# Physics 25L lab manual

Professor Deborah K Fygenson, UCSB Physics Department

*This is a modified version of the original manual*
*written by Professor David Stuart*

April 5, 2019

# Contents

# 3 Interference and Diffraction

**Abstract**: In this lab, you will observe the effects of diffraction of visible light through a narrow slit and of interference of light passing through multiple slits. You will use the interference patterns to measure the wavelength of the light from a laser.

## 3.1 Pre-lab preparation

Interference is a property of waves. Put simply, waves superimpose - meaning that the amplitude at any position and time is the sum of all waves at that position at that time. If the superimposing waves are **periodic** and **coherent**, they combine in ways that lead to striking phenomena: standing waves on a string (discussed in Phys 23), diffraction of water waves around a corner, and interference of sound waves from a pair of speakers (discussed in Phys 24). In this lab, we will examine diffraction and interference more closely using light waves, and then use these phenomena to measure the wavelength of the light from a laser.

Consider two point sources of light that are completely **coherent** (*i.e.*, they emit light of the same intensity and wavelength, and do so in phase with each other). The light from each point source propagates in all directions, but for simplicity we will consider only a single plane. Suppose these point sources are separated by a distance $d$. We'll use the $(x, y)$ plane and place the light sources at points $(0, 0)$ and $(0, d)$ (see Figure 9). We can then determine the intensity of the light at different points along a screen, placed a distance $L$ away on the $x$-axis, by considering the superposition of the two light waves at an arbitrary point, $(L, y)$, on the screen.

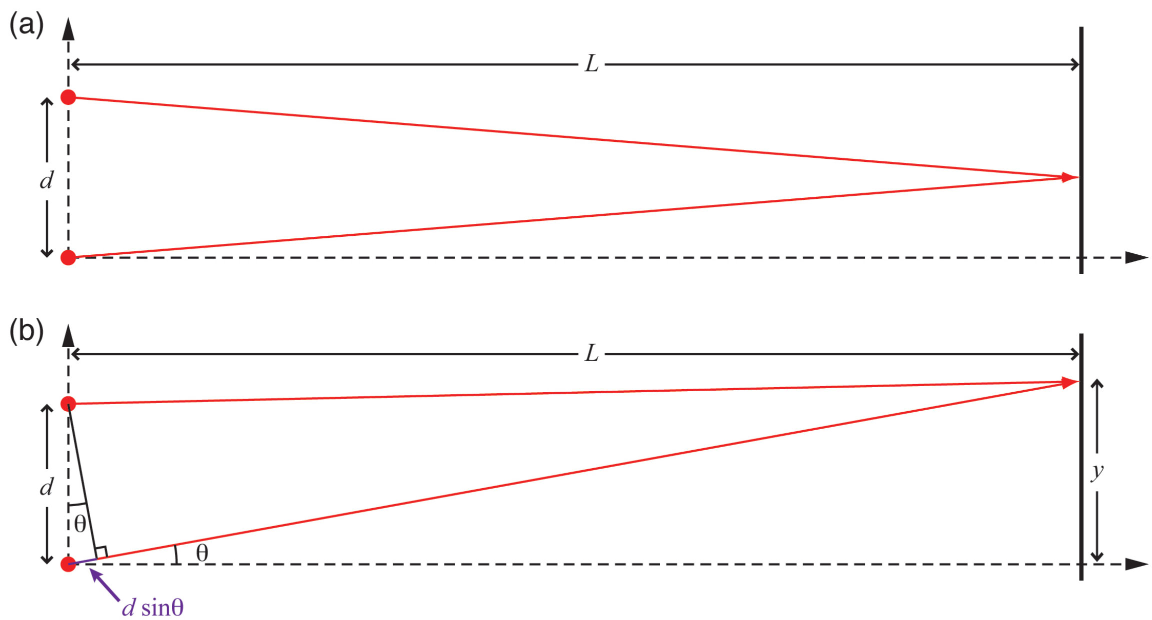


Figure 9: Diagram of two point sources (red dots) used for calculating the interference pattern. The $(x, y)$ coordinate system is shown by the dashed lines. The point sources are separated by a distance $d$, and the interference pattern is calculated considering the light projected onto a screen a distance $L$ away along the $x$ axis. (a) Light rays of equal pathlength reaching a point on the screen; because they traveled the same distance, the light from the two sources are in phase with each other and constructive interference occurs. (b) Light rays reach a point on the screen where their pathlengths differ by an amount $d \sin\theta$, with consequences discussed in the text.

