Physical Optics

Pre-Lab: An Introduction to Light

A Bit of History

In 1704, Sir Isaac Newton postulated in *Opticks* that light was made up of tiny particles that behaved like any other massive object, from planets to protons. He predicted that light is observed to travel in a straight line because it moves at such a high speed, just like a Nolan Ryan fastball appears to travel in a straight line instead of a parabola. The particle model of light also explained many other aspects of light's behavior, such as reflection and refraction (both of which describe the ways in which light bends when in contact with a surface). Newton was the number one name in physics for more than two centuries, so when he espoused a theory, people believed it. It didn't hurt that the particle model readily explained commonly observed phenomenon. Because of this, the particle model of light dominated until Thomas Young, who also helped decipher the Rosetta Stone (boy, was he an overachiever!), performed his double slit experiment in 1801. This experiment conclusively demonstrated the diffraction and interference of light, which are properties that can only be explained by a wave model of light.

Particle or Wave?

Modern quantum theory holds that light has both wave-like and particle-like properties. The act of making an observation forces the light to display its particle or its wave properties (in quantum mechanics, this is called collapsing the wave function). Whether light will display its wave-like or particle-like properties depends on the experimental design, the wavelength of the light, and on the length-scale of the object used to observe the light (e.g., the slit width in Young's double slit experiment). When the wavelength of light is large, the slit width tends to be smaller than or comparable to the wavelength of light and its wave nature dominates. As the wavelength of light decreases, the particle nature of light begins to dominate. In the experiment today, all of the slits through which you will observe light are on the order of the wavelength of the light and you can treat light purely as a wave. Physical phenomenon that can be described by only the wave nature of light are commonly referred to as physical optics. It is more physically realistic than describing light as a ray, as you did in the geometric optics lab (if you are a Physics 118 or 212 student). For additional information on waves, diffraction, interference, and polarization, see: Appendices A and C; Moore E15, Q1, and Q2; and Young and Freedman Chapters 33, 35 and 36.

What is a Polarizer?

> **Do This:** Take the polarizer you received in lab the previous week and look at a variety of objects, both inside and outside. Examples of objects you might look at include, but are not limited to, your computer screen, your phone screen, a light bulb, the table, your lunch, the sun (indirectly, of course!), the sky, etc. Be creative! Try rotating the polarizer to see what changes.

PL1. List at least three objects that appear different when you look at them through a polarizer and three that don't seem to significantly change.

PL2. Describe the effects a polarizer has on the objects that appear to change. What happens when you rotate the polarizer while looking at these types of objects?

Do This: Many sunglasses are polarized. Based on what you've already discovered about how polarizers change the way certain types of objects look, determine if your sunglasses are polarized. Whether or not they're polarized, bring them in to lab! Don't worry, no harm will befall them.

Do This: Use the Pre-Lab link on the lab website to visit http://k12videos.mit.edu/content/3d-glasses-and-the-polarization-of-light and watch an introduction to the science of polarization.

PL3. Before we can talk about 3D, we have to verify that each eye only sees in 2D. To test this, hold your thumb in front of your face (just like the video describes). Look at your thumb out of just one eye (close the other one), and then switch eyes. What happens to the image of your thumb? Why do you see this happen?

PL4. Repeat the exercise you just did with your thumb, now paying particular attention to your depth perception. How is it affected by using just one eye? How does this all verify that each eye can only see in 2D (and it must be your brain that puts the slightly offset images together into 3D)?

PL5. In your own words, describe the analogy the video makes between polarizers, waves, and the cardboard sheet with vertical slits cut into it.

PL6. How do polarized glasses make sure each eye only sees the image intended for it, effectively doing the same thing as closing one eye, without all the squinting?

PL7. Polarization can be a useful tool, even without understanding the science of what's happening. This is true for people (polarization wasn't discovered until 1809 – see Appendix C), plants, and animals. Find an example of how polarization is used, either in nature or by people pre-1809. Describe the phenomenon in a few sentences.

Read This: Polarizers can be made from a variety of materials, but the most common way is by stretching out long chains of organic molecules that are all aligned in a single direction. When light hits the molecules, their electrons oscillate and radiate. Somewhat surprisingly, if the molecules are stretched horizontally, they polarize light in the vertical direction. This is because when the electrons in the molecules oscillate, any radiation that's polarized parallel to the molecule chain is absorbed, while radiation that is polarized perpendicular gets through, thus creating the vertically polarized light. Despite the direction of the molecule chains, we still say that the light is vertically polarized and that the polarization axis is vertical.

