Building a model of optical diffraction and interference for high school students using multiple inquiry-based physics activities.

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Bio: Quinn Thomson graduated from SUNY Geneseo with a double major in physics and adolescent education as well as a minor in chemistry. He started my teaching career at JFK High School in Cheektowaga, NY for three years teaching physics, chemistry and as well as other science electives. I am currently in graduate school at Buffalo State pursuing my master's in physics education. I am currently working at Orchard Park High School as a physics teacher. I like to spend my time with friends, in a number of different activities.

Abstract

In this paper, I present a series of activities directed toward high school regents physics students with the intent of having them investigate concepts behind and practical applications of diffraction and interference, as well as expanding their skills in scientific inquiry. Using experimental guides (Appendices A and C), students are required to make observations and collect data in order to answer questions that help them explore the physical effects of these concepts. Ultimately, students are asked to create and complete their own experiments as a method to assess their understanding of the topics and give them the opportunity to practice the scientific process (Appendices B and D). Several other professionals in my school and I noted that these activities helped facilitate student engagement with the topic and led to discussions between themselves and with the instructor. After these activities' students were able to answer previous regents questions on the subject with 96% accuracy.

Introduction

With the recent implementation of the Next Generation Science Standards (NGSS, 2013) and the New York State Science Learning Standards (NYSSLS, 2016) a focus has been placed on inquiry-based science education. My goal is to make a series of student activities that use the standards listed in the NYSSLS to have students gain an understanding of diffraction and interference. These activities are a mixture of guided inquiry experiments and full student led experiments. In these guided inquiry experiments students are given a simple procedure and asked questions based on what they observe and analysis. The student led experiments are when I give students a goal but offer no procedure requiring students to use there understanding so far to complete that goal.

Scientific inquiry is characterized by the NYSSLS by

> "a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings." Page 64

These guided inquiry experiment follows these values and has students record their observations and work through tougher questions using their observations to help them. By using multiple actives, students can replicate their results in a variety of different ways.

Across the NYSSLS students are asked to demonstrate they understand how to "Plan and conduct investigations" across multiple subjects.

Students during these activities were asked to formulate their own experiments and deal with their own misconceptions with the evidence of their experiments. Student find their own evidence in order to make logical conclusions.

The NYSSLS (HS-PS4-3) states:

> "Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model (quantum theory), and that for some situations one model is more useful than the other.
>
> [Clarification Statement: Emphasis is on how the experimental evidence supports the claim and how a theory is generally modified in light of new evidence. Examples of a phenomenon could include resonance, interference, diffraction, and photoelectric effect.]" Page 62

These activities are designed to give students a closer look at interference and diffraction through experimental evidence. Students are asked to describe and reason with these phenomena using the wave model of light.

Background on DIffraction

Diffraction is the bending of waves around the edges of a barrier. The most common examples of diffraction are the bending of sound waves around an open-door, as in figure 1, or the bending of ocean waves around a barrier, as shown in figure 2.

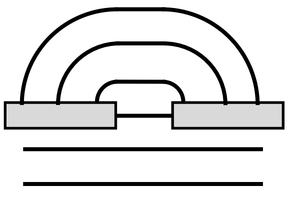


Figure 1: diffraction through a slit

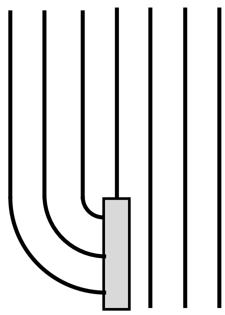


Figure 2: diffraction around a barrier

Interference is when two waves are at the same place at the same time. Unlike matter, waves have nothing preventing them from being superimposed. There are two types of interference: constructive and destructive. These are distinct based on what we observe when they are on top of one another. Constructive interference is when two or more waves form an apparent wave with a higher amplitude than either of the original waves, while destructive interference creates a wave with a smaller amplitude as seen in figure 3.

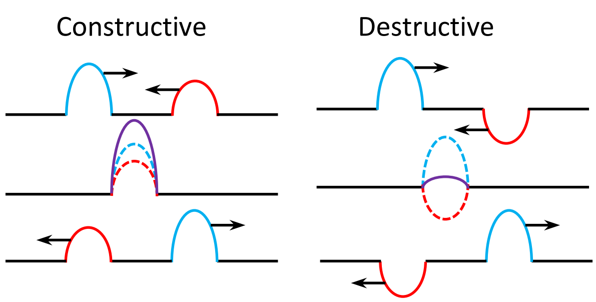


Figure 3: Pulse Interference

The key factor that creates the effect of diffraction is Huygens' principle. Huygens' principle states that every point on a wavefront is a source of new waves (often referred to as wavelets) (Knight 2013). These new waves normally end up interfering and canceling each other out, so it acts as just a single wavefront as seen in figure 4. However, when a wavefront comes across a thin barrier, slit, or multiple slits, the waves no

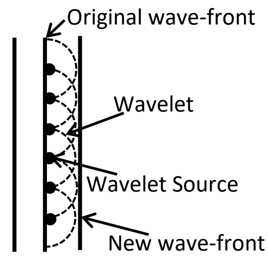


Figure 4: Huygens' principle of a moving wave

longer cancel out their interference and a new pattern emerges that we refer to as diffraction.