As shown in Figure 9(a), at the point $(L, d/2)$, the path length for each of the two light waves is equal. That leaves the two waves in phase with each other, so they add (*i.e.*, interfere) constructively, and make a bright spot at that point on the screen.

At any other point on the screen, the path lengths of the two light waves differ, as shown in Figure 9(b), where the light that comes from the lower point travels an additional length $d \sin\theta$. This light arrives at the screen with a phase that is shifted by $\Delta\phi = 2\pi d \sin\theta/\lambda$ with respect to the light from the upper point. If the additional path length $d$ is such that $d \sin\theta = \lambda/2$ then the phase shift is $\Delta\phi = \pi$. That makes the wave from the lower point exactly the negative of the wave from the upper point, so they interfere destructively and that point on the screen is dark.

We can calculate the $y$-coordinate, $y = L \tan\theta$, of the point on the screen where this destructive interference occurs. If $\theta$ is small (*i.e.*, if $L \gg d$), then we can approximate $\tan\theta \approx \sin\theta$, so $y_{\text{destr}} \approx L \sin\theta = L\lambda/2d$.

Another special point on the screen, $(L, y_{constr})$, is where the path lengths of the two light waves differ by exactly one wavelength, *i.e.*, $d \sin\theta = \lambda$. At this point, the phase of the light that travels the longer path is shifted with respect to that of the light that travels the shorter path by $\Delta\phi = 2\pi d \sin\theta/\lambda = 2\pi$, which has the same effect as no phase shift at all, so the two waves interfere constructively. Mathematically, if $y_{\text{constr}} = L \sin\theta = L\lambda/d$, the point on the screen at $(L, y_{\text{constr}})$ will be bright.

The pattern repeats for larger values of $y$: destructive interference occurs at any point for which $\Delta\phi$ is an odd multiple of $\pi$ and constructive interference occurs at any point where the phase difference is an even multiple of $\pi$. The generalized relations for $y_{\text{constr}}$ and $y_{\text{destr}}$ are key to what you'll do in this lab, so I'll write them here in an easily findable and concise mathematical format These relations are key to what you'll do in the lab, so I'll rewrite them in an easily findable format:

$$y_{\text{destr}} = nL\lambda/2d, \quad \text{where } n = \pm1, \pm3, \pm5, \ldots \tag{10}$$
$$y_{\text{constr}} = nL\lambda/d, \quad \text{where } n = 0, \pm1, \pm2, \pm3, \ldots \tag{11}$$

(The drawing in Fig. 9 includes a coordinate system offset of $d/2$, but this is negligible since we are working in the limit where $L \gg d$.)

I suggest you start taking notes in your eLogbook for Week 2 by writing these equations and drawing a diagram that clearly defines the variables by yourself. Generate the equations in your eLogbook using the Google plug-in Auto-LaTeX Equations so that they are neat and easy to read. Generate the diagram by hand and take a picture, or use a vector graphics app like Adobe Illustrator (*powerful, but expensive*), Affinity Designer (*equally powerful, and not expensive, but not free*), Inkscape (*free, but clunky*), or Vectr (*free and clunky, but works in your browser*). Insert the result into your eLogbook. The act of generating the equations and diagram yourself is a good exercise in using LaTeX and vector graphics. Even if you are already facile with these tools, it can help you think through and really understand the math/physics. If you don't need the practice with the tools, and you already understand the physics, go ahead and just copy and paste screenshots. Just having the equations and diagram in your notes will make them more useful in future reference. You want to learn to keep an eLogbook that is a standalone description of what you are planning, doing, observing and thinking. No one should have to have access to the Physics 25L lab manual to understand what you are doing and why.

In fact, it is a good idea to start writing in your eLogbook before you even go to lab. Write whatever helps you: notes on reading through the manual, questions that occur, ideas for how you might go beyond. Put enough in your notes (*e.g.*, keywords, sketches, highlights, emojis) so that you can find what you need by scrolling through or searching.

