ACKNOWLEDGMENTS

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Revised in spring-summer 2013 by Dr. Michael Ziegler based on input from Harold Whitt and Dr. Jesse Martin.

Revised in spring-summer 2014 by Dr. Michael Ziegler based on lab instructor input.
Physics 1211 Laboratory Manual

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Name ________________________________
Partner(s): ________________________________

Experiment 9 – Geometric Optics and Lenses

Objectives
The objectives of this lab are to:

- Perform a couple of fundamental experiments and test the theory of light called “geometric optics.”
- Observe how “images” describe the way lenses affect light and relate those observations to the way lenses are used in everyday life.
- Use the “lens equation” and the “magnification equation” to quantitatively describe images and provide concrete examples of the types of problems considered in lecture, recitation, and homework.

Note
Two important notes:

- You will be using a laser in this experiment that has the same power as widely available laser pointers. So long as you don’t do anything foolish, these are perfectly safe. However if you point this directly into your eye, it can permanently damage your retina. Do not do this.
- The laboratory measurements are designed around someone with normal or near normal vision. If you wear corrective lenses, you need to leave them on when you make measurements.

Preparation
You will be pressed for time during the lab. Since successful completion of all lab activities counts towards your final lab grade it will be important to be well prepared by doing Pre-Lab assignments and reading the entire lab before attending the lab.

Pre-Lab
Read the Pre-Lab introduction and answer the accompanying questions and problems before this Lab.

Points earned today

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PreLab 9 --- Page 1 of 3
Pre-Lab for LAB 9

1. Isaac Newton’s theory of light, geometric optics, is a wave theory of light or a particle theory of light? (circle correct answer).

2. In geometric optics, what is the straight-line path of a light particle called?

3. Another name for the “geometric optics” theory of light is ______________________.

4. Lenses make images. What is an “image?”

5. What is the difference between a real image and a virtual image?

6. Write the lens equation and the magnification equation.

7. Define “Near Point” and “Far Point” and describe the viewing range of a “Normal Eye.”
Pre-Lab for LAB 9

8. Sketch two rays that can be used to locate the position, size and orientation of the image below. Calculate these values and compare with your sketches.

9. Below, the object has been moved closer to the lens. Sketch rays indicating the position, size, and orientation of the image. Compare with calculations for this case.
Laboratory

Outline of today’s activities

Geometric optics

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Finding images created by lenses: qualitative

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Quantitative study of images created by a converging lens

<table>
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<th>Brief review of key concepts and relevant PreLab questions</th>
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<td>Problem Solving</td>
<td>Demonstration problems using the lens equation</td>
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<td>Lab Activity</td>
<td>Measure images for converging lens</td>
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</table>
Activity 1 - Geometric optics: Single and Double slit measurements

Two important conceptual (and real) problems that we will return to several times in this course are the “single slit” and the “double slit” experiments. For the “geometrical optics,” theory of light, these measurements may seem trivial and indeed you probably could have guessed the results based on the everyday observation that light casts sharp shadows. However, these experiments are useful in delineating the differences between the theories of light we will discuss.

On your optical bench shine a laser through the 1 mm wide “single slit” target and onto a screen located 30 cm downstream. See picture. The laser - target distance isn’t too important --- 10 cm or so should be ok. Turn the laser so its beam is wide, horizontally.

How many spots do you observe on the screen?

What is the approximate width of the spot(s)?

Make a sketch of the pattern you observe on the screen:
Now, put the double slit target in front of the laser and again observe, downstream the pattern of the light on the screen.

How many spots do you see on the screen, this time? □

Make a sketch of the pattern you observe on the screen:

![Sketch of light pattern on screen]

distance on screen (cm)

Explain your observations in terms of the “ray theory” of light and the behavior of “light particles.” You should make a couple of sketches showing how the rays from the laser travel from the targets to the screen.

Have your instructor check your work to here.
Activity 2 - Image formation by lenses

We’ll start our study of lenses with some qualitative observations of the way they work. Briefly stated, the most useful way to describe what a lens does is in terms of images: a lens takes the rays of light coming from an “object” (=physical thing) and bends them in a way such that they appear to be coming from an “image.” It is important to understand that when you look through a lens, you see the image created by the lens NOT the object itself.

1. Identifying converging and diverging lenses: You have two lenses at your set up, one is a converging lens and one is a diverging lens. Shine the laser through each lens and observe the light on a screen. Hold the screen at different distances downstream to distinguish between the converging and diverging lens.

![Diagram of converging and diverging lenses]

Briefly describe what you see for the each lens below. Measure the focal length of the converging lens by positioning the screen to produce a minimum size spot.

<table>
<thead>
<tr>
<th>Diverging lens:</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Converging lens:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f =$</td>
</tr>
</tbody>
</table>

You are done with the laser measurements in this lab and should unplug it now.
2. **Virtual image created by a diverging lens**: Remove the screen, put the diverging lens near the end of your optics bench, and locate an “object” arrow $d_o = 30$ cm in front of it. See the setup picture below. Position your head so that you can *simultaneously* view the image with one eye and the object with the other. This is most easily done if your head is ~30 cm from the lens. Try shifting your conscious attention from one eye to the other and back again; your focus should shift between the image and object as you do this.

![Fig 1](image.png)

*Fig 1.* By positioning your head correctly you should be able to see both the object and the image.

This is a **virtual image** --- the rays coming from the object don’t actually converge and diverge at the point in space of the image. It just appears that way when you look through the lens.

Have one of your lab partners vary $d_o$, i.e. move the object closer and further from the lens, and describe what you see. Note: in your description, be sure to answer the questions: (a) which is closer to the lens, the *image* or the *object*? (b) is the image upright or inverted?

### Qualitative Observations:

**Which is closer to the lens: the image or the object?**

This may not be easy to do. Advice: Focus on the image with both eyes so that you see a single clear image. Then shift your focus to the rim of the lens and back to the image. You should be able to feel your focus moving in and out; this will allow you to place the image in space.

**Is the image upright or inverted?**

**Is there a value of $d_o$ such that a REAL image is produced?**

Now suppose this lens were to act like a prescription lens in a pair of glasses. Slowly move your head until one eye is right up next to the lens (you should close your other eye).

**OBSERVE:** when you look through the lens, both when your eye is far away and when it is close up, you see the *image* created by the lens NOT the *object*, itself
Restating: the rays (coming from an object) that go through the lens are bent so as to appear to be coming from the image. The image is an apparent copy of the object --- usually resized and at a different location. Thus, “Finding the size and position of the image” answers the question “what does the lens do” and is the major activity of this part of the course.

What’s going on with prescription lenses --- regular eyeglasses and contact lenses? On average, human eyes can focus on objects from 25 cm to ∞ away. However, everyone’s eyes are different; a myopic (nearsighted) person can see things close up but not far away, while a hyperopic (farsighted) person can focus on objects far away, but NOT close up.

Prescription lenses bend the rays from an object at a location you can’t focus on, to make an image at a location where you can.