In the first activity, we are using the effects of Huygens' principle in action with human hair. As the light rays strike the hair it prevents some of the wavelets from passing while on the sides of the hair, and they begin to diffract (Messer 2018). The waves formed on each side of the hair begin to interfere causing a pattern of constructive and destructive interference seen in figure 5. Looking at this "interference pattern" is the main point of the activity,

Figure 5: Hair interference pattern

as it gives us information about the object or opening that created it. This is also where the first major misconception for this activity is introduced. Many students assume the pattern created is the "shadow" of the hair on the board as shown in figure 6. The early activities are made to show that this is not what is happening.

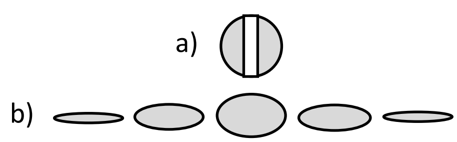


Figure 6: possible hair results
a) shows results expected for the "shadow" misconception of hair blocking light
b) shows the actual results

The double pencil activity offers a different look at diffraction by changing out a barrier with an opening. Using Huygens' principle, we can see why these two seemly different scenarios, a barrier and opening, result in the same pattern. As the wave front reaches the opening, wavelets are allowed to spread out, as

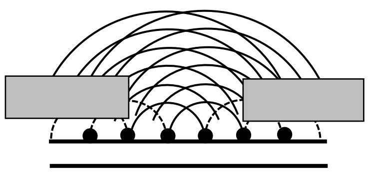


Figure 7: Huygens' principle single slit diffraction

some of the wave is blocked, resulting in the same thing as the hair as seen in figure 7 (Knight 2013).

The gap between the pencils is what is acting as the opening in this activity, which is key because it allows students to adjust the size of the slit. One of the key factors in these series of activities is how the pattern gives us information on the slit or barrier that created it. With these pencils, students can adjust the size of the slit, thus changing the pattern. The relationship they should see is that as the gap between the pencils gets smaller, the pattern becomes more spread out, as shown in figure 8 (Teng, Teng, Hennekens 2018). For students this is most likely an unexpected relationship as they often believe the bigger gap leads to a bigger pattern (McDermott 2000). By using at the Huygens' principle, we can see why this inverse relationship occurs (Knight 2013). Remember: if a wavefront does not come across anything, it remains a wavefront as the wavelets interfere with themselves resulting in a wave that is not changed. When the gap is larger, more of the waves pass through unaffected, leaving the pattern smaller. Conversely, when the gap is smaller the wave spreads out more making a more obvious pattern.

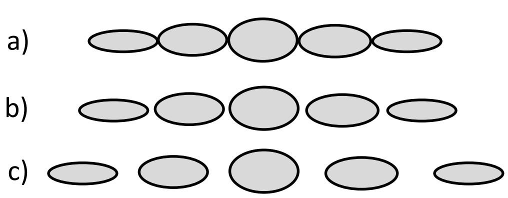


Figure 8: Changing pattern of pencil activity
a) Large starting gap
b) gap slight closed
c) gap pitched nearly closed

The wire mesh works off a similar principle as the previous activities. In this activity the meshes are two-dimensional, unlike the hair and pencil open which act one dimensionally. This leads to a two-dimensional pattern on the screen. As seen in figure 9, as the mesh gets finer the pattern gets larger, similar to the pencil opening. There is an interesting secondary pattern that emerges on the screen where the dots of the main pattern fade in and out. This is due to the thickness of the wires, while the main pattern forms based on the size of the gaps. This secondary pattern is not important within the goals of the activity, but students might notice it, so it is worthwhile to be able to answer any questions regarding this.

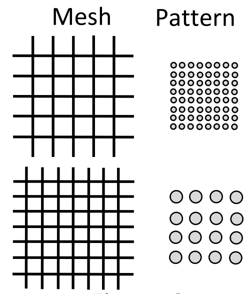


Figure 9
As the mesh gets finer the pattern gets larger and more spaced.

The next half of activity starts to focus more on double slit and diffraction grating interference and their associated formula. This equation comes from Young and his experiment with two slits (Knight 2013). Figure 10 has the basic form of a double slit experiment where a laser interacts with two slits separated by distance d and projects an interference pattern on a nearby screen.