Part I: The Digital Revolution

The Story

You are home for Spring Break and your technologically-challenged grandparents are trying to put one of those new-fangled DVDs into their old CD player. After you introduce them to the DVD player, they ask you why the heck there have to be so many types of discs out there?! What is the advantage of one over another? Your grandparents may not know about Twitter and iPods, but they do remember their college physics. You decide to begin their enlightenment on the myriad of advantages Blu-ray and DVD discs have over CDs by examining the amount of data each disc can hold. Fortuitously lying around their house is the equipment to build an interference experiment (they *really* enjoyed college physics labs!).

Equipment

- Laser Apparatus
- Screen (ruler mounted on ring stand)
- Slide of Double Slits in Holder
- CD (label removed)
- DVD (label removed)
- Transparent vinyl record (you may need to share with a nearby group)
- Meter stick

The first thing you do is explain the basics about compact discs (CDs), digital versatile discs (also called digital video discs, or DVDs), and Blu-ray discs. All three discs are all made through similar processes. The discs are made of polycarbonate (a type of plastic), which are then coated in aluminum and a smooth layer of acrylic, and finally covered by a label. Data is etched onto the bottom surface of the polycarbonate by a laser that creates a series of bumps of equal height, but varying length (Figure 1). The laser in your home CD/DVD/Blu-ray player reflects off the bumps on the disc as it spins and the electronics in your CD/DVD/Blu-ray player then read this reflected light and translate it into a movie or a song. The details of exactly how this happens are complicated and well beyond the scope of your explanation. From the top of the disc (the label side), these bumps appear to be pits, which is what people commonly call them. For a CD, the pits are 500 nm wide, 125 nm high, and a minimum of 830 nm long. The pits on a DVD are 320 nm wide, 120 nm high, and a minimum of 400 nm long. The pits on Blu-ray discs are even smaller. DVDs and Blu-ray discs can have a second polycarbonate layer that also stores data; this is how dual-layer DVDs and Blu-rays are created.

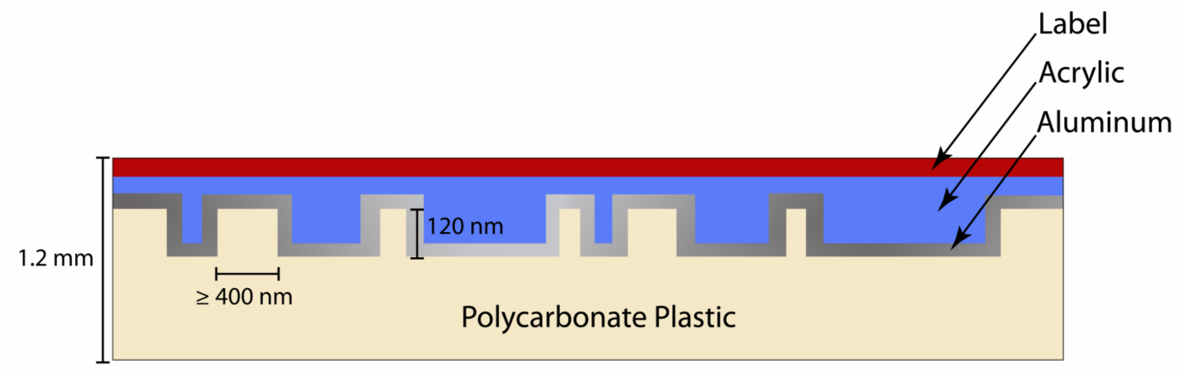

Figure 1: Layers of a DVD (drawing is not to scale)

The pits are laid out on the disc in a spiral pattern that starts at the center of the disc and curves outward toward the edge. The spiral is etched as tightly as possible, and the distance between adjacent rings, known as the "track pitch" (see Figure 2), depends upon a number of variables and is different for each type of disc. The adjacent rings in the tight spiral function like the slits in Young's experiment.

Any arrangement with a very large number of slits is referred to as a *diffraction grating*. A diffraction grating acts like a prism and disperses white light into individual wavelengths. This is why diffraction gratings, CDs, DVDs, and Blu-ray discs all appear to have a rainbow of color on their surface. With this knowledge in hand, you are ready to prove to your grandparents that they can ditch all those bulky CDs and put Barry Manilow's entire repertoire on one convenient disc.

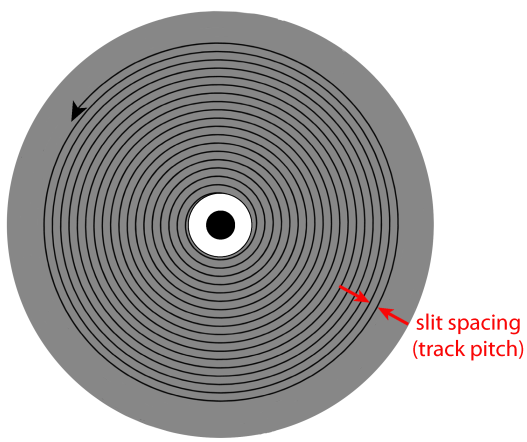

Figure 2: Data is etched by a laser in a spiral pattern on the CD, DVD, or Blu-ray disc. The spacing between adjacent rings in the spiral corresponds to the slit width (d) in Figure 4 in Appendix A. This spacing, called the track pitch, is a constant for each disc type (drawing is not to scale).