Explain, based on your observations, whether this diverging lens (and diverging lenses in general) is more useful for a myopic or hyperopic eye and exactly how it would help the eye. (Hint: Is the image created by the lens closer or further from the lens/eye than the object, itself?)

The power of the diverging lens is −3D. For the case of the object located at \( d_o = 30 \) cm, calculate the position and magnification of the image. Are these results consistent with your observations in the last section? Discuss briefly.

\[
d_i = \underline{\quad} \quad m = \underline{\quad}
\]

☐ Have your instructor check your work to here.
3. Real and virtual images formed by the converging lens

Replace the diverging lens with the converging lens at the end of your optics bench. Move the object arrow to $d_o = 7$ cm in front of the lens. As you did for the diverging lens, position your head so that you can see the image and object simultaneously. This is most easily done if you head is ~10 cm from the lens.

**Qualitative Observations:**
- Are the image and object on the same or opposite sides of the lens?
- Is the image real or virtual?
- Is the image upright or inverted?

Now put the object at $d_o = 25$ cm in front of the lens. Try to find the image (your eye may have to be ~2 m or more from the lens to see this).

**Qualitative Observations:**
- Are the image and object on the same or opposite sides of the lens?
- Is the image real or virtual?
- Is the image upright or inverted?
Have one of your partners vary $d_o$ (move the object closer and further from the lens) and observe the image for each case. You may want to reposition the lens on the bench for some observations.

| Over what range of distances $d_o$ do you get a **real** image? (i.e. an image on your side of the lens): |
| $d_o$ = _______ < _______ < _______ |

At what distance does the image appear to “blow up” (go out of focus)?

| $d_o$ = _______ |

Over what range of $d_o$ can you see a sharp, virtual image when your eye is right up next to the lens?

| _______ < $d_o$ < _______ |

☐ Have your instructor check your work to here.
4. Quantitative study of real images formed by the converging lens

With the object at \( d_o = 25 \) cm from the converging lens, you should be looking at a *real* image, on *your* side of the lens. In the case of a real image, the rays physically converge and pass through the location of the image. Unlike virtual images, real images can be viewed on a screen. To make the image strong enough to see on your screen, backlight the object slide using the white-light LED. Move the screen back and forth until you can see a sharp image.

Sketch and describe what you see:

A quick way to estimate the focal length of a lens is to create an image of a distant object (i.e. \( d_o \rightarrow \infty \)) and measure the distance between the lens and the image. Use the thin lens equation to show why this works:

Point your optical bench toward a distant object (e.g. outside a window), and position the screen such that you can see the image sharply on the screen.
Describe what you see, and be sure to note whether the image is real or virtual, and whether it is upright or inverted:

Measure the focal length, and compare to that you measured using the laser:

\[ f = \text{using laser: } f = \]

How does this relate to the workings of a camera, especially the disposable ones whose focus can’t be changed?
Now we will test the predictions of the lens equation. Measure the image height $h_i$ and image distance $d_i$ for each value of object distance in the table below. Calculate the focal length for each object/image distance using the lens equation, and then find the average focal length.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Object distance $d_o$</th>
<th>Object height $h_o$</th>
<th>Image distance $d_i$</th>
<th>Image Height $h_i$</th>
<th>Calculated focal length, $f$</th>
<th>Magnification</th>
<th>Magnification</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>measured</td>
<td>predicted</td>
</tr>
<tr>
<td>I</td>
<td>60 cm</td>
<td>1 cm</td>
<td></td>
<td></td>
<td></td>
<td>$m = \frac{h_i}{h_o}$</td>
<td>$m = \frac{-d_i}{d_o}$</td>
</tr>
<tr>
<td>II</td>
<td>40 cm</td>
<td>1 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>20 cm</td>
<td>1 cm</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>15 cm</td>
<td>1 cm</td>
<td></td>
<td></td>
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<tr>
<td>V</td>
<td>12 cm</td>
<td>1 cm</td>
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<td></td>
<td></td>
<td></td>
<td>Average:</td>
<td></td>
</tr>
</tbody>
</table>

How does the average focal length you calculated in the table compare with that you measured previously?

The definition of magnification is the ratio of the image height to object height --- i.e. how much bigger is the image compared to the original object. Using geometry, the lens equation predicts that this magnification is equal to $-d_i/d_o$. Compare this predicted magnification with that you measure directly.
Based on your measurements, to get a large, highly magnified image, where should you locate the object relative to the lens? (your discussion should refer to the results in your table and to the lens’s “focal length”).

Try to create a real image on the screen using the object and the diverging lens. If you are successful IMMEDIATELY tell your instructor. If you are unsuccessful, explain why in terms of the lens equation.

☐ Have your instructor check your work before leaving the lab.
Objectives  The objectives of this lab are to design, construct, characterize, and, in the process understand the way some important optical instruments work. We will build on last week’s lab’s study of lenses. First, we’ll use a single converging lens to make a magnifying glass --- also called a simple magnifier. Next we’ll make a compound microscope and finally a telescope. Key to characterizing optical instruments is the concept of “angular magnification,” sometimes called “magnifying power.” We will measure the angular magnification for each instrument and compare with design predictions.

Preparation  You will be pressed for time during the lab. Since successful completion of all lab activities counts towards your final lab grade it will be important to be well prepared by doing Pre-Lab assignments and reading the entire lab before attending the lab.

Pre-Lab  Read the Pre-Lab introduction and answer the accompanying questions and problems before this Lab.

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Pre-Lab for LAB 10

Some review:

1. We will study three theories of light. List them:

2. Which theory of light are we using to study the properties of lenses?

3. When you use prescription lenses or contact lenses, are the images made by the lenses “always real”, “always virtual”, or “sometime real, sometime virtual”? Explain.

4. For a “Normal Eye” to see something --- an object or an image --- the “something” must be between ___ cm and ______ in front of the eye.

5. Define and distinguish: “magnification”, “power” (of a lens), and “angular magnification”.

6. Summary of what you found in last week’s lab concerning images made by a \textbf{convex lens}. (circle correct answers)

   If the object is further from the lens than the focal point, the image will be:

   \begin{center}
   \begin{tabular}{c c}
   REAL & VIRTUAL
   \end{tabular}
   \end{center}

   If the object is closer to the lens than the focal point, the image will be:

   \begin{center}
   \begin{tabular}{c c}
   REAL & VIRTUAL
   \end{tabular}
   \end{center}

   Where should you locate the object to get a LARGE real image?
Pre-Lab for LAB 10

Magnifying Glass

The eyepiece of a compound microscope or a telescope is just a “simple magnifier” = “magnifying glass” To understand these instruments, you need to have a solid understanding of how the magnifying glass works. Your book has a discussion of this.

Note: we always use the simple magnifier right up next to the eye.

The basic idea of the simple magnifier is that it allows you to get your eye very close to an object --- and still be able to focus on the object. The closer you are to an object, the bigger it appears. Note: you will usually use a “magnifying glass” such that the distance to the object is just under the focal length of the lens.

Two ways of thinking about this:

I. The simple magnifier adds power to your eye’s lens and lets you focus on things closer to you.

II. The simple magnifier is like a prescription “corrective lens” for far-sightedness taken to the extreme. It takes a very close object that your eye cannot focus on and creates an image where it can.