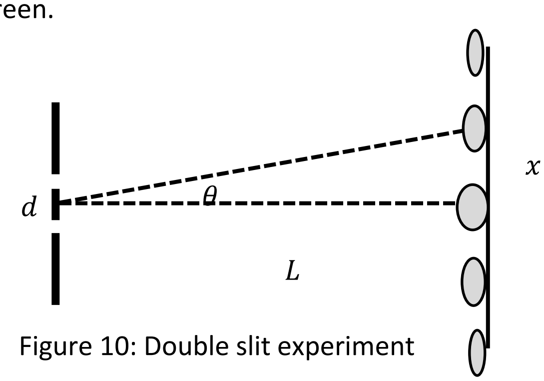


Figure 10: Double slit experiment

Equation 1

$$d * Sin(\theta) = m * \lambda$$

d: distance between slits
m: what bright spot that is being measured.
θ: Shown on figure 6
λ: Wavelength of laser

Equation 1, based Young's experiment, used throughout these later activities. An important part of this equation to understand is that variable m is denotes which bright spot will be used in the measurements where m =0 shows the center, m =1 is for the spots above and below and so on. In order to find the θ in the equation, students need to measure the length to the screen and the distance between bright spots. The basic trigonometric relationship Tan(θ)=x/L (Deweerd 2016). d is often the goal of the activity, due to the fact it is normally too small to measure without the aid of diffraction.

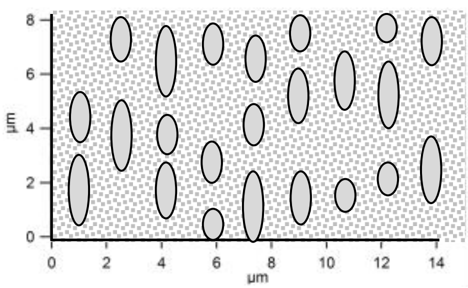


Figure 11: microscopic view of a CD

CDs and DVDs are encoded with information by burning small dot like divots onto the surface as seen in figure 11. This information is read by firing a laser through the disk in order to “read” these dots and extract information from the size and position of the dots. By removing the cover off of a disk, students are able to fire a laser through the disk which cause it to diffract based on the separation of the grooves that this data forms. These grooves are placed so close to one another they act as a diffraction grating, which is when there are multiple slits next to one other. The double slit equation applies to diffraction gratings as well as CD and DVDs and can be used to calculate the spacing between the grooves (Nöldeke 1990). Students calculate that the grooves of a DVD are closer to one another which shows them that more data can fit on a DVD than a CD. Note the actual value of the spacing of a CD is about 1.6µm and a DVD is .74µm.

The next two activities use very similar principles as the activity before. However, it uses a circular shape to create a diffraction pattern. The lycopodium powder and the red blood cells both act as a collection of small circular apertures that form a circular pattern as seen in figure 12 often referred to as an “Airy Disk.” The big difference between this and a standard diffraction grading is the values of m will not be simple integer values. The simple answer to why they are not integer values is that the radii of the minima and maxima spots are not evenly spaced like they are in other forms of diffraction. This uneven spacing causes the m values to also not be even. The more complicated answer involves using equation 2 in order to solve for the maxima and minima locations which require the use of a Bessel function (Sethuraman 2014). Table 1 shows the values for m to use in equation 1. The diameter of a lycopodium particle is around 36.8µm (Sethuraman 2014) and the diameter of a red blood cell can vary greatly but typically falls between 7.5 to 8.7 µm (Diez-Silva et. al. 2010).

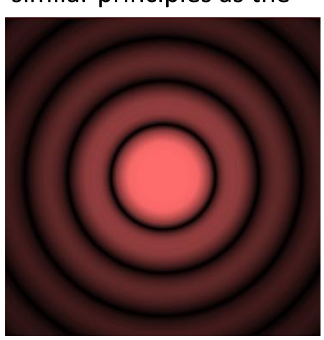


Figure 12: Airy diffraction pattern

Equation 2

$$I(\theta) = I_0\left[\frac{2J_1(kd\ sin\theta)}{kd\ sin\theta}\right]^2$$

I: light intensity
I_0: light intensity at the center
k: is the wavenumber
d: is the radius of the aperture (powder or cell)
J_1: is the Bessel function order 1

***m* values for:**		
	Minima	**Maxima**
1	1.220	1.635
2	2.233	2.679
3	3.238	3.690

Table 1: m values for a Airy Disk

Materials and Safety Concerns

Each student group is going to need the following to complete all activities. Simple office supplies like rulers, index cards, pencils and rubbers bands are used as well. A class set of materials cost around $100 with the exception of the lasers which depend greatly on the brand, style and power you purchase.

