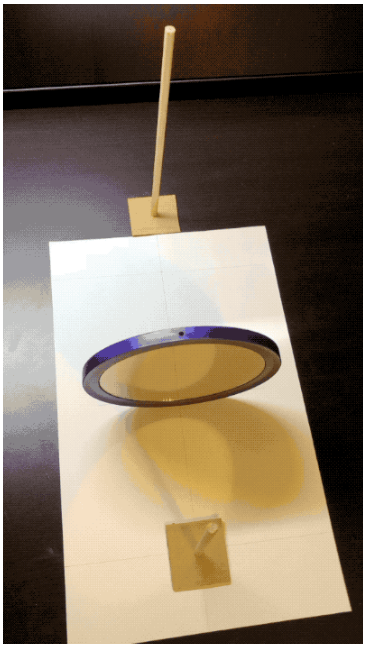
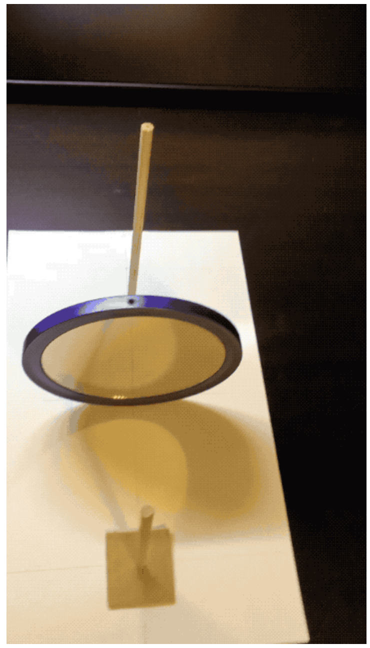


Figure 6.1.4 Reflection Farther than Rod Behind Mirror



We know from our studies of geometrical optics how to find where an image is if we know where the object is, and the sort of path the light has to follow, but this parallax trick gives us a way to *experimentally* determine this. We just move the rod behind the mirror until it remains aligned with the reflection, and wherever we move this rod to is the location of the image. We make adjustments to the position of the "test rod" by noting that if it moves the same way relative to the reflection as our eye moves, then it is too far, and it is too close if it moves the other way relative to the reflection.

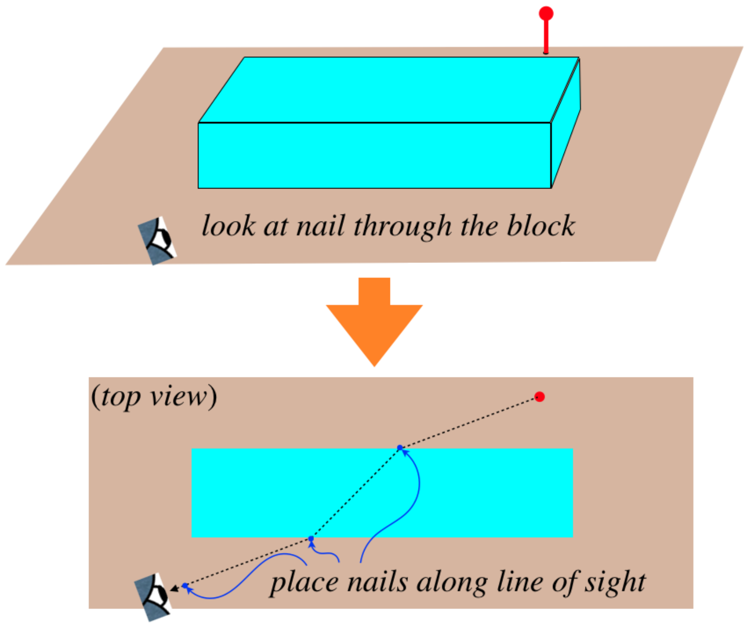
Snell's Law Without a Laser

It is likely that we have seen visual evidence of refraction of light when goes from one region to another with a different index of refraction, using lasers. But this phenomenon has been understood in its present state for over 1000 years (first explained by a Persian scientist, with Snell eventually getting credit for work he did around 1600), and certainly none of them had lasers to work with. To be clear, we are talking again about confirming this law experimentally – the various mathematical proofs (like the one using Huygens's Principle) are not what we are talking about here.

Given that we cannot see rays like we do laser beams, we need to somehow define them another way. Naturally two points define a line, so if we position our eye so that two vertical rods are aligned, then we can be sure that the ray that enters our eye is the one that passes through both of them. If we add more such rods in alignment, the ray passes through all of them on its way to our eye.