1. Preliminary Measurements

You realize that while your grandparents conveniently have a laser set up on the dining room table, they don't know its wavelength. "But the laser is red!" your grandparents protest, eager to get to the data storage experimental punch line. You politely remind them that "red" is not a wavelength; "red" light includes the range of wavelengths from 600 – 650 nm. You realize that before you can learn anything about the track pitch of a CD or DVD, you will need to find the wavelength using a slit of known spacing. Being safety conscious, you issue the following warning to anyone within eyeshot of a laser.

☠Warning: The low-power laser beam used in these experiments will not cause permanent damage to your retina, but it can produce annoying after-images that may persist for several minutes or longer. DO NOT allow the beam to shine (either directly or by bouncing off a shiny surface) into anyone's eyes.

1.1. Look at the slide, which contains four double slit configurations of different separations (see Appendix B). Which configuration will be useful to find the wavelength of the laser? Record your choice and clearly explain your decision. [There is no right or wrong decision. However, there are choices that will make your life harder or easier. You may want to consider some of the following when making your choice of slits: the ease of measuring the relative separation between maxima (the distance y in Figure 4); the resulting size of the interference pattern on the viewing screen; and the effects on the accuracy of the measurements involved in determining the wavelength of the laser.]

1.2. Use the slit configuration you decided on in Step 1.1 and find the separation between the maxima. To reduce your error, be sure to measure the separation between several orders of maxima ($n = 1, 2, 3$).

1.3. Estimate and record the errors on the values you measured in Step 1.2. When reporting errors on a measurement, the *worst* thing you can do is to report your errors as being smaller than they really are. When estimating your errors here, be sure you're being honest. [Hint: why are you asked to make several measurements in Step 1.2? How does this affect the errors in your measurements?]

1.4. Determine the wavelength of the laser. Think very carefully about the validity of any simplifying assumptions before you use them. If you do make assumptions, be sure to carefully explain why they're valid here.

1.5. Did the measurements give you a reasonable value for wavelength? If your answer is "yes", proceed with the rest of the lab; if not, explain where your reasoning failed and repeat the experiment until you have a value for the wavelength that is "red".

1.6. How does this confirm that light is a wave (at least sometimes)? Compare your observations to what you would expect to observe if light were a particle as Newton proposed.

2. Determining Track Pitch

You now have all the tools in place to determine the track pitch of both a CD and a DVD (alas, your grandparents have not yet upgraded to Blu-ray).

2.1. Replace the slide of slits with the CD and use it as a diffraction grating. Determine the spacing between slits, once again measuring the separation between several orders of maxima ($n = 1, 2, 3$), if possible. Draw a picture of your setup and record the distances you measure on your picture. [Note that despite having *many* more slits, the diffraction grating will produce maxima in the same location as predicted by Young's two slit experiment (see Appendix A for an explanation of why).] Be sure to estimate and record the errors on your measurements.

2.2. Repeat Step 2.1 with the DVD as the diffraction grating.

2.3. Determine the track pitch of both the CD and the DVD. Think very carefully about the validity of any simplifying assumptions before you use them. If you do make assumptions, be sure to carefully explain why they're valid here.

2.4. Based on the results of the track pitch and what you know about the amount of data storage on CDs and DVDs, do your answers seem reasonable? Why or why not? When answering, assume the DVD in question is single-layered.

2.5. Based on your measurements of the track pitch of a CD and a DVD, what predictions can you make for the track pitch of a Blu-ray disc? Does the fact that Blu-ray discs utilize a blue laser to both etch the pits that encode data and to read the disc in your Blu-ray player (hence the name) have any effect(s) on the track pitch? Justify your answer.

2.6. Your grandparents excitedly exclaim that they have plenty of old vinyl records in the basement and suggest measuring their track width, as well. Use the clear record as diffraction grating in the setup from Step 2.1. Based on distance between maxima that you observe and everything you've learned in lab thus far, *approximate* the track spacing for the record. You should not do any detailed calculations here; instead, just make an order of magnitude approximation. Does your answer seem plausible? Why or why not. If not, figure out where you went wrong and try again.