The object is too close for your eye to focus on --- much closer than the near point, N. But that’s ok because when your eye looks through the lens, it sees the image. And the image is far enough away for your eye to focus.

The object is too close to your eye to see --- closer than the near point, N. But that’s ok because when your eye looks through the lens, it sees the image. And the image is far enough away for your eye to focus. The “regular way” to use a simple magnifier is for the object to be located just inside of the focal length and the image would be at “infinity” --- i.e. at a good long distance from your eye.
Pre-Lab for LAB 10

We want to see how a simple magnifier with \( f_{mag} = 5 \text{ cm} \) works on an object (arrow) that is 2 mm tall.

First, how well can your eye do by itself? The relevant quantity here is the “angular size.” The angular size determines how much space will be taken up on your eye’s retina and thus how big it appears. The best a normal eye can do is when you bring the object up to the “Near Point,” \( N = 25 \text{ cm} \).

7. A 2 mm tall object is 25 cm in front of your eye. Calculate its “angular size” measured at your eye.

\[
\Delta \theta_{25 \text{ cm}} =
\]

8. Consider a “magnifier/eyepiece” lens with \( f_{mag} = 5 \text{ cm} \). Typically, you’ll locate the object “just inside” the focal length of the lens. Suppose the object is located (just) 0.2 cm closer to the lens than the lens’s focal length: \( d_0 = 4.8 \text{ cm} \).

a) Find the location, magnification, and size of the image made by the lens for this situation.

\[
d_i = \quad m = \quad h_i =
\]

b) Could your eye --- pressed against the lens --- actually see (focus on) the image at this location? Explain.

c) Calculate the angular size of the image measured at your eye. Indicate this angle on the picture on the previous page.

\[
\Delta \theta_{\text{image}} =
\]

d) Calculate the “angular magnification, \( M_{\text{eyepiece}} \)” using the \( \Delta \theta \)’s found in questions above and compare it to \( M = \frac{N}{f} \). Compare to the approximation \( M \approx \frac{N}{d_0} \):

\[
M_{\text{eyepiece}} = \frac{\theta'}{\theta} = \frac{\Delta \theta_{\text{image}}}{\Delta \theta_{25 \text{ cm}}} \quad \quad M = \frac{N}{f} = \quad \quad M = \frac{N}{d_0} =
\]
Pre-Lab for LAB 10

Compound Microscope: A magnifying glass looking at a “pre –enlarged” image

A simple magnifier allows you to get your eye up close to an object. The eyepiece of the microscope is a “simple magnifier.” The trick of the compound microscope is to create a “pre- enlarged” image for the eyepiece/magnifier to look at. This is done with a 2nd converging lens, the objective.

Remember the way you made magnified real images in last week’s lab?

\[ M, \text{ “magnifying power”} = \text{“angular magnification” of a microscope is given by that of the eyepiece, times the pre-magnification of the objective:} \]

\[ M_{\text{microscope}} = m_{\text{objective}} M_{\text{eyepiece}} \]

9. Consider an “objective” lens with \( f_{\text{obj}} = 2.0 \text{ cm} \). Where should you put the object to make a REALLY BIG real image?

10. What is the magnification of an image (e.g. in the above figure) for an object located at \( d_0 = 3.0 \text{ cm} \)? (Note: this won’t make a REALLY BIG image, but you are “pretty close” to the focal length.)

\[ m_{\text{objective}} = -\frac{d_i}{d_o} \]

11. Consider a microscope made by viewing the image of question 11. Using the simple magnifier you calculated in questions 7 & 8. Find the “magnifying power” of this microscope.

\[ M_{\text{microscope}} = m_{\text{objective}} M_{\text{eyepiece}} = \]
Pre-Lab for LAB 10

Telescope design: Design a telescope

12. Design a telescope using an $f = 5$ cm lens and an $f = 20$ cm lens.

A) Which lens should be used as the objective and which as the eyepiece?

B) how far apart should the two lenses be spaced?

C) Calculate the “magnifying power” of this telescope.

☐ Have your instructor check your work to here.
Laboratory

Outline of today’s activities

Group Work Problem

Magnifying Glass

Introduction  Brief review of key concepts and relevant PreLab questions
Lab Activity  Make and characterize a simple magnifier
Problem Solving  Group work problem

Compound Microscope

Introduction  Brief review of key concepts and relevant PreLab questions
Lab Activity  Make and characterize a compound microscope
Lab Activity  Observe a microscopic object

Telescope

Introduction  Brief review of key concepts and relevant PreLab questions
Lab Activity  Make and characterize a telescope
Activity 1: Group work problem: Actual size vs. apparent/angular size of objects and images

The angular size of an object or image describes how big it appears to your eye.

From last week, recall your work with the diverging lens:

The object arrow was 1 cm high. The focal length of the lens is -33.3 cm. Calculate the position and height of the image and indicate your results on the figure:

\[ d_i = \quad h_i = \]

Indicate on the drawing and calculate the angular size of the object and the angular size of the image when viewed 30 cm downstream (as shown in the figure).

\[ \theta_o = \quad \theta_i = \]

Set up this situation on your optics bench. When you view the object and image with your eye 30 cm downstream, which looks smaller? OBJECT  IMAGE

Is this consistent with the angular sizes you just calculated?

This lens could be useful for someone who is near-sighted, as it forms an image of a distant object at a closer location. However, those of you who wear glasses know that the angular sizes of the object and image should be comparable when you put your glasses on or take them off. To see why this is so, consider putting your eye right up next to the lens. Now calculate the angular size of the object and image:

\[ \theta_o = \quad \theta_i = \]

Are these equal?
Activity 2. Measuring the “Magnifying Power” of a Magnifying Glass.

Measure the focal lengths of the three convex lenses at your table. Use the technique from last week where you created an image of a distant object at the lens’s focal length. Record your results below.

| microscope objective (the smallest lens) [labeled “small square”] : |  
| microscope objective |  
|  
| telescope objective (the largest lens) : |  
| telescope objective |  
|  
| magnifier/eyepiece (the middle lens) [labeled “Big square”]: |  
| magnifier/eyepiece |  

1. To make a simple magnifier, set the “magnifier/eyepiece” near the end of your optical bench. Put your eye right up next to the lens, and position the 1 cm “object” so that you can see it clearly.

How does $d_o$ compare with your measurement of the lens’s focal length?

Now predict the angular magnification of your magnifier:

$$M_{predicted} \approx m = -d_i / d_o = N/d_o =$$

2. Magnifying power tells you how much better you can view an object with a lens than without it. Without the lens, an object has its largest angular size when placed at the near point ($N \sim 25$ cm for a ‘normal’ eye), because this is as close as the object can be while remaining in focus. With a magnifying glass, you can do much better by creating a magnified image at the near point.

You can use your binocular vision to measure magnifying power directly. As you did in the last lab, you can simultaneously view an object and its image by shifting your attention back and forth between your left and right eyes. One eye will view the image through the lens (and thus measure $\theta'$), while the other will view a copy of the object on the screen (and thus measure $\theta$).
Don’t move the lens or the object from where you placed them in part 1.