In our experiment we will be using a rectangular prism of some unknown transparent substance, and we can trace the path of a light ray from a nail to the prism, then from the other side of the prism to our eye by placing nails in line with our sight of the original nail.

Figure 6.1.5 Using Nails to Trace a Ray


look at nail through the block
(top view)
place nails along line of sight

6.2: Activities

Equipment

- transparent rectangular prism
- foam board & nails
- protractor & ruler
- optical bench with mounted light source, "object" (arrow) slide, lens, and projection screen
- meter stick

The General Idea

This lab comes in two parts, both of which involve solving a mystery using multiple methods that (should) concur on the answer. In both parts, it will be useful to have an understanding of the effects of parallax. An explanation for how to use parallax to find the position of an image is in the Background Material. For Part 1, the method of creating a ray trace using nails placed in the line of sight of the image is also discussed in the Background Material.

Part 1

In Part 1, you will experimentally determine the index of refraction of a transparent block, using three separate methods:

1. Use the nails-placed-along-the-line-of-sight approach to trace the path that the light takes from the object to your eye (through the block, of course). With a trace of a ray, the angles that the light bends at the two surfaces can be measured, and from that data (and the fact that the index of refraction of air is 1.0) one can use Snell's law to compute n for the block.
2. The next two methods involve finding the location of an image created when looking at an object through the block, and using the known image & object distances (and the appropriate equation) to compute the index of refraction. In both cases, the object (a nail) is placed in contact with one side of the block, so that the light only really bends at one block/air interface.
   - Find the image location using the nails-in-the-path-of-the-light from two different eye perspectives.
   - Find the image location using the parallax method (trial-and-error with another nail that you can move around).

[It should be noted that the formula for the image position of a refracting plane is actually *derived* from Snell's law, so these aren't exactly *independent* confirmation, but that's okay – they are a form of confirmation, and it's interesting to see them both in action.]

Part 2

In this part, light comes from the object and passes through a lens. We are not able to use nails to trace the path the light takes, but we can locate the image and use the object and image distances, along with the thin lens equation, to determine the focal length of the lens. This must be done in two distinctly different cases:

1. The image is located on the opposite side of the lens from the object. (Do at least three separate runs.)
2. The image is located on the same side of the lens as the object. (One run of this kind is sufficient.)

For locating the image, you have at your disposal the parallax method described earlier, and a screen onto which certain types of images may be projected.

Some Things to Think About

Part 1

- You will want to trace out the border of the block on the paper, both to make the later work easier, and so that you know where to place the block in the event that it moves off its original position while you are in the middle of taking data.
- When using the nails to trace the path of the light:
  - Please use a piece of paper, and *not* the styrofoam pad for drawing the rays.
  - Keep in mind that two nails are needed for any straight line you need to draw.
  - The last nail you place looks "fatter" than the previous nails due to perspective (it is closer to your eye), and the fact that it obscures those nails can make it difficult to align it accurately. It may help to look to the left and right of this nail, to see if the perspective with the other nails is symmetric. Moving your eye farther away should also help a bit.
- For the Snell's law portion:
  - Remember that θ is measured with the normal to the surface.

  - There are *two* places where the light bends – you can use this extra data to potentially improve (or at least confirm) your result.
- For the image of the flat refractor portion:
  - Percentage uncertainties are reduced when the object & image lengths are longer.
  - You get the center-line ray trace (the one that passes straight through the block undeflected) "for free". Use it as a confirmation of two other rays.
  - Please don't put the sharp side of the nail against the block when doing the parallax location – scratching the surface of the block makes it less usable for future optics experiments.
- For both ray-trace-with-nails portions, include a photo of the traces you created in your lab report.
- As usual, make estimates of the range (uncertainty) of your length measurements, convert them to percentages, employ the weakest link protocol, and see if the two experiments agree.

Part 2

- You can start by "playing" with the lens to determine if it is converging or diverging. You should know some general characteristics of the two types of lenses that will allow you to make this determination.
- Whenever possible, using the screen and projecting the image onto it gives results that are more accurate and are easier to measure than using parallax. But you need to be aware of which circumstances make the use of a screen possible and which ones do not. When in doubt, think about *what is happening to the light*.
- As with Part 1, compute approximate uncertainties and use them to determine if your measurement is confirmed.

Lab Report

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CHAPTER OVERVIEW

Lab 7: Kinetic Theory and Ideal Gases

7.1: Background Material

Text References

- kinetic theory of gases
- particle speed in a gas
- ideal and non-ideal (van der Waals) gases

van der Waals Gases

In one of the text references above, we encounter a state equation relating pressure, volume, temperature, and particle number (Equation 5.5.4) that is more general than the ideal gas law. It accounts for the size of the particles (they can't occupy the same space), and the attractive forces they feel toward each other (van der Waals forces).