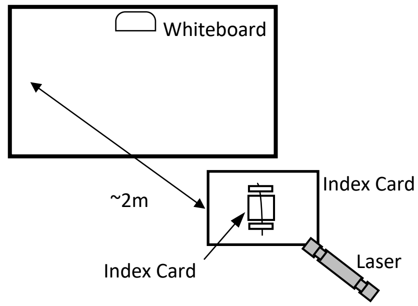
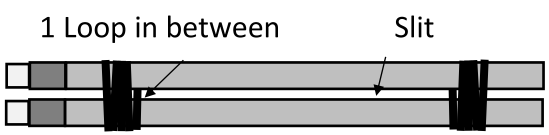
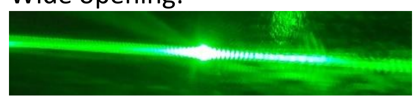
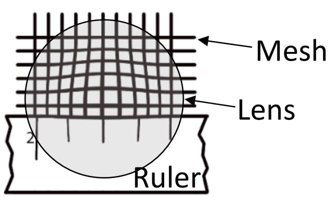
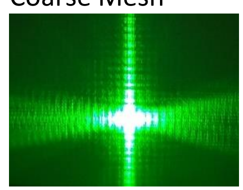
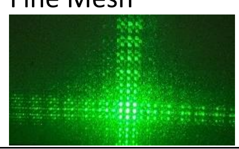
- Laser
  - Any color works; however, a variety of colors would be best so groups can see how different wavelengths effect the patterns
  - A laser that sits flat with a toggle switch makes it easier for students to make the patterns
  - https://laserclassroom.com/product/laser-blox-multi-3-pack/
- Fine Metal Meshes
  - Often called metal mesh or wire cloth.
  - You need 3 different sizes
  - A mesh count of 60 to 120 (number of wires crossings per square inch) should be enough
  - https://www.amazon.com/Activists-Stainless-Steel-Screen-Filtration/dp/B07T5DWP99/ref=sr_1_20?keywords=Activists&qid=1572823108&sr=8-20
- Lycopodium Powder
  - https://www.fishersci.com/shop/products/lycopodium-4/S25396
- A slide with blood cells
  - https://www.carolina.com/histology-microscope-slides/human-blood-film-slide-smear-he/313152.pr?question=
- CD and DVD
  - Strip away the cover part of the disk, leaving it see- through
  - The disk needs to have data
- A sample holder
  - A wooden block with a slit cut into works

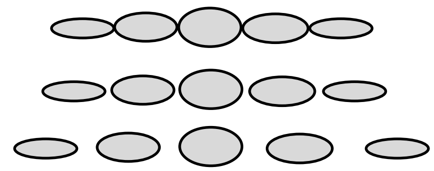
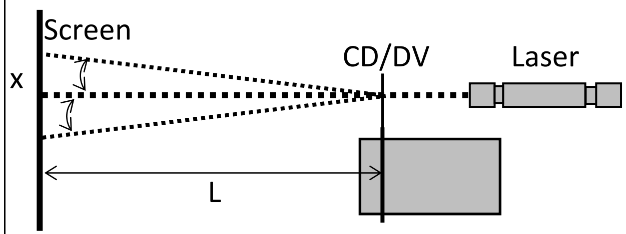
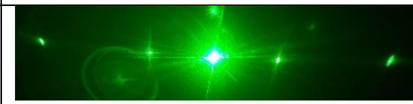
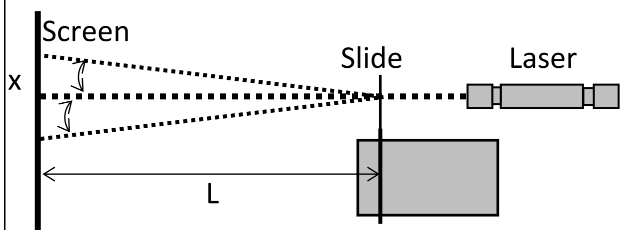
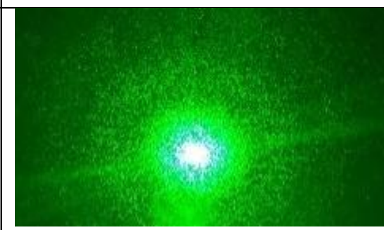
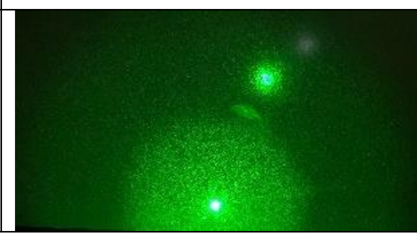
The main safety concern for the students conducting these activities is the lasers. It is important to stress the care while using lasers. There is no need for particularly powerful lasers in these experiments, but students should still be instructed on the main risks with using lasers. Of course, the number one concern is having the laser pointed into a student's eye. One of the advantages of this lab is that laser can be held on the table rather than in their hands. If you do not have a laser that can sit flat on a table and a toggle switch, I would also suggest a holder for the laser in these labs. Something to keep a rounded laser flat on the table and to keep the laser on.