Part II: Puzzling Over Polarization

The Story

Just as you finish with the record, your younger, less academically motivated brother joins you and your grandparents. He is rather dismissive of the experiments you've been doing and he informs you that the only interesting thing about a Blu-ray disc is the movie that's recorded on it. He produces his current favorite, *Mutant Zombie Piranhas from Outer Space in 3D*, which he avows is infinitely more thrilling than science could possibly be. You beg to differ, and seeing a way to reel him in, you mention that modern 3D movies are only possible because of science – namely, polarization. Just as you had hoped, he takes the bait and asks you to explain this. Pleased to have caught his interest and in the number of fish-related puns you were able to utilize, you tell your brother that he'll need to start with the basics if he wants to understand how movies work.

Equipment

- Two pairs of sunglasses
- Round polarizer (note, this is a linear polarizer that is round in shape; it is *not* a circular polarizer like those described in the Pre-Lab video)
- Set of crossed polarizers fixed in place
- Glass plate

3. Polarization by Reflection

You decide to start with something you know your brother has experience with: sunglasses. You grab your phone and pull up some pictures from last winter's family ski trip to Breckenridge, all of which show your brother looking cranky because he couldn't ski after he got some nasty sunburned corneas from refusing to wear goggles. At the time, you made fun of him (as any good sibling would – especially since he was fine in a day or two), but now, a year of physics wiser, you decide educate him on why his vacation was nearly ruined.

> **Read This:** When unpolarized light hits a surface, it becomes polarized in the direction parallel to the surface and creates glare. We call this reflected light. The more reflective the surface, the more the reflected light is polarized. With very reflective surfaces, such as snow or water, the intensity of all that reflected light can actually temporarily damage your eyes (hence the term snow blind). All sunglasses use a tint to reduce the overall brightness of the light, but polarizers actually prevent most of the light from getting through to your eyes.
>
> 3.1. Before you can see the effect polarized sunglasses have on glare, you need to be sure you are looking at an unpolarized light source. Verify that the overhead fluorescent lights are unpolarized. Briefly describe how you verified this.
>
> 3.2. You have two pairs of sunglasses - one polarized, one unpolarized. Look at the reflection of the overhead light off the pane of glass on your table and describe what you see with the

polarized sunglasses versus the unpolarized ones. If you brought your own sunglasses, you can use those instead. Just be sure you look at the reflected light through one set of unpolarized sunglasses and one pair of polarized ones.

3.3. Based on what you've learned about polarization by reflection, in which direction do you suspect sunglasses are polarized (vertically, horizontally, 73° from vertical, etc.)? Explain why this is the most useful direction, given the orientation of reflected light you typically encounter.

3.4. The metal casing around the round polarizer has red and black marks separated by 90°. Which pair of markings indicates the axis of polarization? Explain how you know this.

4. A Second Polarizer

4.1. While wearing the polarized sunglasses, rotate the round polarizer in increments of 45°. Describe what you see at each increment.

Read This: If you did Step 4.1 very precisely over small changes in angle and with a light meter to measure the intensity of the light that passed through the polarizer, you would be able to experimentally verify Malus' Law (see Appendix C). However, your grandparents don't have a light meter in their basement (give them some credit - they had an entire interference setup. They're not Amazon!). Instead, the family just has to take your word for it that they would have verified Malus's Law has the following form:

$$I = I_i \cos^2 \theta$$

where I_i is the initial intensity of light before it passes through the polarizer in question, I is the intensity of light after it has passed through the polarizer, and θ is the angle between the light's initial polarization direction and the axis of the polarizer (Figure 3).

4.2. Plot the relationship between the final intensity and the polarizer angle in Malus' law. You should do this in your notebook – it doesn't have to be perfect. Just be sure to mark a few relevant angles and indicate the initial intensity.

Do This: Verify that your observations qualitatively match Malus' Law. If not, there's an error somewhere, and it isn't with Malus. Go back and verify that everything looks as it should.

Read This: Despite your grandparents' failings in the light sensor department, you realize Malus' Law can be explained using what you already know about electromagnetic waves. You recall from class that the electric field vector is perpendicular to the magnetic field vector, which are both perpendicular to the direction of the wave's propagation. Polarizers are designed to interact with the electric field component, so the direction of the electric field will be our primary concern.