Place a screen ~25 cm upstream of your lens/eye - this distance is your near point $N$. The screen has a calibrated scale, and a copy of the object. Now with one eye look at the image through the lens, and with the other eye look around the lens directly at the calibrated screen. Superpose the two images by adjusting your attention between both eyes --- you may also need to move the screen left-right or up-down. Measure the apparent size of the image using the scale on the screen and compare it to the actual size of the object. Because $\theta$ and $\theta'$ are small, the ratio of apparent to actual size is approximately equal to the angular magnification $M$, which is the “Magnifying power” of the simple magnifier.

Actual size= 
Apparent size at 25 cm= 

$$M_{\text{measured}} = \frac{\text{apparent size}}{\text{actual size}} =$$

Compare this result to the prediction in part 1.

$$M_{\text{predicted}} = M_{\text{measured}} =$$

****DO NOT DISASSEMBLE YOUR MAGNIFIER SETUP****
YOU WILL USE IT BELOW

☐ Have your instructor check your work to here.
Activity 3: Compound Microscope

As you learned in the prelab, there are two lenses in a compound microscope. The microscope **objective** is a converging lens which creates a real, magnified image of the object. The **eyepiece** is a simple magnifier which looks at this intermediate image, creating a second virtual, magnified image which is viewed with the eye.

**Setting up the pre-magnification stage of the objective lens**

*For what follows, don’t disturb the magnifying glass setup from activity 2 --- work near the other end of the optical bench.*

1. Near the far end of the optical bench (left side of figure), set up an object (2mm arrow), microscope objective (refer to pg. 2) and screen. You can backlight the object like you did last week. Adjust \( d_o \) and the screen position \( d_i \) until you get a sharp image that is twice as tall as the object \( (m = -2) \).

\[
\begin{align*}
h_o &= h_i = \\
d_o &= d_i = \\
m_{objective} &=
\end{align*}
\]

Microscope setup: The objective lens creates a \( m=-2 \) “premagnified” real image on the screen. In step 3, you take the screen out and move the rest of the assembly to where the image is formed on the back of the “object” target of the eyepiece assembly.
2. Now remove the screen, and move the remaining objective assembly (light source + object + objective lens) as a whole, toward the eyepiece assembly. Be careful to maintain the same value of \( d_o \) as you move the post holders. The real, magnified image produced by the objective lens should come into focus on the back side of the intermediate screen in the eyepiece assembly. Once this is so, take out the intermediate screen. Your simple magnifier/eyepiece should now be looking at the image created by your objective lens. This is now an aligned compound microscope! You may need to make small adjustments to the objective lens to bring the image into focus.

**Note: the microscope will be easiest to use if the lenses and object are at the same height.**

3. Predict your microscope’s angular magnification using your measured value for the magnifying power of the eyepiece lens (Activity 2) and the pre-magnification of the objective lens (previous page).

\[
M_{\text{predicted}} = m_{\text{objective}} M_{\text{eyepiece}} =
\]

4. Measure the “Magnifying power” of the microscope as you did with the simple magnifier using a scale 25 cm upstream of your eye. One eye should be looking through the microscope and the other at the target. Sketch what you see. Compare your measured “magnifying power” with the prediction above.

Sketch:

\[
M_{\text{measured}} =
\]

Comparison

☐ Have your instructor check your work to here.
Activity 4: Higher power microscope

In high power microscopes, the final image is usually formed at \(-\infty\), and the sample is placed very near (but just outside) the objective’s focal point. Under these conditions, the magnifying power of the microscope can be approximated as:

\[
M_{\text{microscope}} = m_{\text{objective}} M_{\text{eyepiece}} = \left( \frac{N}{f_e} \right) \left( \frac{L - f_o}{d_o} \right) \approx \left( \frac{N}{f_e} \right) \left( \frac{L - f_e}{f_o} \right)
\]

Here, \(L\) is the length of the microscope, which is equal to the distance between objective and eyepiece lenses; the distance from the object to the objective lens is approximately equal to the focal length of the objective lens: \(d_o \approx f_o\). You can see that if you increase \(L\), you can increase the magnifying power of the microscope. Operationally, this corresponds to bringing the object very close to the objective’s focal point, while at the same time moving the objective away from the eyepiece.

1. Get a microscope slide from your lab instructor --- you’ll use the microscope slide “end on” in the holder. Be careful not to drop the slide!

2. Increase the power of the microscope you’ve built by moving the objective lens further away from the eyepiece. Try setting \(L \geq 40\) cm; the larger the \(L\), the higher the power, but also the trickier the microscope will be to align.

3. Estimate the power of this microscope using the equation:

\[
M_{\text{microscope}} =
\]

4. Next you need to determine where the intermediate image should be formed. View the large screen at your setup through the eyepiece lens and adjust the screen’s height and position so that the arrow on the screen is centered and in focus. This is where the intermediate image will be formed.

5. Place the sample slide from your instructor upstream of the objective lens.

6. Make small adjustments to the slide’s height and position until a sharp image is formed on the back side of the large screen. The microscope is roughly lined up now.

7. Backlight the slide by passing light from the LED at your setup through a diffuser screen: the diffuser screen will make it easier to view the sample. Now, take the large screen out of the intermediate image plane, and look through the eyepiece at the object. You may need to gently change the position of the object to achieve a good focus. Sketch what you see:

|| Have your instructor check your work to here.
Activity 5: Telescope

Finally, we’ll make a telescope using the “magnifier/eyepiece” lens you have been working with and the “telescope objective” in your lab setup. As you learned in the PreLab, the basic idea of the telescope is similar to that of the microscope. The objective lens makes an image of the thing you’re looking at and the eyepiece allows your eye to see the image close up.

1. Record the focal length and calculate the power of the “telescope objective” lens.

\[ f_{\text{telescope objective}} = \quad P = \]

2. Referring to the schematic in the PreLab, how should you go about making a telescope from these two lenses? In particular:

A) How far apart should you space the lenses?

B) Where will the “intermediate image” be formed?

C) What is the predicted “magnifying power?”

3. Make a telescope based on your design. While looking through the eyepiece at a distant object, adjust the distance between the two lenses (a little) if necessary to bring the image into focus.

A) predicted vs. actual lens spacing

B) predicted vs. actual location of the intermediate image,

☐ Have your instructor check your work to here.
Experiment 11 – Superposition, Interference, and Diffraction

Objectives

A key objective of this lab is to examine the relationship between the two theories of light “ray optics” and “wave optics.” Wave optics explains some light phenomena that ray optics gets wrong. In this lab you will observe phenomena that can only be explained by wave theory of light --- single slit diffraction and Young’s double slit interference. It turns out that the wavelength of light is very short. We will use a Young’s double slit to measure the wavelength of laser light. We will then see how to improve on this measurement using many slits --- the principle behind the “diffraction grating.”

Preparation

You will be pressed for time during the lab. Since successful completion of all lab activities counts towards your final lab grade it will be important to be well prepared by doing Pre-Lab assignments and reading the entire lab before attending the lab.

