CHAPTER 6: WAVE PHENOMENA

If you take two pairs of polarizing sunglasses and rotate a lens of one pair in front of a lens in the other pair, at some point you will block all light from passing through (Figure 6.1)! That won’t happen with ordinary sunglasses, but it happens with polarizing sunglasses because of the properties of polarized light. In the process of polarizing the light, the lens blocks 50% of the light that enters it. So if two polarizing lenses are used together, and both have the ability to block 50% of the light entering them, then it is possible to get the pair to block 100%.

Now even though no one has a problem with 50% and 50% adding up to 100%, our experience with sunglasses makes this simple sum seem unlikely when applied to lenses. It seems more reasonable for the second lens to just block 50% of the 50% that gets through the first lens. And … that’s exactly what conventional sunglass lenses do. You’re probably not familiar with the wave phenomenon of Polarization. Chances are that you don’t know much or anything about diffraction (another wave phenomenon) either. At this point, you do know a bit now about how waves behave. Studying wave reflection, the Doppler Effect, wave interference, and standing waves in musical instruments has given you a foundation in wave phenomena that allows you to appreciate wave-related topics. This chapter will give you a broader understanding of waves with a look at some new topics. We’ll also look at some wave phenomena that you already have some exposure to, but at a deeper and richer level. We’ll start by revisiting interference.

Revisiting Wave Interference

From observations of waves on slinkies, you already understand a little bit about wave interference, but the subject is much richer than what you’ve seen so far. When waves interfere on a slinky or in a musical instrument, you know that it’s possible to create a standing wave condition in which there are stable nodes and antinodes (see Figure 6.2). However, the presence of nodes and antinodes is not limited to one-dimensional standing waves.

When two closely spaced wave sources produce waves of the same frequency in a two-dimensional medium (like the feet of the duck in the water of Figure 6.3), the result is an interference pattern that is characterized by nodes and antinodes. The most obvious difference is that nodes and antinodes in the interference pattern are not located at points on the medium (like in the standing waves you’ve seen). The nodes and antinodes of interference patterns, are lines – hyperbolic lines. A quick glance at Figure 6.3 shows two ducks creating waves as they move through the water. A closer look shows lines in the
wave pattern (nodes) that are actually undisturbed water! Along these lines, destructive interference between the waves caused by each of the two duck feet is continuously occurring. The rippled sections in between the nodes are where the constructive interference is occurring. Antinodes like these (but caused by radio waves instead) are responsible for providing the Boeing 747 autopilot with the information it needs to land the big jet without the aid of its human counterpart. And it turns out that the spacing between the nodes and antinodes is linked to the wavelength of the wave producing the pattern. So measurements of the nodes or antinodes can be used to calculate wavelengths. In the third lab of this chapter, you will use an ordinary ruler and this principle of wave interference to measure the wavelength of light, many thousands of which would fit into the smallest division of the ruler.

Wave interference is also responsible for the colors you’ve seen in the oil on a rain-soaked roadway or in the film of a soap bubble. Those colors are due to thin film interference. In this case, the waves are light waves and the sources of the waves are the top and bottom of the film (see Figure 6.4). When light strikes a thin film, a portion of the light reflects and a portion of it enters the film. Some of the light entering the film will reflect off the bottom of the film. These two portions of the light, reflected from the top and bottom of the film interfere either constructively (to reinforce a particular color of light) or destructively (to cancel a particular color of light). In addition to producing the colors in soap bubbles and oil slicks, optical engineers can use this phenomenon to coat optical devices with thin films that will selectively reflect or transmit particular colors of light.

Your goal in the next lab, is to not only learn to recognize and interpret two-source wave interference patterns, but also to use measurements of the nodes and antinodes to calculate the wavelength of the waves producing the interference pattern.
LAB

TWO DIMENSIONAL WAVE INTERFERENCE

INTRODUCTION
Tap a stick repeatedly in the water of a pond and you get what you've always come to expect … a succession of circular waves. It makes sense, because if the energy from the stick moves in all directions at the same rate, then the shape of the wave front would geometrically have to be a circle. But try tapping two sticks simultaneously and close together and you would see something very different. You would (if you looked closely enough) see an interference pattern (Figure 6.5). The pairs of outward moving circular waves from the two sources combine (or interfere) in a pattern that is absolutely motionless and stable. The pattern consists of lines (actually pairs of hyperbola) that represent regions of either constructive interference (crests from one source meeting crests from the other source) or destructive interference (crests from one source meeting troughs from the other source). The lines where constructive interference occurs are called antinodes or maxima. The lines where destructive interference occurs are called nodes or minima.

To understand the physics of antinodes and nodes, first consider that the two sources of waves are separated by a bit. This means that when each of them is producing waves, there will be points out beyond the two sources where a wave from one source has traveled a different distance than a wave from the other. If the sources are in phase (in step with each other, producing pulses at the same time), then there will be points where the waves will no longer be in step. If at one point they are out of step by a full wavelength, then the crest of one would be in line with the trough of the other and they would cancel each other out. This would be a point of destructive interference (Figure 6.6). This would also be the case if the waves were out of step by one-and-a-half wavelengths (or any number of odd half wavelengths).