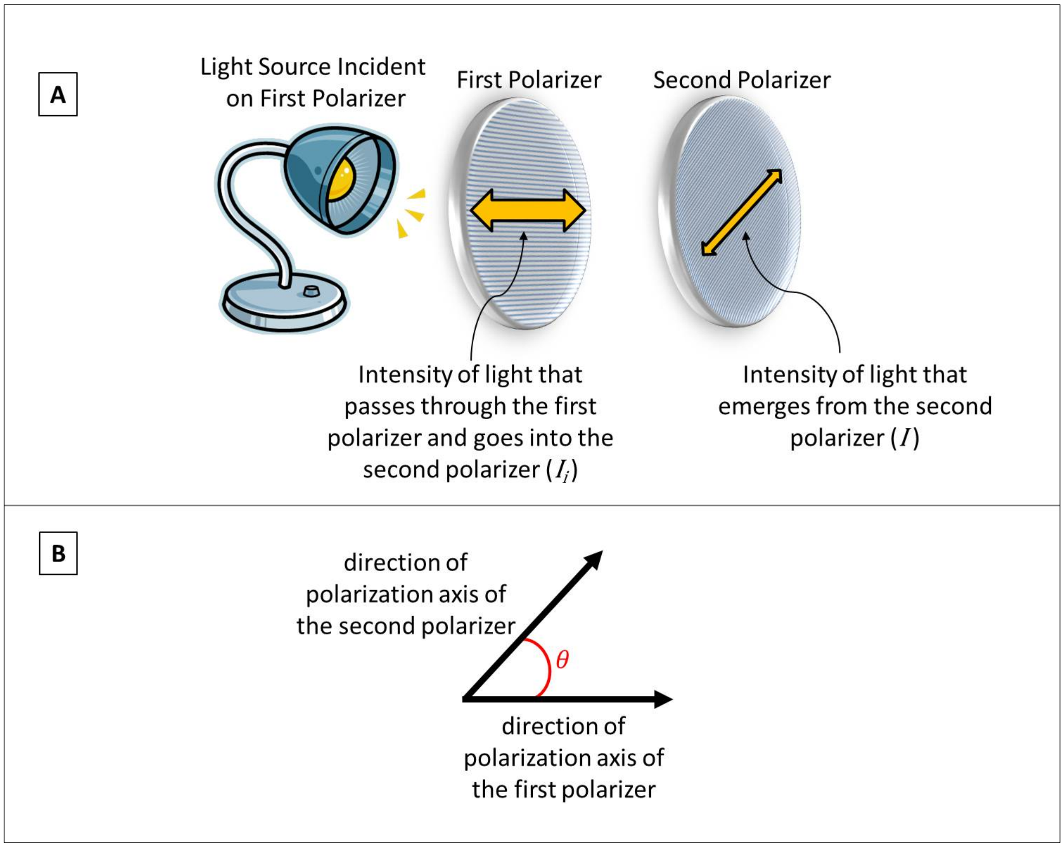

Figure 3: A) Unpolarized light from a lamp enters the first polarizer, which has a horizontal axis of polarization. The light that emerges from the first polarizer (I_i) enters the second polarizer, which is oriented at some angle θ, relative to the first polarizer. According to Malus' Law, the light that emerges from the second polarizer has some intensity I, such that $I \leq I_i$. B) The angle θ is defined as the angle between the polarization axes of the two polarizers.

Read This: Figure 4 shows a diagram of your experimental setup when the polarizers are aligned with each other ($\theta = 0$). For clarity's sake, the polarizers are oriented as having a horizontal axis of polarization, but there is nothing special about that direction.

Read This: If the source of the light is unpolarized, the electric fields are oriented along every possible direction (the only constraint is that they must be perpendicular to the direction of the wave's propagation). The first polarizer only lets the portions of the electric field through that are parallel to the axis of polarization. This becomes the incident light on the second polarizer. Since both polarizers are parallel, everything that gets through the first polarizer will also get through the second polarizer . This is consistent with Malus' Law

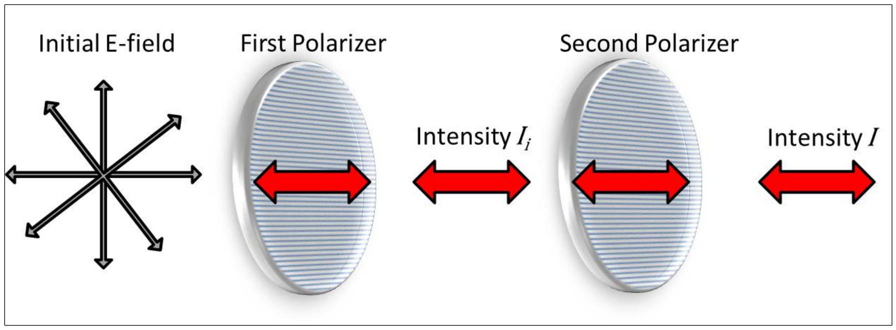

Figure 4: The electric field vectors of unpolarized light are randomly oriented before they hit the first polarizer. Only components of the electric field that are parallel to the first polarizer can pass through it. Therefore, the electric field is entirely in the horizontal direction after passing through the first horizontal polarizer. The electric field has intensity I_i here. When the electric field reaches the second polarizer, only components parallel to the axis of the second polarizer are allowed to pass through it. The light that passes through the second polarizer has a final intensity I. In this case, since both polarizers are horizontally polarized ($\theta = 0$), all of the light that passed through the first polarizer also passes through the second, so ($I = I_i \cos^2 0 = I_i$).