Pre-Lab

Read the Pre-Lab introduction and answer the accompanying questions and problems before this Lab.

Points earned today

<table>
<thead>
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<th>Points earned today</th>
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<td>Pre-Lab</td>
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Instructor Initials

Date
Pre-Lab for LAB 11

First some review:

1. We will study three theories of light. List them:

2. Which theory of light did we use to study the properties of lenses?

3. Is ray optics a Particle or Wave theory of light?

4. Reproduce below the patterns you observed in Lab 9 when laser light hit single slit and double slit targets.

5. Laser light hits two very narrow slits that are separated by 0.1 mm and is viewed on a screen 2 m downstream. Sketch on the axis below what the ray theory of light predicts you will observe for this situation.

6. Instead of the ray theory prediction, you actually observe:

This is a breakdown of the ray theory of light, but can be explained by the wave theory of light. In fact, using the wave theory of light, you can use this observation to calculate the wavelength of the light making the pattern.
Pre-Lab for LAB 11

The $m^{th}$ order maximum in a double-slit interference pattern occurs at a position on a screen that can be calculated using trigonometry and the equation: $m\lambda = ds\sin\theta$. Use the information provided in questions 5 & 6 to calculate the wavelength of the laser used in the experiment.

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

7. Similarly the wave theory of light makes predictions for the single slit at odds with those of ray optics. For example, laser light with $\lambda = 500$ nm hits a single slit and 2 m downstream you observe the following pattern:

For single slit diffraction, the $m^{th}$ order minimum occurs at a position on a screen that can be calculated using trigonometry and the equation: $m\lambda = w\sin\theta$.

Calculate the width of the slit responsible for this pattern.

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

☐ Have your instructor check your work to here.
## Laboratory

**Outline of today’s activities**

**Review results from Ray optics**

<table>
<thead>
<tr>
<th>Introduction</th>
<th>Brief review of key concepts and relevant PreLab questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstration</td>
<td>Examine single slit and double slits from Lab 9 more closely</td>
</tr>
</tbody>
</table>

**Characterizing the targets**

| Lab Activity                  | Examine and measure the single, double, and multiple slit targets used below. |

### Single slit diffraction: Qualitative

| Introduction                  | Brief review of key concepts and relevant PreLab questions |
| Lab Activity                  | Study laser light passing through a single narrow slit |

### Young’s double-slit interference and gratings

| Introduction                  | Brief review of key concepts and relevant PreLab questions |
| Lab Activity                  | Observe double-slit interference & use to measure laser wavelength |
| Lab Activity                  | Observe interference from several slits & use to measure laser wavelength |
| Demonstration                 | Transition to spectroscopy |

### Single slit diffraction: Quantitative

| Group work                    | Wide slit from Lab 9: ray optics vs. wave optics |
| Lab Activity                  | Measure width of human hair |
Activity 1  Geometric Optics vs. Wave Optics

To understand the behavior of light, which should we use, the geometric optics (ray) model or the wave optics model? A key idea is that wave optics is necessary if diffraction is significant. Diffraction is the bending/spreading of waves as they pass an object or barrier. What does it mean “if diffraction is significant”? Well, this involves the details of exactly what measurements you are making. IF you had measured the single slit pattern formed on a screen in Activity 1 of Lab 9 extremely accurately, you would have observed a little spreading in the pattern caused by diffraction. This spreading was easy to overlook because it was small compared to the size of what you were observing; the width of the pattern appeared to be the same as the width of the slit: diffraction was not significant.

Part 1. Investigation: geometric (ray) optics vs. wave optics --- Wide slit from Lab 9

Recall in Activity 1 of Lab 9 that you sent a laser beam through a 1 mm-wide “single slit” and observed the pattern on a nearby screen on your lab table. We claim there was diffraction present, but its angular spread was too small to see because the screen you used was too close to the slit; the pattern could not attain sufficient angular width to be noticeable. Try again, send a laser beam through a single slit as you did before, but this time let the pattern form on a screen several meters away, on the other side of the room. DO NOT LET THE DIRECT BEAM ENTER YOUR (OR ANYONE ELSE’S) EYES.

Compare this pattern to what you observed in Activity 1 of Lab 9. Is there evidence of diffraction? Make a sketch of the pattern you observe on the screen:

-4 -3 -2 -1 0 1 2 3 4

distance on screen (cm)
Part 2. Group Work: Particle ⇔ Waves

As pointed out above, the spreading caused by diffraction is easy to overlook if it is small compared to the size of what you were observing. In Activity 1 of Lab 9, the width of the entire pattern appeared to be the same as the width of the slit: diffraction was not significant. Presumably, in Part 1 of Activity 1 of this lab, when you looked at the pattern farther “downstream” you were able to observe a single-slit diffraction pattern.

Diffraction would definitely be significant if the spreading were equal to the size of the slit itself, resulting in the entire pattern being greater than the width of the slit. When such a situation occurs, you MUST use the wave theory of light. When is this?

Problem Your laser has a wavelength of about 650 nm. Consider laser light passing through a slit 1 mm wide. You have learned that when light passes through a slit, a diffraction pattern occurs. Calculation: How far downstream (= \( L \)) is the spreading of the central maximum due to diffraction equal to the width of the slit itself, 1 mm?

You will use:

\[
\sin \theta = \frac{\lambda}{D},
\]

and for the small angles of this problem, \( \sin \theta = \theta = \frac{s}{L} \), where \( s \) is the half the width of the central maximum of the diffraction pattern. You should work in units of radians.

So, think of the width of the laser beam passing through a 1 mm slit as the sum of the 1 mm you start out with + the spreading due to diffraction. The spreading due to diffraction is given by the above equations.

(As always) You should start by a sketch. Again, the goal is to Calculate: How far downstream (= \( L \)) is the spreading of the central maximum due to diffraction equal to the width of the slit itself, 1 mm?
Activity 2 --- Measuring the slit patterns

1. In this lab we will be studying laser light passing through narrow, closely spaced slits that have been patterned in a dark glass slide. Hold the slide up to a light to see the three distinct patterns in the slide: a single slit, a double slit, and a multi-slit. We need to accurately measure the width and/or spacing of these slits. Because they are so narrow, this is difficult with the unaided eye. Instead, we will use a lens to make a magnified, real image of the slits – do not confuse this with a diffraction pattern. Once you have measured the spacing of slits in the image, you can calculate the spacing of slits in the object knowing the magnification provided by the lens.

2. You should find a lens with a focal length about 2.6 cm at your station. On one end of your optical bench, backlight one of the 2 mm arrow objects using the laser (rotate so the long axis of the beam is vertical), and position the lens to create a large, real image on a screen at the other end as shown below. Make as large an image as you can fit on your optical bench --- at least a magnification of 20.