In this lab, we will be examining the kinetic theory of gases with a simulator, and the simulator includes an option for allowing the particles to collide elastically with each other (they behave as "hard spheres"), but the particles are still not allowed to attract each other. Including this feature would complicate the picture beyond our current study of gases, because at low temperatures these attractive forces will cause our "gas" to start changing phase into liquid and solid.

We can therefore cut down the full van der Waals equation for the purposes of this lab. Another useful change is to change the variable for number of moles to number of particles, since the simulator will not have anything close to 10^{23} particles involved. The modified van der Waals equation that applies to our simulator is therefore:

$$P\left(V-N\beta\right)=Nk_BT \tag{7.1.1}$$

We have replaced the constant b with a new constant $\beta=\frac{b}{N_A}$. The simple physical interpretation of β is that it is the volume of a single particle. Multiplying it by the particle number gives the total volume of all the particles combined. Subtracting this from the total volume of the chamber gives the spatial volume available for the movement of the particles, which is what is needed in the state equation. If the gas is ideal, then the entire volume of the chamber is available, giving us $\beta=0$ and the usual ideal gas law.

7.2: Activities

Equipment

- laptop

The General Idea

Typically in labs we explore the real-world applications of physical principles, but the topic of kinetic theory presents us with a problem on that count. We can (and will) explore the *results* that come from kinetic theory, namely the relationships between macroscopically-measurable quantities like pressure, temperature, and volume, but the theory itself involves linking a microscopic model to the macroscopic world, and given this involves a number of particles on the order of 10^{23}, this cannot be directly observed. So instead we'll explore this theory by cutting down the number of particles to a manageable level, and use computer simulation to model what we want to examine. [You can click on the link now to run the simulator in a separate window. If you are reading this on your own device and wish to use the laptop in the lab room for this purpose, you need to log into eduroam, run the browser, then look under "simulators" for "kinetic theory."]

What we will be doing with the simulator comes in two parts. The first is rather unusual, inasmuch as it tests/demonstrates the limitations of the particular simulator we are using to reflect correct physical behavior. Namely, the behavior of the particles in the animation implies that the gas should behave like a van der Waal gas, and we will test whether this is happening. The second part ignores its limitations and moves on to examine the system it is intended to simulate – a volume of an ideal gas.

Things to Think About

Part 1 - Critiquing the Simulator

Normally when we use a simulator, we take the numbers it provides as gospel, but this simulator is a bit different. It exhibits observable behavior of particles in an accurate manner, and it provides numbers that are correct under the certain assumptions, *but the observable behavior does not match these assumptions*! The behavior of the particles on the screen model one physical system, and the thermodynamic quantities displayed numerically model a different physical system. Normally a flaw like this would preclude our using the simulator at all, but it turns out that rooting out these problems is highly instructive, so for the first part of this lab we will do exactly this.

Open the "Energy" panel of the simulator and configure it as follows:

- **Open the "Particles" and "Injection Temperature" drop-downs (the "Average Speed" and "Speed" drop-downs should already be open, but if they are not, then open them as well).**
- **Select the units for the Pressure gauge to be kilopascals (kPa).**
- **Uncheck the "Collisions" box in the "Particles" drop-down.**

A few useful features of the simulator to know about:

- All the particles injected into the chamber come in with the same kinetic energy (which is proportional to their "temperature"). The injection temperature can be selected, or the default injection temperature is the same as the current temperature of the gas in the chamber.
- You can inject 50 particles at a time of a single variety with the button (fully extending the pump does the same, if you are into the animation). Using the button injects one particle at a time. The similar buttons whose arrows point to the left remove particles in the same number. [These removal buttons are of little use, as they choose particles at random to remove, and may select more "hot" particles than "cold" ones, meaning that while we can add particles without changing the gas temperature, we cannot remove them without changing the gas temperature.]
- You can remove all of the particles from the chamber at once with the button.

The first thing we will look at is the effect of allowing particle collisions. **Inject a few hundred of the "light" particles into the chamber by clicking the 50-particle button several times.** With the collisions box unchecked, you'll note that the particles follow very predictable, "non-random" paths. They are not interacting with each other, which is a critical element of being an ideal gas, but they fail to exhibit the "randomly-distributed motion" element also required of an ideal gas.