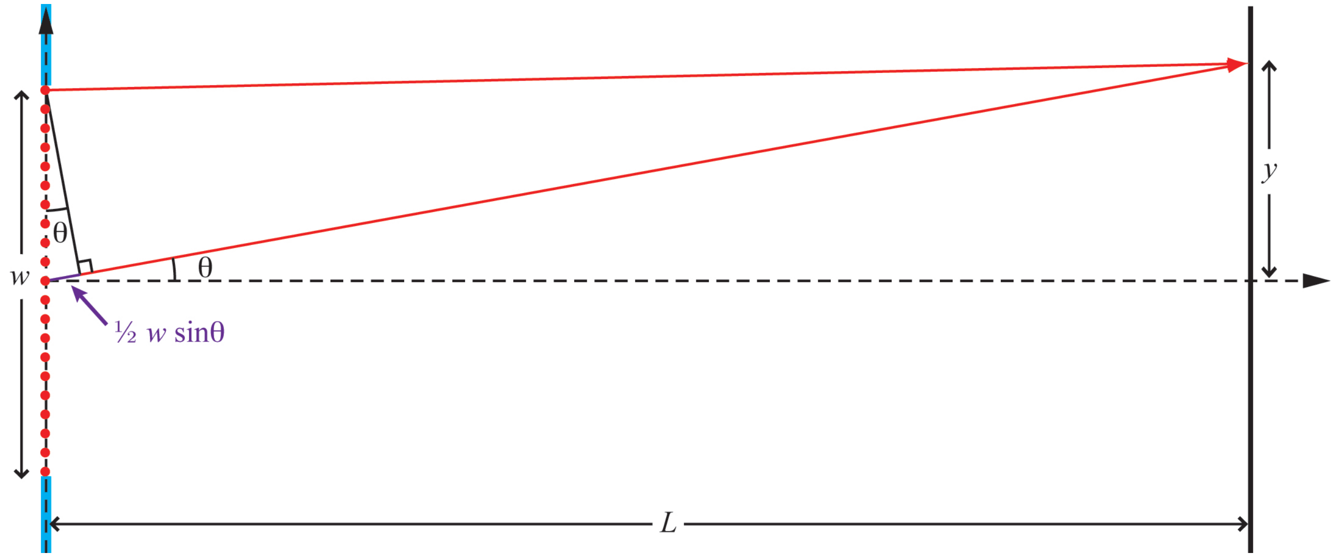


Figure 10: Diagram of multiple point sources (red dots) used for calculating the diffraction pattern of a thin slit. The blue lines are a material blocking all light except for the thin slit of width $w$, which is situated symmetrically across the $y$-axis. Interference of light from two points separated by $w/2$, one above and one below the $y$-axis, have pathlength difference of $\frac{w}{2}\sin\theta$ when reaching the screen placed at $x = L$, with consequences discussed in the text.

An experimentally direct way to create two coherent light sources is to shine a single laser on something opaque that has two very small holes poked in it. If the holes are small enough, they will each behave as a point source from which spherical light waves emanate. Because the incident laser light is coherent, the holes will be coherent light sources.

This is basically the approach that we'll use in this lab, but we'll use *slits* rather than holes. We are only looking in two dimensions, $(x, y)$. A slit in the $z$-direction is the same as a hole for that purpose, with the added benefit that we can illuminate a slit without having to aim the laser as carefully!

A possible problem with this approach is that our slits are not necessarily narrow enough to be truly "point" sources in the plane. So, let's consider the effect of passing light through a finite slit width. We'll do that by considering a single slit of width $w$ as shown in Fig. 10. We'll again consider only the $xy$-plane, and following Huygen's principle, we can consider the wavefront at the slit as a series of coherent point sources, illustrated by the red dots in the figure.

It is easy to see that there is constructive interference at the point $(L, 0)$ because for every point source in the slit, at a position of say $(0, y_1)$, there is another point source at $(0, -y_1)$, symmetrically across the $y$-axis, which therefore has the same pathlength to the point $(L, 0)$. As a result, there is constructive interference, and hence a bright spot, at $(L, 0)$.