3. Measure the height of the image arrow on the screen and calculate the magnification. Check your calculation against the predicted magnification.

\[ m \equiv \frac{h_i}{h_o} = \]

\[ d_i = \text{___________} \quad d_o = \text{______________} \quad m_{\text{predicted}} = - \frac{d_i}{d_o} = \]

4. Replace the arrow slide with the single slit target. Measure the slit width in the image, and use your measured magnification to calculate the actual width of the slit. Sketch and describe what you see below.


width of slit in image = ________ width of slit in object = \( w = \) ________
5. Repeat this for the double slit target. Sketch and describe what you see. Measure the actual spacing, \( d \), between the slits (center-to-center) as accurately as you can. Estimate your uncertainty.

<table>
<thead>
<tr>
<th>Sketch:</th>
</tr>
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<tbody>
<tr>
<td>Spacing between two slits in image =</td>
</tr>
<tr>
<td>Spacing between two slits in the object : ( d = \pm )</td>
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</tbody>
</table>

6. Do the same for the “multi-slit” target. Sketch and describe what you see. Note: you should measure similar spacings for the double slit and multi-slit target.

<table>
<thead>
<tr>
<th>How many slits are there?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing between slits in image =</td>
</tr>
<tr>
<td>Spacing between slits in object =</td>
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</tbody>
</table>

☐ Have your instructor check your work to here.
For the remaining Activities, you do not use the lens. Remove it from the optical bench.

Activity 3 --- Single Slit Diffraction

1. At one end of your optical bench shine your laser through the single slit target onto a screen that is 80 cm downstream. Compare what you observe with what you’d expect if light was just a stream of particles that travel along straight line rays, as in the ray optics theory of light (c.f. your PreLab).

This is a phenomenon that cannot be explained with Newton’s theory of ray optics, in which light is a stream of particles that travel in straight lines. Why did Newton and others get it wrong? When encountering an obstacle (e.g. a slitted screen or anything with a sharp edge), waves can mimic particle behavior if the wavelength is very short compared to the size of the obstacle. It turns out that the wavelength of light IS very short (< 1 x 10^-6 m), so that improvements in fabrication techniques were needed before narrow slits and other objects could be made.

☐ Have your instructor check your work to here.
Activity 4 --- Two-slits and more + measuring the wavelength of light.

1. At one end of your optical bench shine your laser through your “double slit” target onto a screen that is 80 cm downstream from the target. What you are looking at is called a “Young’s Double Slit” interference pattern. When it was first seen in 1801 it was absolutely definitive evidence against Newton’s view of light as particles traveling along straight-line rays.

Again compare what you observe with the expectation from ray optics:

observed pattern:

![Image of observed pattern]

distance on screen (cm)

pattern according to ray optics:

![Image of pattern according to ray optics]

distance on screen (cm)

2. Calculate the wavelength of your laser based on the method you used to solve problem 6 in the PreLab. Show your work in the box. (Use the $d$ you measured in Activity 2).

\[ \lambda = \]
3. In the double slit interference discussion in your book, the double slit pattern should go on “forever,” on either side of the central fringe. But in your measurements you saw a finite, “modulated” fringe pattern. Why? (Hint: compare the single slit and double slit patterns.)

4. Replace the double slit target with the multiple slit target. Measure and sketch what you see at the screen.

5. Compare and contrast (in words) the multiple slit pattern at the screen with the double slit pattern:

6. Your multi-slit target is a miniature diffraction grating. In commercial gratings such as the one you will use in you next week’s spectroscopy lab there are thousands of slits spaced extremely closely together. The maxima of a diffraction grating follow the same equation as for a two-slit pattern. Measure the wavelength of the laser light, this time using the multi-slit target. Explain why more slits is better for this measurement.

\[ \lambda = \]

☐ Have your instructor check your work to here.
Activity 5 --- Diffraction from hair

We focus on single slit diffraction simply because it is the most straightforward case to analyze. But diffraction is ubiquitous. It turns out the analysis that is used for the bending of light around the edges of a single slit (e.g. problem 7 in the PreLab) also works for the bending of light around small obstacles, such as a human hair for example:

\[ \sin \theta = \frac{\lambda}{W} \]

\( W \) in this case is the width of the hair.

**How thick is your hair?** Pick out a hair and tape it to a microscope slide --- line it up carefully and be sure part of the hair is clear of the tape. Put the hair in front of the laser and create a diffraction pattern on a screen 80 cm downstream. Use analysis similar to that in problem 7 of the PreLab to measure the width of the hair. Show your work below.

\[ \theta = \]

\[ W = \]

4. Compare the width of a human hair to the wavelength of the red light of your laser.

**Width of a human hair \( \approx \) ___ wavelengths of red light.**

Before you leave: Please remove the hair from the slide and replace the target slide(s) in its envelope.

☐ Have your instructor check your work to here.
Name ________________________________
Partner(s): ________________________________

**Experiment 12 - Optical Spectrometry**

**Objectives**
1) Understand the physical principles of a spectrometer
2) Use a spectrometer to analyze emission from atomic gases
3) Calculate the Balmer series of lines for hydrogen and compare with measurements

**Preparation** You will be pressed for time during the lab. Since successful completion of all lab activities counts towards your final lab grade it will be important to be well prepared by doing Pre-Lab assignments and reading the entire lab **before** attending the lab.

**Pre-Lab** Read the Pre-Lab introduction and answer the accompanying questions and problems **before** this Lab.

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<td>Date</td>
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Points earned today

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**PreLab 12: Page 1 of 7**
A spectrometer is an instrument that can be used to measure the wavelengths of light emitted by a source. To do this, light from the source must be separated into its constituent colors, a process called ‘dispersion’. Either a prism, which relies on the refraction of light, or a grating, which relies on the diffraction of light, can be used to disperse the light into its colors. You will use a grating spectrometer in this lab to study the emission from different atomic gas lamps. To understand the physical principles of this instrument, consider a simple spectrometer formed by placing a grating close to the eye and looking at a light source some distance away through a narrow slit.

Figure 1 A simple spectrometer.

A spectrometer of this type has been set up in the hallway display case outside room 2012, Smith Lab. By getting the eye close to the grating taped to the glass window, looking through the grating to the left and to the right, and depressing the power button, you should see the line spectrum of mercury. The following questions require observations of the spectrum of mercury in the display case.
Pre-Lab for LAB 12

Note the position of the light source in the middle of the board at the back of the display.

1. What is the color of the line closest to the middle? This is called the zero-order line.

2. Looking to the left or right, list the colors of the lines you observe starting from the middle and working outward.

3. Can you see any lines in the second order spectrum? What colors are they? Is there any difference between first and second order spectrum?

4. Select one of the lines in the 1st order spectrum. What color is it? 

Record the positions of the line on the meter stick:
   a. On left side. 
   b. On right side. 
   c. Position of central (zero-order) line.

5. Using these values, compute the distances $x_L$ and $x_R$ to each line from the middle (c.f. Fig. 1)
   a. $x_L = $ 
   b. $x_R = $ 

6. Knowing these values and the distance $L$ from the grating to the slit (see note on the case), you can compute the angles $\theta_L$ and $\theta_R$ by using $\tan \theta = x/L$.
   a. $\theta_L = $ 
   b. $\theta_R = $ 
   c. $\theta = $ (average value of a and b).
Pre-Lab for LAB 12

7. Next you will find the wavelength of the line for which you have determined the diffraction angle by using the grating equation:

\[ d \sin \theta = m \lambda \]

where \( d \) is the grating spacing, \( m \) is the order number (\( m = 1 \) in this case) and \( \lambda \) is the wavelength of your selected line.