Before we introduce some randomness, make a note of the number in the "Average Speed" dropdown for future reference. Also, have a look at the histogram in the "Speed" dropdown, which indicates that every particle has the same speed (which is apparently equal to the average speed). If every particle has the same speed, then it's easy to show that the rms speed equals this same speed. **Empty the chamber and repeat this process for the "heavy" particles, then solve the puzzle that follows.**

1. Assume that the particles are occupying a three-dimensional volume (not withstanding the two-dimensional screen where they are displayed). The "light" and "heavy" particles are modeled after specific gases. Of the five gases listed below, one is represented by the light particles, and one by the heavy particles. Your task is to determine which is which. You are of course free to look up properties of these atoms and molecules to help you make this determination.

$$H_2\;,\quad He\;,\quad N_2\;,\quad O_2\;,\quad Ne$$

Okay, so let's use the simulator's means for randomizing the velocities. **Check the "Collisions" box in the "Particles" dropdown and observe the behavior of the particles.** Also note that the histogram of particle speeds has diversified from the single spike to a wide spectrum of speeds, and that this histogram fluctuates with time.

2. Discuss what happens when the change to "collisions" mode is made.
   - How does this change affect the distribution of the speeds of the particles?
   - How does this change affect the average and rms speeds of the particles?
   - Does turning off collisions return the gas to its previous state?
   - Which of the three states (before turning on collisions / having collisions turned on / after turning collisions off) most closely represents what we have been using as a model for an ideal gas? Explain.
3. (**simulator flaw**) After watching the action for a short time, it's clear that the particles in "collisions" mode never go past each other without deflecting, which means that these particles are in fact confined to *two* dimensions, not three. If we follow this strictly, we find that the particles don't represent any of the gases in part (1). Why is this? [*You may want to look back at the text reference where kinetic theory is discussed to help you answer this.*]

From the Background Material, we know that collisions between particles in the gas leads to a state equation that differs from the ideal gas law. We should be able to measure this change with the simulator. To do this, configure the simulator as follows:

- **Empty the chamber.**
- **Select the "Set to:" radio button in the "Injection Temperature" dropdown.**
- **Set the injection temperature to 100K.**
- **Make sure that the "Collisions" box is checked.**
- **Inject 1000 heavy particles (this is the maximum number) into the chamber.**
- **Wait until the particles fill the chamber and the gas appears to be in equilibrium.**

4. (**simulator flaw**) Now to test the simulator.
   - If we turn off collisions, what variable in the "modified van der Waals equation" given in the Background Material, changes? What does it change to? [*Hint: What happens to the space available to a given particle when the collisions are turned off?*]
   - When we turn off collisions, the volume and particle number are not affected, so the relationship between the pressure and temperature must change if the equation of state changes. Do we observe this?
   - Is it possible that the constant β in the modified van der Waals equation is just negligibly small for this simulation, accounting for what we see? Explain.

Part 2 - Ideal Gases

Okay, so the simulator has a few flaws with regard to how the displayed particle motions fit with the measured thermodynamic quantities. Let's move past this and assume from now on that the simulator does represent a 3-dimensional ideal gas (i.e. ignore that collisions are occurring). **Change the pane of simulator to "Ideal."** Configure it as follows:

- **Select the units for the Pressure gauge to be kilopascals (kPa).**
- **Check the "Width" box.**
- **Leave the "Nothing" radio button selected in the "Hold Constant" list.**
- **Open the "Particles" dropdown.**

[*Note: Unlike the previous simulator, this one allows for an adjustment of the volume by dragging the handle on the left wall of the container, and you can heat or cool the gas to a new temperature using the bucket below the container.*]

The volume of this container can only vary along one dimension (left-to-right on the screen), and we can only measure length along this direction, so we will assume that whatever the dimensions of container are, they remain constant. Calling the measurable width x and the cross-sectional area resulting from the other two dimensions A. Then the ideal gas law is:

$$PV = P \cdot (Ax) = Nk_BT \tag{7.2.1}$$

We are going to confirm and then use this equation, but to do this, we need to take measurements of the pressure, and the value jumps around in the gauge. So we will do this by randomly sampling:

- **To take a pressure measurement, freeze the simulation and read off the number.**
- **Repeat this several times, giving you several measurements (at least 4, but more is better).**

1. Compute the average value and the statistical uncertainty (standard deviation). For a refresher on how to compute standard deviation, review this from your very first 9A lab.
2. Using different values for P, N, T, and x for two different states, determine whether the simulator confirms the ideal gas law within the uncertainty. For a refresher on how to compare two uncertain numbers, review this from 9A Lab #4. [*Note: The only variable that comes with uncertainty here is the pressure, so its percentage uncertainty equals the percentage uncertainty for any product or quotient of these values.*]
3. Using one of your two sets of data from above, compute the value of A, the cross-sectional area of the chamber (don't worry about the uncertainty).