Using a similar argument, we can see that destructive interference will occur at some point $(L, y_{\rm destr})$. This happens because light from the point at $(0, w/2)$ and light from the point at $(0, 0)$ have a pathlength difference of $(w/2)\sin\theta$. If that pathlength difference equals $\lambda/2$, then the light rays will combine out of phase and destructively interfere.[6] Given that the light from the point $(0, w/2)$ is canceled by the light from $(0, 0)$, it follows that light from the point $(0, w/2 - \Delta)$ is canceled by light from $(0, -\Delta)$. In fact, at $y_{\rm destr} = L\lambda/w$, the light from any point in the upper half of the slit is canceled by a point that lies a

[6] Note that, when solving for $y_{\rm destr} = L\lambda/w$, the two factors of $1/2$ cancel and the "small angle approximation" allows us to set $\tan\theta \approx \sin\theta$.

distance $w/2$ below it, in the lower half of the slit. As a result, all of the light from the slit undergoes destructive interference at the point $(L, y_{\text{destr}})$; the point appears dark. The same argument applies for any point with a $y$-coordinate that is an odd integer multiple of $\lambda/2$, so there are dark spots for

$$y_{\text{destr}} = n\lambda L/w, \quad \text{where } n = \pm 1, \pm 2, \pm 3, ... \tag{12}$$

This is called a *diffraction pattern*; it is a special type of interference pattern that results from light passing through different parts of a finite width slit. The light is said to "diffract" through the slit. (Notice that as the slit width $w$ goes to zero, the point of destructive interference moves out to infinity along the $y$-aixs and we get the spherical wave pattern of a single point. In the opposite extreme, as $w$ goes to infinity, the spacing between dark points goes to zero so no pattern is discernible.)

In this lab, you will look at both the diffraction pattern from a single slit and the interference pattern from two, or more, slits. The pattern from two slits will be a convolution of the interference pattern from the two slits and the diffraction from each slit. A typical two-slit pattern is sketched in Figure 11. The number of interference maxima within each diffraction peak depends on the ratio of the slit width to the slit spacing, so the pattern you observe may be substantially different in this respect.

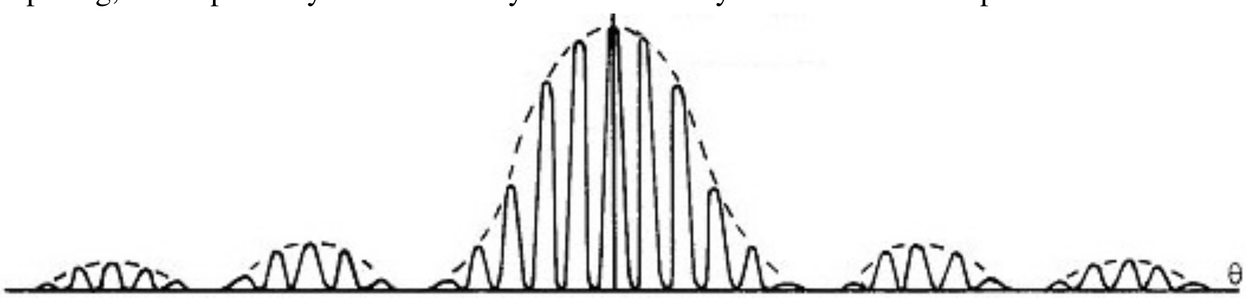


Figure 11: Cartoon of the pattern expected from two thin slits. The diffraction pattern (dashed line), defined by the slit width, is convolved with the interference pattern, defined by the slit spacing, to give the intensity *vs* position shown by the solid line.

### 3.1.1 Experimental planning

In this lab you will *observe* the qualitative features of interference and diffraction patterns and then use them to *measure* the wavelength of the laser. Since the wavelength of visible light is less than a micron, you will need to use some clever experimental "tricks" to extract a precision measurement.

The first trick will be to leverage the fact that an interference pattern scales with the wavelength times $L/d$. You will use small slit spacings, $d$, and a long optical path, $L$, to make the pattern visible. Even so, the pattern will still only be a few centimeters across. How might you precisely measure the positions of the maxima and minima? Think for a minute or two before reading further to see if you can come up with an idea.

The next trick will be to make a precise measurement of the distance between the slits. The apparatus provided will specify the width and spacing for each set of slits. The available slit-widths range between 0.02 mm and 0.16 mm, and the slit-spacings range from 0.25 to 0.5 mm. (You could just use the advertised sizes, but for a serious measurement you don't want to simply trust what the sales department says! You should measure it yourself!) How might you measure these small distances with precision of 10% or better? Again, think a bit and come up with your own ideas for this before reading further. Go ahead and write your thoughts in your eLogbook, while you're at it!