Lycopodium Powder should also be a consideration for safety. It is considered a category 1 flammable solid-combustible dust. We are using small amounts to make covered slides however it should be noted then when it is in a dust in air it is highly flammable. Protective googles should be used to avoid eye contact. Please read all safety information that is provided with the powder.

Activities

The handouts with the instructions for students are found on appendices A through D. The guided activies found on appendices A and C walk students through a several observations of physical objects using diffraction and interference. The activity in part A just require students to take a qualitative look, where they need to look at the relationship between the object and the pattern that it creates. Qualitative activities end with the activity found on appendix B where students need to create their own experiment using this relationship. Appendix C starts the quantitative activities where they need to take careful data and use equation 1 to find the size of objects. Likewise, in Appendix D students need to use a similar technique to find the size of a red blood cell by creating their own experiment. The students' ability to create and successfully analysis these experiments help determine if they understand the material.

Experiment	Diagram of Setup	Image Diffraction Pattern	Purpose	Key Question(s)
Hair thickness (Appendix A)			Pre-assignment. Also to have students see a sample lab setup and a distinct diffraction pattern	How is diffraction related to the pattern you are seeing? How is interference related to the pattern you are seeing? How do you think the size of the object relates to the pattern created?
Pencils' gap (Appendix A)		Wide opening:  Narrow Opening 	Completely qualitative look at how the size of the object relates to the diffraction pattern.	How does the size of the slit relate to the pattern created? Important to check with your teacher before you move on.
Mesh (Appendix A)		Coarse Mesh  Fine Mesh 	A quantitative look to see how the size of the object relates to the diffraction pattern.	State the mathematical relationship between the mesh size and the pattern separation.

Which hair is bigger? (Appendix B)		Hair getting progressively smaller 	Students make their own lab to test whether they understand the previous activities.	Students should write a procedure and conclusion. Note whether they understood the relationship between the size of the object and the pattern.
DVD/ CD track spacing (Appendix C)		 	Students learn how to use the equation 1 for a diffraction grating.	Students should make calculations using the Fraunhofer formula.
Lycopodium powder granular size (Appendix C)			Students learn how to use the equation 1 with a “correction” for circular apertures.	Students should measure the location of the minima and maxima area. Using these values, they should calculate the size of the powder.
Red-blood cell size (Appendix D)			Students make their own lab to find the size of a red-blood cell and whether they understand the previous activities.	Students should create their own lab and find the size of a red blood cell.

Reflections on Qualitative Activities:

I found these activities very useful for getting students to understand the basic physical relationships without allowing students to just use formulas without understanding the underlying physics.

The first activity where students view the interference pattern created by hair was gave students little trouble. I found that it allowed students to know what pattern they are looking for in future activities. Something that was worth mentioning to the students is they do not have to yank their hair out, just brush their hands through their hair and they are bound to get a loose strand or two.

After reviewing the results of the activities, the pencil activity was one of the toughest for students to understand. Many students had trouble identifying the interference pattern due to the challenging nature of making the gap between the pencils small enough to show changes the pattern, while holding it steady. Because this aspect of the activity is so important to the students' basic understanding of the concept, I stepped in to discuss the groups' results and make sure they were focusing on the correct phenomena. Telling or showing the students beforehand what pattern to expect may lessen this problem.

The mesh activity was very smooth, and students got great results with little help. I did use a zoomed in photo of the mesh next to a ruler to show students how to properly count the wires (Figure 13). Students can use either their own phones or a microscope to better see the fine mesh.

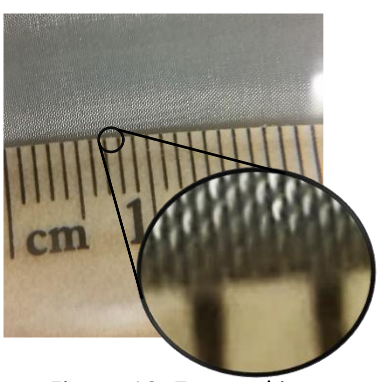


Figure 13: Zoomed in view of a ruler on mesh

The capstone challenge was successful overall. Students were able to construct a working experiment and the vast majority, 83%, were able to specify the proper relationship between the pattern and the object. The biggest misconception that I noticed was that students still believed the dim spots were the shadows of the hair. In this experiment, many measured not the distance between bright spots like the mesh activity, but only measured the very small width of a dim spot, which was often less than a millimeter. Although the correct answers can be achieved with this data, it is indicative of a misunderstanding how the pattern is formed. To combat this issue, I would suggest having a discussion with students on how they answer the "shadow" questions before the capstone challenge.

Reflections on Qualitative Activities:

The qualitative activities were also quite successful. Overall, students were able to use the things they learned in the previous activities plus equation 1 to find the sizes of different objects.