(Figure 6.6). This would also be true if the waves were out of step by two wavelengths (or any integer number of whole wavelengths). However, if the waves at one point are out of step by a half wavelength, then the crest of one would be in line with the trough of the other and they would cancel each other out. This would be a point of destructive interference (Figure 6.6). This would also be the case if the waves were out of step by one-and-a-half wavelengths (or any number of odd half wavelengths).
PURPOSE

- To recognize wave interference patterns.
- To learn to use wave interference patterns to calculate the wavelength of the waves causing the pattern.

PROCEDURE (PART 1)

1. Set up the ripple tank as shown in Figure 6.7. When the waves produced by the bobbers reach the end of the tank, they may reflect back, obscuring the interference pattern. If this happens, line the rim of the tank with paper towels to absorb the wave energy.

2. Set the wave sources at the proper distance apart and set the motor at the proper frequency so that a stable interference pattern is formed (Figures 6.5 and 6.8).

QUESTIONS

1. State the relationship between the source separation and the space between the nodes. Specifically, what happens to the distance between the nodes when the distance between the sources (bobbers) increases?

2. State the relationship between the wavelength and the space between the nodes. (Increasing the motor frequency decreases the wavelength.) Specifically, what happens to the distance between the nodes when the wavelength increases?
BACKGROUND FOR PART 2

You’ve seen that when two wave sources have the same frequency and are reasonably close together, they form a stable interference pattern. It’s possible to calculate the wavelength of the waves producing this pattern with three measurements from the interference pattern. In order to make these measurements, a point must first be labeled on one of the antinodes. The location of this point is somewhat arbitrary, but should be in the center of the antinode and as far from the sources as possible. Any antinode can be chosen. After the point on the antinode is chosen, three measurements must be made (see figure 6.9):

- \( L \) = the distance from a point midway between the sources to the point on the antinode.
- \( x \) = the distance perpendicular from the middle of the central antinode to the point on the antinode.
- \( d \) = the distance between the centers of the sources.

You also need to know the number of the antinode, \( m \), that the point is on. Antinodes are numbered from the central antinode (\( m = 0 \)), starting with \( m = 1 \). Antinodes are counted as positive when going either to the left or to the right of the central antinode. (The point in Figure 6.9 is on \( m = 2 \).) You can use \( x \) and \( L \) to calculate the angle, \( \theta \), shown in Figure 6.9. Then, to calculate the wavelength, \( \lambda \), of the wave, use the following equation:

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

The diagram on the following page represents the image of an interference pattern. Choose a point on an antinode and make measurements to calculate the wavelength of the wave producing this interference pattern. Then measure in between two of the wave crests to check your calculation.
**PROCEDURE (PART 2)**

1. Establish an interference pattern with four clear antinodes on each side of the central antinode. Don’t change motor speed. If the motor speed changes, begin Part 2 again.

2. Locate four **distant** points on four different antinodes. It’s very helpful to have two on each side of the pattern so the drawings don’t get too crowded. Use pencils and a ruler to draw lines that show all variables $d, x, L$.

3. Measure and record $d, x, L,$ and $m$ for each of the points in the data table on the next page.

4. Call me over to make a measurement of your actual wavelength.
DATA AND ANALYSIS

1. Calculate the \( \sin \theta \) for each trial using \( x \) and \( L \).
2. Calculate the wavelength for each trial as well as the average wavelength.
3. Calculate the experimental error:

<table>
<thead>
<tr>
<th>trial #</th>
<th>( m )</th>
<th>( d ) (cm)</th>
<th>( x ) (cm)</th>
<th>( L ) (cm)</th>
<th>( \sin \theta )</th>
<th>( \lambda ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
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<td>4</td>
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</tbody>
</table>

Average wavelength

Known wavelength: __________
Average exp. wavelength: __________
Percent error: __________

CALCULATIONS

<table>
<thead>
<tr>
<th>TRIAL 1</th>
<th>TRIAL 3</th>
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<tbody>
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</table>

<table>
<thead>
<tr>
<th>TRIAL 2</th>
<th>TRIAL 4</th>
</tr>
</thead>
<tbody>
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<td></td>
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</tr>
</tbody>
</table>
**CHECK YOURSELF – WAVE INTERFERENCE**

Choose the correct answer and then give an explanation below the question.

The first five questions refer to an interference pattern generated in a ripple tank by two point sources $S_1$ and $S_2$ that are in phase. The wavelength of the waves produced is $\lambda$. The distance of any point $P$ from $S_1$ is $L_1$, and from $S_2$ is $L_2$.