4.3. Draw a diagram similar to Figure 4, but this time give the second polarizer a vertical axis of polarization (θ = 90°). Assuming the incident light is still unpolarized, draw in the component of the electric field vector that gets through the first polarizer.

4.4. What percentage of the light that passed through the first polarizer will also pass through the second polarizer? Indicate this on your diagram. Does this result qualitatively match your observations?

4.5. Repeat Steps 4.2 and 4.3, this time with the second polarizer at an angle of 45° to the first polarizer. Remember that electric fields are vectors and you can always break a vector down into its components. Be sure your diagram in some way indicates where the $cos\theta$ term in Malus' Law originates. Does your diagram qualitatively match your observations?

4.6. If unpolarized light is incident on a perfect polarizer, the polarizer will always allow exactly one-half of the incident light to pass through it, regardless of the orientation of the polarizer. Explain why this happens (a picture may be of help).

5. The Strange Case of Three Polarizers

As the *coup de grâce*, you decide to show your family the effects of three polarizers. You let your brother take a look for himself and then ask him to figure out what's going on based on what he's already learned. If he can figure it out, you promise to watch *Piranhas are from Mars, Zombies are from Venus*, or whatever he said his new favorite was.

Do This: Look through the two square shaped polarizers at the unpolarized light coming from the overhead lights. These polarizers are fixed so that their axes of polarization are $\theta = 90°$ apart (this setup is referred to as crossed polarizers). Verify that they look just like your sunglasses and the round polarizer did when they were crossed.

5.1. Predict what will happen if you place the third polarizer in front of, behind, and in between the crossed polarizers. Very briefly explain why you think this will happen.

5.2. Place the round polarizer behind of the crossed polarizers (closest to your eye) and look through all three polarizers at the light. Does the amount of light transmitted to your eye look significantly different from what you saw with just two crossed polarizers? What if you rotate the round polarizer? Be sure to rotate it through a complete 180° (you may use increments of 45°).

5.3. Now place the round polarizer in front of the crossed polarizers (closest to the light) and look through all three. Describe any significant differences you see with this setup. Be sure to rotate the round polarizer.

5.4. Why did the third polarizer have the effect that it did when it was in front of or behind the crossed polarizers?

5.5. Finally, put the round polarizer between the crossed polarizers. Rotate it through 180° and describe any significant changes that you see in the intensity of light. If the intensity changes, roughly where is it a maximum and where is it a minimum?

5.6. The obvious question is *why* adding a third polarizer has the effect that it does when it's between crossed polarizers. Start by drawing a diagram similar to what you did in Section 4. For simplicity, keep the first polarizer (closest to the light source) oriented horizontally, meaning the third polarizer (closest to you eye) will have a vertical axis. Draw the middle polarizer in whatever orientation gave you the maximum intensity of light.

5.7. Draw the orientation of the electric field that passed through the first (horizontal) polarizer. Next, draw in the orientation of the electric field that passes through the middle polarizer. Finally, draw in the orientation of the electric field that passes through the last (vertical) polarizer. [Hint: remember that the electric field is a vector and therefore has components. It may help you to orient your x-axis along the horizontal polarization axis and the y-axis along the vertical polarization axis. In that case, what are the components of the middle polarizer's axis?]

5.8. For an ideal polarizer with its axis oriented 45° from the axis of the first polarizer, exactly ¼ of the light that passes through the first polarizer will make it through the last polarizer. Explain this result based on your drawing in Step 5.7.

5.9. Does Malus's law agree with what you found for three polarizers? Once again, consider the case where the outer polarizers are crossed and the middle polarizer is oriented 45° from the axis of the first polarizer. [Hint: Malus' law applies to *each pair* of polarizers. You will therefore need to consider the first and middle polarizer together and determine the intensity of light that emerges from the middle polarizer. That light then becomes the incident light on the last polarizer.]

Read This (Physics 198 only): In 1930, Paul Dirac, one of the founders of quantum mechanics, used the familiar three polarizer experiment to explain complicated new ideas in quantum mechanics. For example, each polarizer acts very much like a Stern-Gerlach (SG) device – the polarizer fixes the direction of the electric field of a photon that passes through it, while a SG device fixes the projection of an electron's spin onto one axis. A vertical polarizer will not let any horizontally polarized light through it, just as a SG(+z) device will not produce any particles with spin aligned with the negative z-axis. Both devices take a wave, which is a superposition of many states, as an input and produce just a single state as an output. Adding a second polarizer or SG device verifies this, which is just a manifestation of the Collapse Rule. When a third device is added, strange things seem to happen for both polarizers and SG devices, but this phenomena can still be explained by remembering that waves are a superposition of states.