Lab Report

While this is not a traditional lab, you still need to put together a lab report with your group. In it, you need to document your work address the questions indicated. As always, every member of the group must upload a separate digital copy of the report to their lab assignment in Canvas *prior to leaving the lab classroom*. These reports are not to be written outside the lab setting.

CHAPTER OVERVIEW

Lab 8: Gas Processes

8.1: Background Material

Text References

- isochoric process
- gamma gas constant
- adiabatic process

A Cyclic Process

In this lab we will be using a cyclic process and a measurement of only pressure to compute the constant γ for the confined gas (which is just air). The process goes like this:

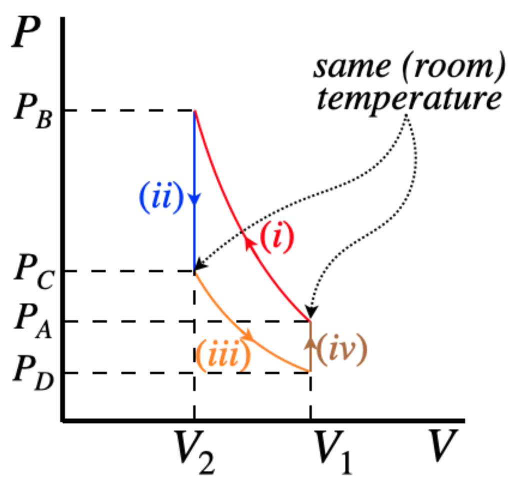
i. Air that is confined to a plastic soda bottle at room temperature is very suddenly compressed to a smaller volume with a boom arm.
ii. The air, which is now hotter from the sudden compression, is held at the same volume (the boom arm is held in place) while it slowly returns to room temperature.
iii. The boom arm is now removed, very suddenly returning the air to its original volume.
iv. The air, cooler from the sudden expansion, is kept at the same volume while it slowly returns to room temperature.

Throughout this cyclic process, we monitor the pressure. It should be clear that the pressure changes 4 times during this process – it increases when the air is compressed (i), decreases as it cools at constant volume (ii), decreases as it expands (iii), and increases as it warms (iv). Considering how many times the gas changes temperature and volume, one might think that one or both of these quantities are needed to compute the value of γ, but surprisingly this is not the case.

The secret to deriving γ purely from the pressure measurements lies in the *types of processes* involved in the cycle. From the text reference regarding adiabatic processes, we saw in Example 2 that sudden compressions (and expansions) can be modeled with adiabatic processes. This accounts for two of the processes, and the other two occur at constant volume. Equations of state that apply to these processes link their endpoints to each other, and we also know something about the endpoints. In particular, the temperature before process (i) is the same as after process (ii) and after process (iv) (indeed the entire thermodynamic state is the same before (i) as after (iv), as the cycle is complete).

A major part of this lab is figuring out the "physics problem" that outlines the process for computing γ, so we won't do that here, but it is helpful to look at the cycle in a PV diagram, labeling every part of it that we can:

Figure 7.1.1 – PV Diagram of Cycle



The only quantities that matter are at the endpoints of these processes. Our measurements will give the four pressure values. The volumes and temperatures are unknown, but the endpoints are related to each other. Two of the endpoints have the same temperature, the endpoints of process (ii) have the same volume (as do the endpoints of process (iv)), and the endpoints of process (i) are related by the adiabatic equation of state, as are the endpoints of process (iii)). Along with this, the air also satisfies the ideal gas law. Combining all of these together will lead to a solution for γ in terms of three of the four measured pressures. You will need to work this out before inserting the data to get an answer. [*Hint: You will find that this goes much easier if you express everything in terms of* P *and* T*, rather than* P *and* V.]

8.2: Activities

Equipment

- two-liter bottle with sealed-tube connector
- compression arm apparatus
- Pasco box, pressure sensor, and software
- air pump

The General Idea

The constant γ for a gas tells us a lot about that gas. Most notably, it (indirectly) tells us the number of modes available for the equipartition of energy in that gas, which also tells us the heat capacity of that gas under various processes. In this lab, we will use what we know about the composition of air to form an hypothesis of the value of γ for air, then test it with a simple experiment where we force a trapped quantity of air to undergo some well-known processes and measure the values of the pressure at endpoints of these processes. This is a lab where taking the data is the easy part – doing the analysis and accounting for possible sources of error are where the main challenges lie.

Some Things to Think About

This lab is unusual in that the experiment itself is very short. It mostly boils down to "solving the physics problem", which is never an easy task, so you should not expect to cruise through this quickly. Engage your group to figure out the important relevant ideas, and then put them together. Extracting what you are looking for from what is seemingly too little information is always very challenging but is also very satisfying when it is finally accomplished.