The number of lines per unit of length in the grating, which you are using in this activity, is written on the display case.

a. The number of lines per mm is ________.

b. The number of lines per meter is ________.

c. The spacing, \( d \), is ___________ meters.

8. Compute the wavelength of the line: \( \lambda = \___________ \) nm

9. Is this consistent with the wavelength range for visible light?
Pre-Lab for LAB 12

Spectrometer: The spectrometer you will use in the laboratory is mounted on a turntable that allows you to measure angles directly, so that the calculations you did in questions 5-6 above will not be necessary. These angles are measured with respect to a reference position, which is defined such that the zero-order line in the diffraction pattern is centered in the telescope. Relative to the angular scale on the turntable, this reference position is close to 180°, but may differ by a small uncertainty ±ε. This uncertainty can be canceled out by computing the difference: $\theta = (\theta_R - \theta_L)/2$ (c.f. Fig. 2), where $\theta_R$ and $\theta_L$ are the angles of spectral lines to the right and left of the reference position.

![Diagram of spectrometer setup](image)

Figure 2: A spectral line is measured from a reference position. The telescope can swing to the left and right.
Pre-Lab for LAB 12

Vernier Scale Reading: If you are not familiar with reading a Vernier scale, you need to study the following section carefully. A Vernier scale extends the precision of a ruler’s tickmarks. The spectrometer you will use in the laboratory has a Vernier scale that allows you to measure angles very accurately, e.g. to the nearest minute. Recall that one minute of arc is \( \frac{1}{60} \) of a degree. Figure 3A shows a picture of a Vernier scale, which consists of two sets of ticks; the right set are a coarse scale with \( 0.5^\circ \) (30’) resolution, and the left set are a fine scale with 1’ resolution. To read the angle on the coarse scale, note that the zero tick mark on the left falls after the \( 15^\circ 2^\prime \) tick mark on the right, but doesn’t yet reach the \( 15^\circ 2^\prime 30^\prime \) tick mark (in fact, the zero tick is just a little more than half way to \( 15^\circ 2^\prime 30^\prime \)). To read the fine scale, find where the ticks on left and right best line up. The corresponding reading on the left scale is the number of minutes added to the coarse reading. In Fig. 3A, the ticks at 18’ line up best. The precise reading of the Vernier scale is the sum of the two readings, which gives \( 152^\circ 18^\prime \). To check if it makes sense, recall that the rough scale reading was a little more than half-way between \( 152^\circ \) and \( 152^\circ 30^\prime \), so that an angle of \( 152^\circ 18^\prime \) is consistent with our expectation.

Figure 3 Vernier Scales.
Pre-Lab for LAB 12

10. For practice, read the angle to the nearest minute on the scale in Figure 3B and record it here.

_______________________________________________

11. Using the value of $\theta_L = 152^\circ 18'$ and your value of $\theta_R$, compute the diffraction angle:

$$\theta = (\theta_R - \theta_L)/2 = \text{_______________}$$

12. Light from a red laser diffracts at this angle from a grating with 600 lines / mm.

   Calculate the grating spacing, $d = \text{___________} \text{ m}$

   Use the grating equation, $m \lambda = d \sin \theta$, for 1$^\text{st}$ order ($m = 1$) to calculate the wavelength:

   $$\lambda = d \sin \theta = \text{___________}$$

Is your calculated wavelength consistent with a red source?

If not, you may want to double check your calculations.

Have your instructor check your work upon entering the laboratory.
Laboratory

Today’s Activities

Problem Solving  Using the Bohr model
Problem Solving  Diffraction gratings
Lab Activity     Spectrometer calibration using sodium lamp
Lab Activity     Measurement of hydrogen’s Balmer series of emission lines
Problem Solving  Using the Bohr model

Demo problem: Calculation of the energy level diagram and Balmer series of lines using the Bohr model for hydrogen.
Group work Using the Bohr model

1) Using the Bohr model, identify the transitions \((n_i \rightarrow n_f)\) associated with the following series of hydrogen emission lines:

![Wavelength diagram]

- a)  
- b)  
- c)  
- d)  
- e)  

Calculate the energy of the light (in eV), and wavelength for emission lines (a) and (b):

\[ E_a = \quad \lambda_a = \quad E_b = \quad \lambda_b = \]

2) A hydrogen atom is in the \(n = 5\) excited state. Within the Bohr model, which of the following illustrates possible emission lines? _________
Concept Questions  Diffraction gratings

3. Sunlight impinges on a diffraction grating as shown.

What color is the central maximum?

Explain this by referring to the diffraction grating equation:

Label the diffraction orders $m$ in the figure.

4. A laser ($\lambda = 589$ nm) illuminates a diffraction grating with a spacing of $1667$ nm between slits. How many spots are visible on the screen?
Lab Activities

**Introduction:** Good teamwork is needed to take high quality measurements within the lab period. A suggested division of labor is:

1. Recorder 1 - records observations and does calculations.
2. Recorder 2 – helps with recording and calculations (optional)
3. Observer – changes the telescope angle and sets crosshairs on spectral lines.
4. Reader 1 - reads angle scale and reports to Recorder.
5. Reader 2 - reads angle scale to verify Reader 1’s result. The two readers must agree before result is recorded. Careful measurements can easily yield wavelengths accurate to 0.1 nm or better.

All members of the team must rotate through all the positions so each person has a turn at each job.

**Description of Spectrometer:** Figure 4 shows the grating spectrometer. Light from a source passes through a slit; diffraction of light by this slit determines the resolution of the spectrometer. The light is collimated and dispersed by passing through the diffraction grating. The grating should be placed in the holder, perpendicular to the incident light (an eyeball setting is sufficient). The telescope is positioned at the diffraction angle for a particular wavelength of light present in the source emission. You will see an image of the illuminated slit through the telescope. The image is superimposed on a cross-hair pattern. To measure the angle of a spectral line, the telescope angle is adjusted until the slit’s image lines up with the vertical cross-hair.

![The Gaertner-Beck grating spectrometer.](image)

The angular scale is set such that the entrance collimator is at 0° and the straight through reading is nearly (but not exactly) 180°. As discussed in the PreLab (page 4), you will measure angles for spectral lines on both sides of this reference position. This corrects for any uncertainty in the exact reference position, and also corrects for slight misalignments of the diffraction grating.
Lab Activity 1: Spectrometer calibration using the sodium lamp

Observation of the sodium lamp:
The sodium lamp takes about 5 minutes to warm up, so turn it on now. Glowing sodium vapor emits yellow light with a wavelength of about 589 nm. Once the lamp is shining brightly, position it so that the entrance slit of the spectrometer is well illuminated. The lamp housing should be about 3 cm away from the slit. To maximize the light passing through the slit, have one person slowly move the lamp from side to side as another looks through the telescope.