6. Polarization and 3D Movies

True to your word, you explain a bit about 3D movies to your brother.

Read This: The polarizers used in 3D movies are very similar to those you've been studying today, except that 3D movies use circularly polarized light. Instead of the electric fields being polarized horizontally, vertically, or at some angle in between (as with the linear polarizers you looked at today), the light is polarized into a corkscrew pattern twisting clockwise or counterclockwise. Two films are actually played by special projectors at the same time – one projector shows the movie with light that is polarized in the clockwise direction and the other projector is polarized in the counterclockwise direction. The two versions of the movie are slightly offset. The 3D glasses you wear are polarized so that one eye sees only the clockwise polarized light and the other eye sees the counterclockwise polarized light. Your brain puts the two images together and *voilà* – 3D!

6.1. There is no fundamental reason why 3D movies couldn't use linear polarization – the projectors would just need to produced vertically and horizontally polarized light and you would wear the corresponding glasses. However, there is one major practical issue. What happens to the movie if you tilt your head wearing linearly polarized glasses? Explain the problem and why circularly polarized light is a solution. Use either a drawing or Malus' law to support your argument.

Head-Scratchers

Don't forget to complete the following problems. They should be at the end of your lab report. If you want to work on them during lab, start a new page in your lab notebook.

- 1.6
- 5.6
- 5.7
- 5.8
- 5.9

Appendix A: Diffraction and Interference

Huygens's Principle states that given a wave front at some initial time, subsequent wavefronts can be constructed at some later time by treating each point on the initial wavefront as the source of a circular wave that spreads out with a fixed amplitude and speed. Diffraction occurs when a wave bends around an obstacle it encounters, such as a slit, and subsequently spreads out into a circular wave according to Huygen's Principle. This will create points of constructive and destructive interference, resulting in a diffraction pattern.

When there are multiple slits, each wave not only constructively and destructively interferes with itself, as in diffraction, but also with the wavefronts from the other slits. The resulting sequence of bright and dark spots is called an interference pattern. This is true for all types of waves, including sound, water, and light waves.

The location *P* of the n^{th} point of *constructive* interference is governed by the following equation:

$$d \sin\theta = n\lambda$$

The location *P* of the n^{th} *maxima*, as measured from the central axis is given by the following equation:

$$y = D\tan\theta$$

Where: n is an integer describing the *maxima* of interest, located on a screen at point *P*; θ is the angle between the central axis ($n = 0$) and *P*; y is the distance between the central axis and *P*; D is the distance between the slit and the screen; λ is the wavelength of light; and d is the center-to-center distance between the slits (Figure 5).

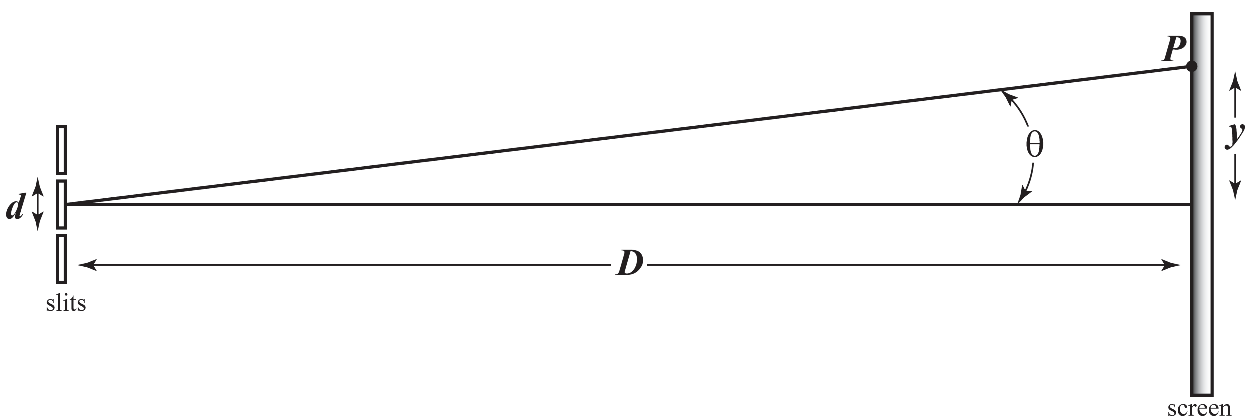

Figure 5: Young's double slit experiment

Diffraction gratings, like the ones used in this lab, can have many slits, all with the same separation d. You have to add in the extra waves at *P* from each of these extra slits, taking proper account of their phase shifts. Each new slit will add in a wave shifted in phase by δ from the one before. This makes for significantly more complicated interactions. However, the condition for constructive interference of the light from all the slits is unchanged - the interference maxima remain at the same angles as in the case of two slits. The main difference is that the maxima become narrower and narrower as the number of slits increases.