With the CD/ DVD activity, students not only calculated the spacing difference between the two disks but also discussed how that could make them work differently. Many struggled with using the equation for the first time. I found asking them to draw triangles that represent the path of the light helped them visualize what they needed to find the angle. Some students also needed assistance finding the value of m. Using a diffraction grating as an example I showed the students how each dot relates to specific value of m and had them compare it to their observations of the disks.

The Lycopodium powder activity went smoothly for students. The only part that was tough for students was dealing with the different shape of the pattern and how to relate it to the other activities. The circular pattern means they need to change the values of m they use to nonwhole numbers. By this point, students were able to correctly draw the relationship between pattern and object with 89% accuracy. It was also helpful to tell them beforehand to measure to the center of either the dark rings or the light rings rather then the edge.

In the final activity, all groups were successful in finding the size of a red blood cell. By the end of the activity I could tell students were very proud of the fact that they were able to measure something so small in an experiment that they made themselves. The average size of red blood cell is 7.5 to 8.7 µm and students results ranged from 4 to 12 µm.

Student and Professional Feedback:

Overall, I got a lot of positive feedback from students and other professionals when conducting these activities in the classroom. Students reported that they enjoyed the activities and it was easy to see the joy they got from completing the final activity without any predetermined procedure or help. During the first two activities, some students struggled with the limited instruction. However, as the lessons continued, they got significantly more comfortable with the idea of inquiry activities. The two areas where my students seemed to struggle the most was the new unit prefixes in these activities and converting between them and using equation 1. Although I practice unit conversion during the beginning of the year, the addition of micrometers and nanometers led to some confusion. This is my students' first experience with trigonometry in physics and this equation in particular is difficult to understand at first. Even with the difficulty of these new concepts, these activities led to some great interactions between the students and instructors.

Another physics teacher and my school's administrator observed these activities in action. My administrator found the activities to be "highly effective" at engaging students in effective discussions. He also noted that these activities had students "actively participating by measuring, documenting, calculating, setting up the testing devices, etc." Another physics teacher, whose own interpretation of these activities helped inspire my own instruction, finds these activities useful in helping the students understand the material and its real-world applications, such as its use in the discovery of DNA."

Conclusion:

Students do not often have the opportunity to work with the diffraction and interference of light and when they do, they are often not asked to explain the relationship between these concepts and the patterns they create. (Arons 1997). These activities give students the chance to not only create these patterns with many different setups, but they are asked to find the subtle differences between them. They are asked to explain, draw pictures and discuss what they are seeing which provides students a chance to really learn and use the concepts.

Before I used these activities, diffraction and interference was a quick lesson where I lectured to my students, gave a teacher run demonstration, and asked example questions. However, when my students conducted these activities, they had great discussions within the activities and showed some genuine excitement at the results of their self-ran experiments. These types of inquiry activities are great at promoting this type of engagement with students and I am glad I have switched how I teach this concept, even when it takes a bit longer to do. Overall, these activities brought a lot of excitement to the classroom and students had a genuine good time using the lasers to experience some weird and unexpected phenomena.

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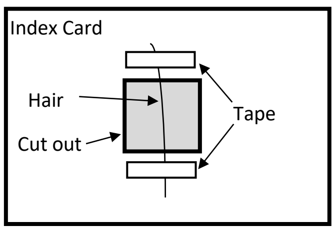
Appendix A

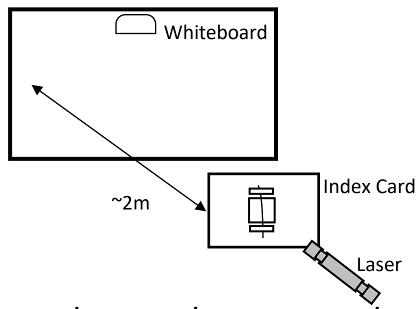
Qualitative Diffraction and Interference

The Strand of Hair:

Setup:

- Construct a sample holder using an index card with a square cut in it. Tape a piece of your hair so it goes across the opening. (shown below)
- Hold the sample about 2 meters away from a screen (our whiteboards)
- Fire the laser at through the hair and at the screen.





Questions:

1. Sketch the pattern the laser makes on the screen when hitting the hair.

2. Does the pattern on the screen just look like the "shadow" of the hair? Explain how it's the same or different than just the "shadow."

   ____

   ____

   ____

3. This experiment helps us see the property of waves known as diffraction. Explain what diffraction is and how we are seeing it in this experiment.

   ____

   ____

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4. Rotate the hair by 90^o and observe the pattern made by the laser now. How is the direction of the spread-out beam relative to the orientation of the hair?