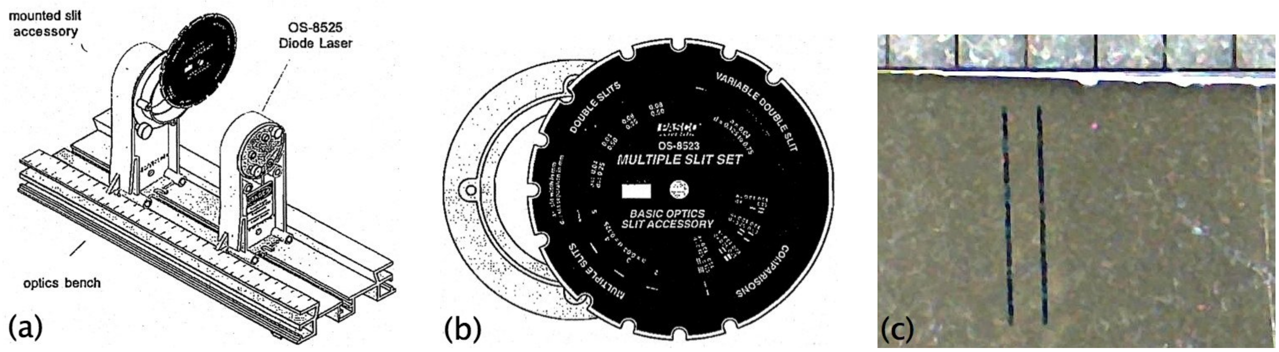


Figure 12: (a) The PASCO OS-8515 Basic Optics System with a OS-8525 Laser Diode assembly and OS-8523 slit accessory mounted. (b) A close-up of the Multiple Slit Accessory. There is a similar Single Slit Accessory; each accessory allows you to change which slit (or set of slits) is in the laser beam by rotating part of the device. (c) A close-up of one pair of slits, taken through a microscope; a ruler with 1 mm divisions is placed at the top of the field of view to calibrate the scale.

### 3.1.2 Apparatus

The apparatus you will use is an **optics bench** with a movable laser mount, a movable slit mount and a movable screen mount, as shown in Fig. 12(a). The "bench" provides a robust way to set and measure the positions of each of the movable mounts.

**Measuring positions of maxima and minima:** One way to measure the positions of maxima and minima in the interference pattern is to take a photo of the pattern with a ruler placed in the field of view. You can then use image analysis software to measure the spacing of the maxima and minima in units of pixels within the image and scale that by the number of pixels per mm using the ruler. Ruled graph paper works just as well as a ruler, and can be easier to attach to the screen, but make sure the light pattern itself falls on a blank (*i.e.*, unruled) background so that the rulings don't impose intensity variations on top of the pattern you are trying to measure. (Attach a piece of graph paper or a ruler to the screen with clips; don't write directly on the screen.)

Your cell phone is a convenient tool for taking the photos. You can use your own laptop or the computers in the lab to view, process and analyze your image data. The computers in the lab have a powerful image analysis software installed called Fiji. This free software is developed and maintained by the National Institutes of Health and works on Macs as well as PCs. If you are already familiar with a different image processing software, feel free to use that instead.

**Measuring the slit width and spacing:** You can also make a precise measurement of the slit width and spacing with a camera and image processing, *if you have enough zoom* in your camera. But, even then you'd have a hard time holding the camera still enough to get a well focussed image. So, we have a couple USB microscopes that will serve the same purpose. They're basically a webcam with microscope optics attached. They have enough magnification to resolve the slits with a reasonably large number of pixels. So, you can get an image with a length scale (ruler) within the image, and process the image as discussed above. Note that the magnification and resolution is probably insufficient to measure the slit width. However, the spacing can be measured reasonably well, and that is the important independent variable for an interference pattern.

### 3.1.3 Safety

The lasers you will use in this lab are not high power, but they can still impair or permanently destroy your vision if the beam strikes your eye directly. A few safety precautions are appropriate:

- Do not look directly into the laser beam.
- Use caution when adjusting the optics to avoid accidentally reflecting the laser toward your, or anyone else's, eyes.