1. Move the telescope off to the side and look straight through the grating at the illuminated slit. Move your head in an arc while looking at the slit through the grating. At certain angles, you will see the illuminated slit again. How often does this happen over the full 180 degrees?

How does this compare with your answer to concept question #4? ____________

Determination of the grating spacing \( d \):
2. View the illuminated slit through the telescope, positioned at about 180°. The sodium lamp is bright enough that you can reduce the slit width so that the slit image appears as a fine, vertical line. You may need to adjust the eyepiece position so that the slit’s image is in focus. You should also be able to see the crosshairs in the telescope. If the cross-hair is not visible, ask your instructor for assistance.

Recall the diffraction grating equation: \( m \lambda = d \sin \theta \)

You first need to calibrate the spectrometer by determining the grating spacing \( d \). This is done by measuring \( \theta \) for a known wavelength \( \lambda \).

3. Now adjust the angle of the telescope until you can see the 1st order \((m = 1)\) diffraction pattern. The yellow light from the sodium lamp is actually at two distinct wavelengths or “lines”. In your telescope, the lines are so close together, that they may overlap and thus appear as one thick line. If you do not see the separate lines, adjust the eyepiece focus or reduce the slit width. The sodium D1 line has a wavelength of 589.5944 nm, and the D2 line has a wavelength of 588.8877 nm.

Which line should appear at the larger diffraction angle? ____________

You may also see other lines which are from contaminants. You may wish to look for other lines as well: you can compare the sodium spectrum you observe with that on the poster in the lab. Be sure that all team members have the opportunity to observe all spectra.

4. With the telescope on the left side, have the Observer adjust the angle until the crosshairs are centered in the middle of the two yellow lines (or, if you still not able to see two separate lines, on the center of the thick yellow line). Reader 1 then records the angle in the table below as \( \theta_1 \). Move the telescope angle off, and have another Observer reposition the telescope. Reader 2 then records the angle as \( \theta_2 \). Compute the average of the two values, \( \theta = (\theta_1 + \theta_2)/2 \). Call the result \( \theta_L \) and record it in the Table 1.

Retake the measurements if \( \theta_1 \) and \( \theta_2 \) differ by more than 10 minutes (10').
5. Now repeat this procedure with the telescope on the right side. The average of the two values, $\theta = (\theta_1 + \theta_2)/2$ is now $\theta_R$.

| Telescope on left side $\theta_1$ | Telescope on right side $\theta_2$ | $\theta = (\theta_1 + \theta_2)/2 = \theta_R$ |

6. Now compute the diffraction angle $\theta$:

$$\theta = (\theta_R - \theta_L)/2 = \text{______________}.$$ 

7. Using the grating equation (as in the PreLab Page 3), you can now compute the grating spacing and the lines/mm. Use the average of the D1 and D2 wavelengths ($\lambda = 589.2411$ nm), since you measured the angular position of the middle between the lines (or if your focus was off, the center of the overlapping lines).

$$d = \text{______________}, \ \text{lines/mm} = \text{___________}$$

⚠️ Have your instructor check your progress to this point.

*** Turn off the sodium lamp when finished! It will not be needed anymore. ***
Activity 2. Measurement of the Balmer series: You will now use the grating spacing from your spectrometer calibration to measure the wavelengths of the Balmer series of emission lines.

1. Replace the sodium lamp with the atomic hydrogen lamp. Adjust the position of the hydrogen lamp and the slit width to maximize the light you see in the zero order diffraction pattern.

2. Measure the angles of as many lines as you can see (about 4) in the first-order spectrum of hydrogen. Also, if you can see them, try measuring the angles of at least one second-order line. As in Activity 1, calculate the diffraction angle by averaging $\theta = (\theta_R - \theta_L)/2$, where $\theta_R$ and $\theta_L$ are each the average of the two Reader’s measurements. Calculate the measured wavelengths ($\lambda_{\text{measured}}$ in Table 2) using the grating spacing $d$ from your grating calibration.

Make sure your answers are consistent with the lines’ visible appearance! For example, red light should have a wavelength in the range 620 nm to 700 nm or so.

3. Compare your measured wavelengths with those predicted from the Bohr model ($\lambda_{\text{Bohr}}$), as calculated at the beginning of class.

| Color and order $m$ | $\theta_L$ (deg) | $\theta_R$ (deg) | $\theta$ (deg) | $\lambda_{\text{measured}}$ (nm) | $\lambda_{\text{Bohr}}$ (nm) | % error $|\lambda_m-\lambda_B|/\lambda_B$ | Transition: $n_i \rightarrow n_f$ |
|---------------------|------------------|------------------|----------------|-------------------------------|-------------------------------|--------------------------------|--------------------------|
| red $m = 1$         |                  |                  |                |                               |                               |                                 |                           |

4. Does the Bohr model do a good job of predicting the measured wavelengths? If not, what may cause the discrepancy?

Have your instructor check your work before leaving.
Appendix

Introduction to LoggerPro

To start data collection, click the green “Collect” button on the tool bar. There is a delay of a second or two before data collection starts, so don’t try to time clicking the button with your actions.

Many parameters in the software are adjustable, like the sample collection time. Adjusting them is done through the menus, but some common commands and parameters are available through the toolbar. For example, click the clock icon to change the sample rate or time.

Often you will be told to load/open a file. Such files will set all the relevant parameters for the experiment.

Graph parameters can be changed by clicking on the graph to select it and using the menus, or by right-clicking on the graph. Common graph commands include zoom and autoscale.

Note that LoggerPro typically measures position-like variables and calculates derivatives like velocity and acceleration.

If LoggerPro crashes restart the program and re-open the last initialization file used. Any changes you may have made to LoggerPro’s configuration by hand will have been lost and will have to be re-performed if desired.

If you can’t see your data (the graphs appear blank) or the data is a flat line at zero you probably need to adjust the graph scaling. Start with “Autoscale from 0”, then zoom-in or adjust the axes.

If the data look good at first but suddenly become choppy or weird while using the position detector the object you are measuring has probably moved outside the detector’s measurement cone. If this is a cart & track experiment, try adjusting the hinge of the detector. The sensor might be tilted too far back.

If the “collect” button is gray and can’t be clicked then there may be a problem with the sensor hardware. Make sure the cable to the sensor is snapped in place and likewise with the cables going to the interface box. (The cable from the sensor goes to the
interface box; just follow it.) If the button is still gray, the problem might be the software. Quit out of LoggerPro and restart it.

If all else fails, ask your lab instructor for help.
A Brief LoggerPRO Guide

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Key to Toolbar

Start collecting
Stop collecting data
Erase (clear spectrum)
Ampl/HV/ADC
Preset Time
Presel Integral Count
Peak Report
Data Report
Mark the ROI
Y axis down
Y axis up
Y axis left 16
Y axis right 16
X data contract
X data expand
X axis left 16
X axis right 16
X axis left 256
X axis right 256
Toggle Y lin/log axis
Preset Integral Count
Amp/HV/ADC
Stop collecting data
Erase (clear spectrum)