Our experimental apparatus is simple in the extreme. We have the ability to compress the gas with the compression arm (though not in a particularly controlled manner), and we can measure the resulting pressure of the gas in real time. What we *cannot* do with this setup is measure either the volume or temperature of the gas. So we need to make the most of what we do have control over. We are looking for γ, and the first thing that comes to mind is the role that this constant plays in the mathematics of the adiabatic process, so it stands to reason that having the trapped air follow an adiabatic process will be useful for our experiment.

- The Pasco application you will be using is called "Gas_Processes."
- You will find that the experiment works a little better if the air in the bottle starts at a pressure a bit higher than atmospheric. Before performing your experiment, run the software to measure the pressure, and if it is below $140kPa$, use the pump to bring it up to around $145kPa$. If you run the software for awhile, you may detect a slow leak. As long as it is very slow, it shouldn't be a problem. If it is losing pressure too fast (say faster than $1kPa$ per 20 seconds), talk to your TA to get help fixing the leak.
- An adiabatic process is one in which no heat it exchanged. How can you change the state of the trapped gas with only the compression arm available, such that no heat is exchanged during that process? Note that you are not able to insulate the bottle of air.
- Assuming you know how to achieve an adiabatic process, what mathematical relationship exists between the pressure and temperature just before the process, to the pressure and temperature after the process? [*If all you know is the relationship between the pressure and volume, then perhaps the ideal gas law can be of assistance.*]
- You will need to do multiple processes to get your final value of γ. Besides the adiabatic process, what other special process(es) (isochoric, isobaric, isothermal) are you able to achieve with this rudimentary setup?
- Using whatever processes you have available, you can measure the beginning and ending pressures of these processes (actually, the pressure sensor will measure several pressures along the way, but these intermediate values are not useful). Using these values, as well as what you know about the processes and the ideal gas law, you should be able to do the math to extract the constant γ.
- Once you have a value for γ, compare it with your hypothesized value, noting in particular whether the experimental value is higher or lower. Discuss in your lab report why this might be the case, based on the following two considerations:
  - The criteria you used to estimate the value of γ for air – what omission(s) might throw-off your result, and in which direction will it be thrown-off?
  - Limitations of the measuring device (other than poor calibration) that might lead to systematic error in one direction. In particular, think about the effect of the *sampling frequency* of the pressure sensor.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

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CHAPTER OVERVIEW

Lab 9: A Heat Engine

9.1: Background Material

Text References

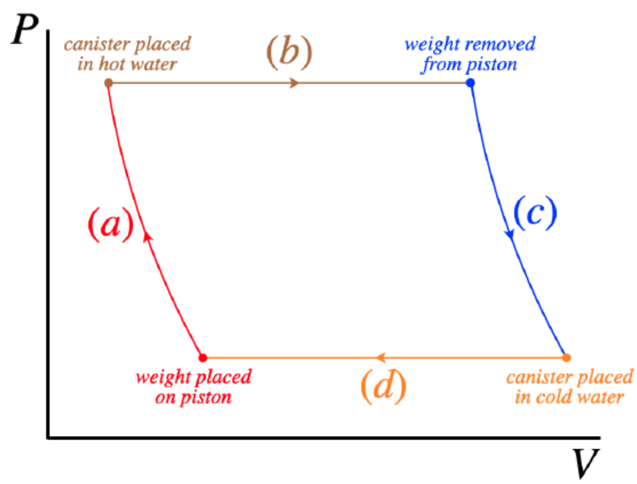
- engines & thermal efficiency

Our Heat Engine

In this lab, we will be using a simple heat engine which consists of an airtight piston and two thermal reservoirs. The cold reservoir is an ice water bath at $273K$, and the other is boiling water at $\approx 373K$. We will extract work from this engine by placing a weight on the piston when the trapped air is cold, then heat the gas so that it expands and the piston raises the weight. After it is raised, the weight is removed, and the engine is returned to its initial state to complete the cycle.