## 3.2 Getting started and gaining familiarity

The first thing you should do in lab is play around with the optics bench to understand how it works. Slide the mounts around, and set up your screen. If you like, take a photo of the setup with your cell phone for your logbook. You don't need to immediately insert the photo into your eLogbook, but it is a good habit to note the time you took it. Alternatively, you could draw a schematic your setup. Honestly, a schematic is often a lot more useful. Photos capture tons of information that can obscure, or just distract from, the essential. A schematic captures only what you want it to and is easily labeled. Either way, you should note the make and model of the various components in your setup as best you can.

## 3.3 Qualitative observations of interference and diffraction

Use the Single Slit Accessory, view the diffraction pattern using *at least* three different slit widths. Take photos of the patterns for your logbook. Write your name, the slit width and any other variables that you suspect effect the pattern on a post-it note and include that writing in the photograph's field of view. In general, it is a good habit to include such "metadata" directly in your experimental data whenever possible because doing so can resolve ambiguities that might arise later on down the line.

Write a brief qualitative summary of your observations. For example, you might conclude that the separation of the maxima and minima increases as the slit width decreases. Of course, that is what you expect from equation (12), but the point of doing an experiment is to record what you observe in a clear and concise way. Imagine that the theory of the diffraction pattern where not yet understood, and write your conclusions with the intention of defining the experimental facts that a developing theory must explain.

## 3.4 Measurement of the wavelength of a laser

The observations you just completed were a qualitative way to get familiar with the phenomenon of interference. Now, it's time to make a measurement. Your goal is to measure the laser's wavelength as precisely as possible. You will do this using the the Multiple Slit Accessory and the relations in equations (10) and (11), where you can measure $L$, $y$, and $d$ and extract $\lambda$.

Start by thinking about the uncertainties. In your logbook, calculate how the uncertainty on $\lambda$ depends on the uncertainties in the things you will measure. Then make some estimates. What do you think the uncertainties will be in each of the three parameters, i.e., $\delta L$, $\delta y$, and $\delta d$? Which of the three do you expect to dominate the total uncertainty in $\lambda$?

Recall from section 3.1.1 that you should measure $d$, not just take the advertised values for granted. We have a couple USB microscopes available as well as some zoom lenses that you can fit over your cell phone's camera. You'll want to take several different photos and obtain multiple measurements. Averaging these measurements gives you a more precise result, and looking at the root-mean-squared deviation (RMS) of the measurements helps you determine a valid uncertainty. You can make the slit measurement at the beginning or end of the interference pattern measurements, however you prefer.

Next, you should think about possible systematic errors. While the fractional uncertainty in $L$ is probably going to be smaller than the other uncertainties, it is something that could easily have a systematic bias. For example, while the optics bench provides a nice way to measure the position of the little tab that sticks off the side of the mounts, that isn't necessarily the position of the slit or the screen. The difference between those two positions will be a systematic bias on $L$.

There is, however, a trick to avoid that systematic uncertainty in $L$: measure $y$ as a function of $L$ and fit the results to a straight line. The slope of that line gives $\lambda$ (after correcting for $d$). The systematic uncertainty from the difference between the mount's position and the actual slit position changes the intercept of the line, but not its slope. Measuring the dependence of two observables and extracting a desired quantity from a fit is a common trick because of its ability to do away with certain systematic errors, and because it is a very good way to validate the data. For example, the goodness of the fit (the $\chi^2$ per degrees of freedom) shows whether the measurements are behaving properly within the determined uncertainties. If the $\chi^2$ is too small, the uncertainties may be overestimated. If the $\chi^2$ is too big, either the uncertainties are underestimated or there is something else going on beyond what is assumed in the model (*i.e.*, the equation to which the data is being fit).

You should make measurements for several different values of $L$ and use a fit to extract $\lambda$. As discussed in section 3.1.2, you can obtain a more precise measurement of the positions of the maxima and minima by photographing the pattern and using image analysis software to determine the positions in pixels, and calibrating pixels to distance. Think a bit about how you will do this. Write your thoughts in your notes.