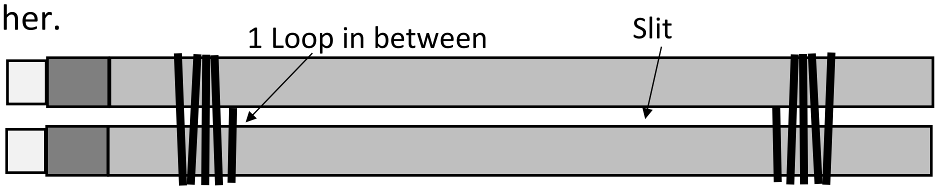
   ____

   ____

Two Pencils:

Setup:

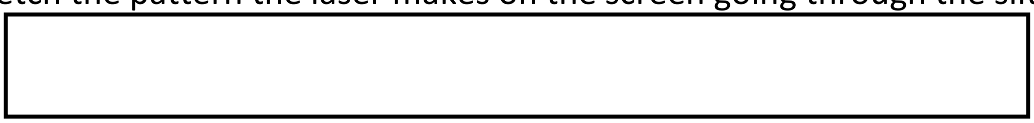
- Construct a narrow slit by attaching two number 2 pencils together using two rubber bands. Its important to have one section of the rubber bands in between the pencils. Wrap the band tightly so they are help closely together.



- Use the same setup as the last lab just replace the index card for the double pencils.

Questions:

1. Sketch the pattern the laser makes on the screen going through the slit.



2. Does the pattern on the screen just look like the "shadow" of the opening? Explain how it's the same or different than just the "shadow."

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3. Squeeze the pencils together to make the slit narrower. Describe how the pattern changes.

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4. This experiment helps us see the property of waves known as interference. Explain what interference is and how we are seeing it in this experiment.

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5. Describe the similarities between the pattern made by the hair and the one created by the slit.

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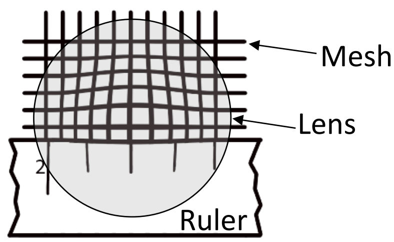
Wire Meshes:

Setup:

- Collect 4 different meshes. Use the provided sample holder and place them within them. Make a similar setup to the previous labs substituting for the mesh sample holder.

Measurements for Each Mesh:

- Using a ruler measure the separation between the bright spots of the pattern created on the screen.
- Using the magnifying lens and possibly the aid of your smart phone camera measure how many wires are in one millimeter of the mesh



Questions:

1. Sketch the pattern the laser makes on the screen going the coarsest mesh and the finest mesh.

Coarsest Mesh

Finest Mesh

2. Complete the following data table based one your measurements

Mesh	Distance between nearest bright spots in the pattern (x)	Number of wires in one millimeter (n)	Distance between wires (d=1/n)
Coarse			
Medium			
Fine			
Finest			

3. How does the pattern change as the wires get closer together? What type of mathematical relationship is this?

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Appendix B

Capstone Challenge: Who has the thickest hair:

Instructions: Construct and conduct an experiment to show which person in the group has the thickest hair and which has the thinnest.

1. **Procedure:**

2. **Data/ Observations**

3. **Analysis**: Write about why your data is important and how you use it to prove your conclusion

4. **Conclusion**

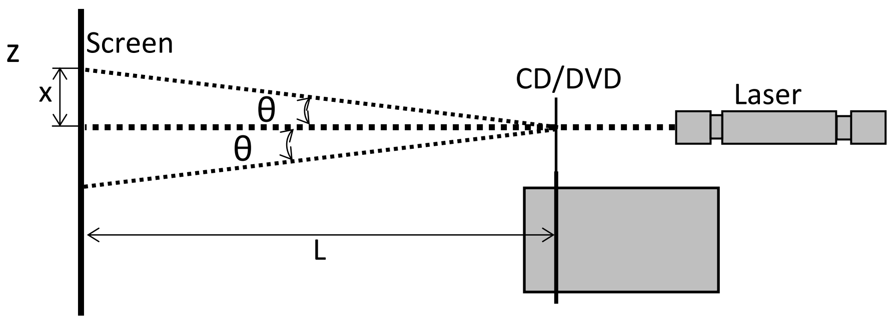
Quantitative Diffraction and Interference

<u>DVD versus CD:</u>

Background: CDs and DVDs act as a diffraction grating due to the incredible small parallel tracks burned into them. We are going to attempt to find the spacing between these tracks and compare CDs to DVDs.

Setup:

- Place the CD on the sample holder. Make sure that the bare section that is cut into the CD is visible.
- Place the CD with the holder close to the screen (about 20cm) and look for the pattern on the screen.
- NOTE: that small cracks in the CD can cause a second pattern from being formed, you are looking for the 3 to 5 dots being created.



Measurements:

- With a ruler, measure the distance between the central dot and the first dot (x).
- Measure the distance between CD/ DVD and the screen (L).

Questions:

1. Based on the diagram above what trigonometric function should you use to relate x, L and θ? Write out the complete formula for θ in terms of x and L.