We don't want to over-complicate the cycle we are looking at, so we would like it to consist of just four processes. The weight is placed atop and later removed from the piston very suddenly, so these two processes occur with very little time for any heat to be exchanged. The expansion and compression of the piston occur while the same weight is pressing down, so during these processes, the gas is held at a fixed pressure. Given the properties of these processes, we would expect a PV diagram to look roughly like this:

Figure 9.1.1 – Our Engine Cycle



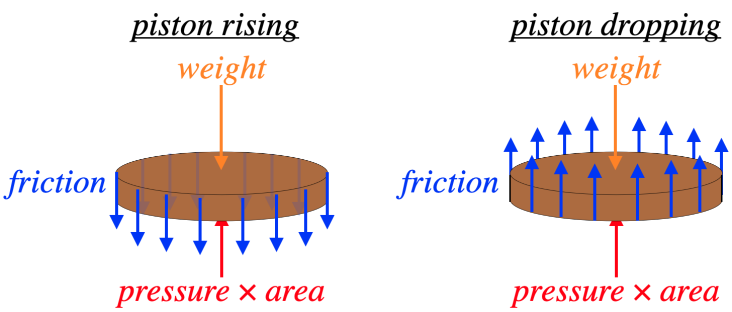
While the four actions we have to take are clear (moving the weight and changing the reservoir), actually achieving this process requires some careful timing. Consider, for example, what happens after placing the weight on the piston. Process (a) in the diagram occurs very quickly, and then it is time to start process (b). This means that the reservoir needs to be swapped essentially *during* the very brief time that the weight is placed. What is wrong with placing the weight first and delaying the swap of reservoir? Well, the sudden compression of the air by the placement of the weight increases its temperature, and if the canister is left in the cold water, the air will begin to give back heat to the water. This results in a constant-pressure *compression* at the end of process (a), before starting process (b) (which is a constant pressure expansion). This shows up as an ugly "notch" in our PV diagram in the upper-left corner. Similarly, to prevent unwanted intermediate energy exchanges between processes (c) and (d), it will be important to swap the thermal reservoir while removing the weight from the piston.

Dealing with Friction

In order to ensure that no gas escapes the engine, the piston needs to rub against the inner surface of the cylinder. This is obviously going to introduce friction into our process. The potential energy of the weight is changed by the total work performed on it, which is the combination of the positive work done by the engine and the negative work done by friction. So in order to confirm that work we compute from the PV diagram equals the work that goes out, we need to find both the change in potential energy of the weight *and* the work done by friction. We will be able to measure the mass of the lifted object and the height it is raised, but we need to be clever to determine the work done by friction.

We begin with a free-body diagram of the piston. The weight on it always acts downward, and the force by the gas is always upward, but the friction force direction depends upon whether the gas is expanding (piston moving up) or compressing (piston moving down).

Figure 9.1.2 – Forces on the Piston

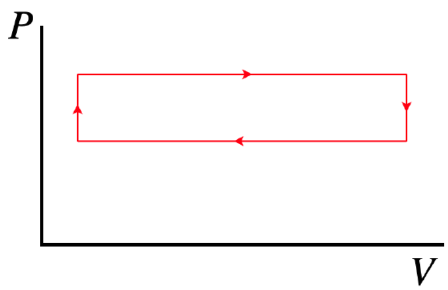


The piston moves at a pretty steady, slow rate, so its acceleration is negligible, which means the net force on the piston is zero. The friction depends upon the contact force and the coefficient of friction between the surfaces, so it is the same whether the piston is rising or falling. The weight also obviously remains the same for both directions of piston movement. So this means that the force by the gas when the piston is rising is greater than the force when it is falling. If we measure the pressure in both cases, we can use the two numbers to compute the friction force:

$$\left.\begin{array}{l}(P_\uparrow A)-f-W=0\\(P_\downarrow A)+f-W=0\end{array}\right\}\quad\Rightarrow\quad f=\frac{P_\uparrow-P_\downarrow}{2}\cdot A \tag{9.1.1}$$

So all we need to do is run our engine in a cycle without ever removing the weight. The output should look something like this:

Figure 9.1.3 – The "Friction Run"



The vertical segments occur because the piston doesn't immediately move when the gas starts warming or cooling. This is because when the piston stops, static friction takes over for the rubbing friction, and the static friction needs to adjust to the changing external force before the piston can start sliding again. In any case, reading off the pressures for the top and bottom segments of this cycle gives us the friction force. With this and the distance that the piston travels, we can compute the work done by this force.

One might ask why we don't just find the area in this cycle to get the work done by friction for the cycle, rather than computing the friction force. The answer is that while we expect the friction force to be the same for every run, we cannot say that the piston will travel the same distance in the "friction run" as in the a-b-c-d cycle of our main experiment. Most notably, the friction run does not include the displacement of the piston that occurs during the quick compression/expansion that occurs when the weight is placed/lifted.

Engine Efficiency

The efficiency of this (and any) engine is the ratio of the net work that comes out and the heat *that comes in from the hot reservoir* (the heat that exits into the cold reservoir is not included). This engine is connected to the hot reservoir during legs (a) though (d). We know what types of processes these are, so with this information and the fact that air is a diatomic molecule, we can determine the heat transferred during each process in terms of changes of pressure and/or volume that we read off the PV diagram.