It is, in general, a good idea to plan your experimental protocol before you begin. Here are some tips that might help you plan:

- Make a table in your logbook where you record information about each measurement. It should include a unique identifier for each measurement (*e.g.*, a number, letter, or combination thereof).
- Write that identifier on a piece of paper that you can attach to the screen so it is visible in the photos as metadata.
- Note the filename (or equally identifying information) for each photo in your logbook. (You need not print out and tape in these photos, but you should save the files somewhere you will be able to find at some far future time when you might need to revisit this.)
- Take more than one photo for each value of $L$. This will allow you to select the best one, *e.g.*, if some have focus, lighting or perspective problems. It will also allow you to compare the measured $y$ values between two or more good photos to assess whether the uncertainties are as you estimate.
- It is more precise to measure the difference between the +1 and -1 maxima and then divide by two than it is to just measure the difference between +1 and 0. Similarly, you might find it more precise to determine the position of the minima than the maxima.
- Leave enough space in your table to add comments or other information later.

- Using a larger number of slits gives narrower, more sharply defined maxima.

Once you have thought through your plan, summarize what you have decided to do and why in your logbook. Now you are ready to start taking data. (Of course, your actual procedure may differ from your plan as have ideas, make mistakes, gather new information. If it does, just note how and why - you don't have to re-write the whole plan unless you want to (*e.g.*, to make it easier to reconstruct later). As President Eisenhower famously said, "Plans are useless, but planning is essential!"

Ideally you would analyze each photo as you take it, but given your limited time with the equipment, doing so would not allow you to make enough measurements to get good precision. Still, you should promptly analyze at least the first photo, *i.e.*, copy it into your image processing software and extract a distance to make sure the photo has all the qualities that will make it easy to analyze. This is a good habit because it is best to find problems at the beginning rather than after you've spent 30 minutes collecting data.

### 3.4.1 Image analysis

You are free to choose whatever method you prefer to measure the positions in your images. As mentioned above, I recommend the NIH ImageJ-based package called Fiji because it is platform independent, has an intuitive user interface, a complete suite of tools, and good documentation. I encourage you to download it onto your own computer so you can play around with it any time. It is also available on the computers in the Physics 25L lab room.

Within Fiji you can draw a line anywhere on your image, in any direction, and of any thickness (double-click on the line-selection tool in the toolbar to set the thickness, *a.k.a.* line width) Once you've drawn a line, you can use `Analyze` ⟩ `Plot Profile` to create a plot of intensity values (averaged across the width of the line) versus position along the length of the line. Pushing the List button gives a list of the intensity values used to create the plot. These values can be copied and pasted into your favorite graphing program for further plotting and fitting. Read more about this and other commands available in the `Analyze` menu in the on-line documentation.

Feel free to brainstorm with your classmates about how to best get at the information you want. If you get a particularly good idea from a classmate, feel free to use it for your measurement, but you should cite them in your logbook as the source of the idea.

### 3.4.2 Putting it all in your logbook

Whatever analysis method you use, the goal is to obtain a set of measured $y_{\mathrm{destr}}$ or $y_{\mathrm{constr}}$ values. These should go into a table in your logbook. And you should make plots of them (e.g., $y_{\mathrm{destr}}$ vs $L$ with a linear fit). **Paste the plots into your logbook.**

Finally, make sure that your logbook has a clear and concise conclusion. It should state the qualitative features you observed and the wavelength value that you measured *complete with uncertainty* in your measurement.

## 3.5 Going beyond

There are several opportunities for you to go beyond the minimal requirements, and I encourage you to do so. This class will prepare you for an experimental research position or internship and ultimately for experimental research in graduate school. I'm often asked by students of lab courses to write letters of recommendation for their graduate school applications. Saying that they did everything required of them is underwhelming, but it is great when I can point out where they have pursued additional ideas and/or tried their own methods. Make doing so your habit.

Here are a few additional things you could measure or explore if time allows.

- Measure the positions of the minima in the photos of your single slit diffraction patterns and plot them vs the slit width. Does it fit to $1/w$?
- Measure the spacing between the first, the second, and (maybe) the third minima in either the diffraction or the interference patterns. Are they equal?
- Observe the patterns from other features on the Single Slit Accessory, *e.g.*, there is an opaque line that can be compared to a transparent slit.
- A CD or DVD consists of circular tracks with a small spacing. Light passing through (or reflecting from) those tracks will generate an interference pattern. Now that you know the wavelength of your laser, determine the track spacing for a CD or DVD.
- Measure the thickness of your hair.