   ____

2. Complete the data table below using your measurements and your trigonometric formula to find the angle.

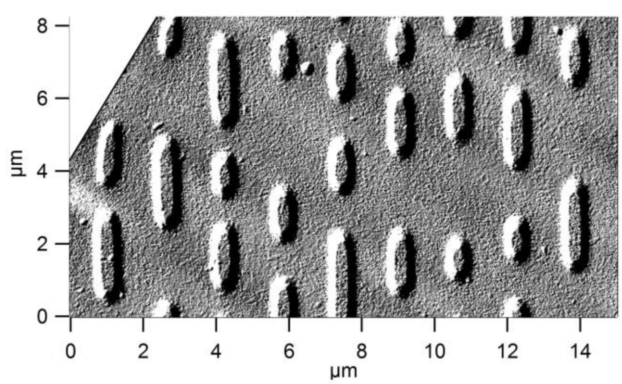
Media	x (cm)	L (cm)	θ
CD			
DVD			

3. Using the double slit equation $m * \lambda = d * Sin(\theta)$ find the spacing between the tracks for the CD and DVD. Note that you can find wavelength of your laser on the written on the laser. Show all work below.

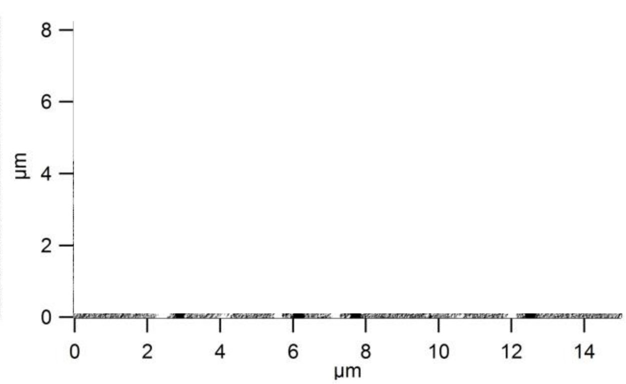
CD track spacing: _______________ DVD track spacing: ________________

4. Using the drawing below which shows CD under a microscope.
   a. Measure the horizontal space between the tracks below.
   b. Calculate the percent difference between your measurement here and your calculated value above.
   c. Make a quick sketch on how you predict the DVD track spacing will look like given the value you found above.

CD



DVD



*CD Image courtesy of Freiermensch under GNU Free Documentation license

CD track spacing: _______________

CD percent difference: ___________

5. A CD can store 0.65 gigabytes whereas a DVD can store 4.7 gigabytes of information. How does the data and calculations you made show that DVD can store more information within the same size?

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Lycopodium Powder:

Background: Lycopodium powder is made up of spores from clubmoss planets. These are very small and highly flammable in air. They are also roughly circular in shape.

Setup:

- Sprinkle a very small amount of lycopodium powder onto a glass slide. Title the slide over a waste beaker to remove excess powder. You should be left with a slide that is lightly dusted with the powder.
- Use the laser to view the diffraction pattern of the powder.

Observation: Draw the pattern you are detecting on the board, make sure to note the bright (Maxima) and dim (Minima) areas.

Measurements:

- With a ruler, measure dimeter (D) of the first minima circle.
- Measure the distance between the slide and the screen (L).
- Laser Wavelengths (λ) are found on the lasers.

Questions:

1. Based on previous lab and your drawing above what trigonometric function should you use to relate D (the diameter of the circles), L and θ? Write out the complete formula for θ in terms of D and L.

   ____

2. Complete the data table below using your measurements and your trigonometric formula to find the angle.

Laser Color	λ (nm)	L (cm)	Diameter (cm)	θ

3. What is the relationship between the wavelength and the diameter of the pattern?

____

____

4. Due to the fact that this is circular pattern the m values will not be whole and half integers in the diffraction formula: $m * \lambda = d * Sin(\theta)$. Instead we use the values shown on the chart below. Based on the diameter (D) you measured what value of m should you use?

____

m values for:		
	Minima	**Maxima**
1	1.220	1.635
2	2.233	2.679
3	3.238	3.690

5. Find using the data in your chart find the value for the diameter of the lycopodium powder spore (d) for each color of your laser. Show all work for the red laser.

Red Laser: _________ Green Laser: __________ Blue Laser: __________

6. Take the average of d and do a percent error calculation with the actual value of the diameter of a lycopodium powder spore (33 μm).

% Error: ______________

7. If you were to test on object that had a bigger diameter, how would that change the interference pattern shown on the board? Do a quick sketch to show the pattern created by the lycopodium powder and this new bigger object to illustrate the difference.

Lycopodium Powder	Larger Circular Object

Appendix D

Capstone Challenge: Size of a Red Blood Cell:

Instructions: Construct and conduct an experiment to find the size of a red blood cell.

1. **Procedure**

2. **Data/ Observations**

3. **Analysis**:

4. **Conclusion**

5. **Question**: Explain how diffraction and interference play a role in your experiment

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