When you make this calculation in the lab that follows, you may be troubled by how low the efficiency comes out to be. To assuage your fears, you may want to consider that if this was the most efficient engine possible (a Carnot engine, which follows only isothermal and adiabatic curves), for the two temperatures we have available, the efficiency would be:

$$e=1-\frac{T_C}{T_H}=1-\frac{273K}{373K}=27\% \tag{9.1.2}$$

Now when you take into account that we are assuming that the various processes are reversible (which they clearly are not, since the temperature difference between the gas and the reservoir is virtually always finite), we should expect the efficiency to be *significantly* lower than this number.

9.2: Activities

Equipment

- gas piston with plunger, in sealed attachment with metal canister
- Pasco box, pressure sensor, displacement sensor pulley, and software
- bottle "claw" clamp for holding canister in hot water
- pot of boiling water
- mug of ice water
- $200g$ weight

The General Idea

The concept of a *heat engine* is the focus of this lab. All of the critical features for a heat engine are present:

- There is a confined "working gas."
- The engine completes a full cycle – the working gas returns to its original thermodynamic state at the end of the cycle – which means that all the energy that comes into the engine (in any form) exits the engine by the end of the cycle (also in any form).
- Two thermal reservoirs are available to the engine for accepting or dumping heat energy.
- In the final accounting, there is a net amount of heat that enters the engine which equals the net amount of work that exits the engine, some of it going into gravitational potential energy of a weight, and the rest into work done by friction.

In this lab, we will "peek-in" on what is going on thermodynamically within the gas during the cycle, by keeping tabs on its pressure and volume. This will allow us to plot a cyclic P vs. V diagram, which contains all the information we need to compute the work done by the gas (a quantity we can verify by other means, since the work consists of lifting a weight), and the efficiency of the engine.

Some Things to Think About

The details of what is going on in this procedure are pretty well spelled-out in the Background Material, but there are a few things that bear emphasizing...

- ***Safety first! When immersing the cannister into the thermal reservoirs, you want to submerge them the best you can, but not at the expense of burning your fingers on the hot reservoir. Keep in mind that you don't need to touch the boiling water to burn yourself – steam does this very efficiently. Please use the "claw" to keep your fingers a safe distance from the steam.***
- The Pasco application you will be using is called "Heat_Engine."
- You should double-check the arrangement of the apparatus. The computer measures the displacement of the piston by detecting the rotation of the pulley. It does this by assuming the string doesn't slip over the pulley, and "knowing" its radius. The pulley has three radii available, and the one that the computer assumes is the *one in the middle*. Also, the computer will treat expansions of the piston as positive displacements only if the pulley rotates *clockwise* as the pulley rises. And finally, you want the piston to start somewhere near the center of the cylinder. If it is not located there, ask your TA for assistance.
- Two important bits of information you will need are the cross-sectional area of the piston and the mass of the weight placed on the plunger platform of the piston. These values are $8.3\times10^{-4}m^2$ and $200g$, respectively.
- You should obviously include a screen capture of your graphical data in your lab report.
- Do a "friction calculation run" (discussed in the Background Material) before moving on to the main event. The two processes you need may be a bit choppy, but a reasonable estimate for the two pressures you need should be obtainable.
- The PV diagram of your cyclic process, if done correctly, will look very much like a parallelogram. You can estimate area accordingly – there's no need to count boxes or rely on the touchy "area under curve" tool in the Pasco software.
- The work done by the engine is used to lift the weight from the height that you put it on the plunger to the height you take it off, *not* the distance that the plunger raises the weight during the "hot reservoir" process.
- The amount that the weight is lifted can be measured externally using the marks on the cylinder, and this might make a good double-check, but the computer/pulley provides this information, assuming you extract it correctly from the PV graph output.
- Be sure to discuss places where errors are likely to come in, and possible ways to improve the results.
- When computing the efficiency of the engine, you will not have *direct* measurements of heat exchanged, but you know some important facts that can still get you these values. You know what types of processes are occurring in the four legs (it's okay to ignore the small blips in the upper-left and lower-right corners for this part), and you know that the trapped gas is air, which is

basically diatomic. These facts give you a way to determine heat exchanged from work done, the latter of which you *can* measure.

Lab Report

Craft a lab report for these activities and analysis, making sure to include every contributing group member's name on the front page. You are ***strongly encouraged*** to refer back to the Read Me as you do this, to make sure that you are not leaving out anything important. You should also feel free to get feedback from your lab TA whenever you find that your group is at an impasse.

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