For N slits, the angular width of the maxima (θ) is given by:

$$d \sin \theta = \frac{\lambda}{N}$$

Narrow maxima are just what the doctor ordered to distinguish two almost equal wavelengths. This is why diffraction gratings with $N \geq 10{,}000$ are so useful in studying atomic and molecular spectra.

Appendix B: Double Slit Slide

All four configurations are double slits, but the separation between the two slits differs for each pattern. Use the center-to-center slit separation (printed below each pattern, in mm) as the quantity d in the formula in Appendix A. Each individual slit is 0.15 mm wide.

Our slits are very exotic, imported all the way from Germany (Guten Tag!). This means that the numbers are written in the European style, so commas are used in place of what you are used to seeing as a decimal place. Therefore, the first pair of slits has a separation of 0.25 mm, etc.

Figure 6: Slide containing four double slit patterns

Appendix C: Malus' Law

In 1808, physicist Etienne-Louis Malus was gazing through a piece of Icelandic spar, a very clear type of calcite crystal, at the sunset reflecting off the windows of the Luxemburg Palace in Paris. He noticed some very strange things happening when he rotated the crystal, a property that would eventually be understood as double diffraction. Malus' observations on that evening prompted him to explore the phenomenon further, leading to the first scientific explanation of polarization. For his troubles, Malus received the very nifty honor of being one of 72 French scientists, engineers, and mathematicians to have their names inscribed on the Eiffel tower (other names you might recognize from this semester are Ampère, Fourier, and Coulomb).

At its most basic level, Malus' Law mathematically describes how polarizers affect the light that passes through them. When unpolarized light passes through a polarizer, only components of the electric field vector parallel to the axis of polarization will get through. This is true for each polarizer, whether there is one, two, or twenty.

Let's take the relatively simple case of two polarizers. If we want to know how much light from the first polarizer will make it through the second, we can just look at what's going on with the electric fields vectors. As Figure 3 shows and Figure 7 reiterates, only components of the electric field parallel to the axis of polarization (and therefore parallel to E_2 – see Figure 7) will be able to pass through the second polarizer. However, remember that the electric field that already passed through the first polarizer (E_1) and is now incident on the second polarizer is composed of two component vectors: one parallel to E_2 and one perpendicular to E_2. These components are labelled $E_\parallel$ and $E_\perp$, respectively, in Figure 7.

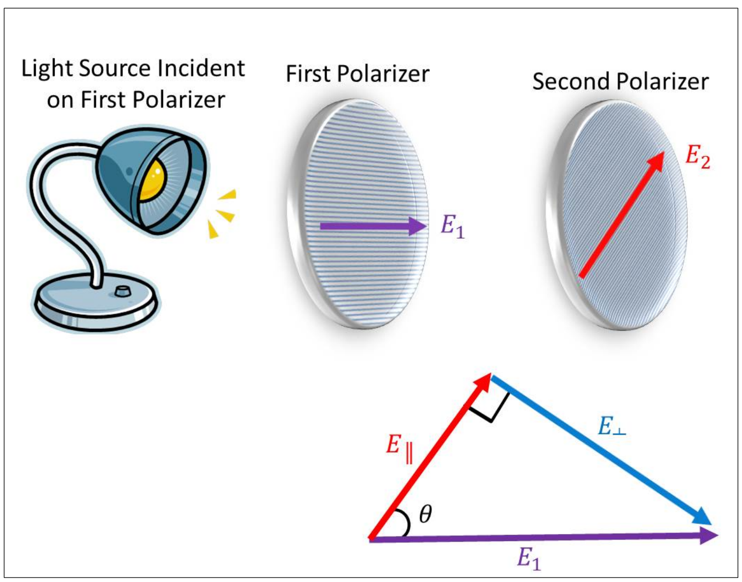

Figure 7: Components of the electric field that will pass through polarizers oriented at an angle θ with respect to one another.

Therefore, the fraction of the electric field (E) that passes through both the first and second polarizer is equal to:

$$E = E_1 \cos\theta$$

Since the intensity of light is proportional to the square of the electric field, the total intensity of light that (I) that passes through both the first and second polarizer is equal to:

$$I = E_1^2 \cos^2\theta = I_1 \cos^2\theta$$

Finally, if we generalize this equation to match the notation in Figure 3, in which the light that passes through the first polarizer and is incident on the second polarizer has the subscript i we have Malus' Law:

$$I = E_1^2 \cos^2\theta$$