1. _____ A condition that must be fulfilled for “P” to be on an antinode is that the difference in distances from “P” to each of the two sources is equal to zero or:
   a. $\lambda$  
   b. $2\lambda$  
   c. $\frac{3\lambda}{2}$  
   d. $\frac{5\lambda}{2}$  
   e. “a” or “b”  
   f. “c” or “d”

2. _____ Waves from two sources are in phase and produce an interference pattern. When do waves from the two sources, arriving at the first node, have a phase difference of one-half wavelength?
   a. never  
   b. once every half cycle  
   c. once every cycle  
   d. twice every cycle  
   e. at all times

3. _____ If the wavelength of the two sources is doubled, there will be:
   a. fewer nodes  
   b. more nodes  
   c. formation of a central node

4. _____ If the sources $S_1$ and $S_2$ are put into opposite phase (one is down when the other is up):
   a. there will be no interference pattern.  
   b. there will be the formation of a central node  
   c. points satisfying the condition $L_1 - L_2 = \frac{\lambda}{2}$ will be on a node.  
   d. the interference pattern will be changing continuously.

5. _____ If the separation between the sources increases, what happens to the distance between the antinodes?
   a. it decreases.  
   b. it remains the same.  
   c. it increases.  
   d. there is not enough information to determine.

6. _____ The nodes in an interference pattern are caused by:
   a. constructive interference  
   b. destructive interference  
   c. crests from one source interfering with crests from the other source  
   d. troughs from one source interfering with troughs from the other source

7. _____ Two radio transmitters oscillate in phase and transmit radio waves of wavelength 1000 m and equal amplitudes. If $L_1$ and $L_2$ are the distance of an observer from the two radio transmitters, the observer will get the poorest reception on his radio set when he is at a point such that:
   a. $L_1 = 2000$ m; $L_2 = 2500$ m  
   b. $L_1 = 1500$ m; $L_2 = 2500$ m  
   c. $L_1 = 2000$ m; $L_2 = 3000$ m  
   d. $L_1 = 2500$ m; $L_2 = 4500$ m

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1. Sources $S_1$ and $S_2$ are in phase. Point $P$ is on the $m = 6$ antinode. Calculate the wavelength of the wave.

2. What exactly causes the first node to the left (or right) of the central antinode to occur where it does?

3. What exactly causes the third antinode to the left (or right) of the central antinode to occur where it does?

4. Find the wavelength for an interference pattern from point sources 2.3 cm apart where a point on the first maximum is 2.4 cm from the central maximum, and 5.4 cm from the midpoint of the sources.

5. Two radio antennas simultaneously transmit signals of the same wavelength and in phase. A radio in a car receives the signals. If the car is at the second maximum of the interference pattern produced what is the wavelength of the signals? Refer to the drawing on the right.

6. In a sound interference pattern, the first node is located at 10° from the central antinode. What is the pitch of the sound wave?
LABETTE

WAVE DIFFRACTION

INTRODUCTION

If you’re in one room and you want to say something to a friend in another room nearby, you can just call out. He would probably hear you. Part of the reason for this is that the sound waves you produce get reflected by various surfaces in the rooms between you and your friend. But if these surfaces were all modified to be anechoic (non-reflective for sound waves), you would probably still be heard. This is because, in addition to reflecting from surfaces, sound waves will also bend around barriers and corners. Wave bending, or diffraction, is nice if you want to get hold of someone in another room, but it is also the cause of resolution problems in optical devices. The bending of light waves as they pass through the lenses of microscopes and telescopes causes images to blur and can cause two closely spaced images to merge, as though they were one – not good if you are an astronomer trying to distinguish between the two stars in a binary star system. In this lab you will investigate the factors that contribute to wave diffraction as well as deciding what must be done to minimize or maximize the effect.

PURPOSE

• To recognize wave diffraction patterns.
• To learn how to minimize and maximize wave diffraction.

PROCEDURE (PART 1)

Begin with a long aluminum barrier about 10 cm from the plane wave generator, and generate waves with wavelengths of about 3 cm. Look for evidence of a shadow (a region of no wave movement) behind the barrier. Next, change the wavelength (by using the frequency knob) and note the difference in the pattern behind the barrier when the wavelength is much smaller or much larger than the original wavelength. Draw the pattern you see for both large and small wavelengths below.

QUESTIONS

1. What condition is necessary for maximum diffraction (smallest shadow) beyond a barrier?

2. Why are FM radio stations so much harder to pick up than AM radio stations in the mountains (FM radio frequencies are in megahertz and AM radio frequencies are in kilohertz)?
PROCEDURE (PART 2)
Now set up the two aluminum barriers parallel to the ripple generator leaving a small opening (~4 cm) between them. Leave the size of the opening fixed and vary the size of the wavelength. Draw your observations carefully below. Be patient, this can be a bit difficult to see clearly, but it’s very important!

![Diagram of large wavelength and small wavelength](image)

Finally, leave the size of the wavelength fixed (~3 cm) and vary the size of the opening. Again, draw your observations carefully below.

![Diagram of large opening and small opening](image)
**QUESTIONS**

1. You’ve looked at how diffraction changes when the wavelength ($\lambda$) of the wave changes and when the size of the opening ($d$) the wave is passing through changes. How is the ratio of these two measurements, $\frac{\lambda}{d}$, related to the degree of diffraction? That is, when the ratio is large, is the degree of diffraction larger or smaller?

2. Light does not appear to diffract under normal conditions.
   a. Does this preclude it from being a wave? Why or why not?
   
   b. Propose an experiment to observe its diffraction. That is, what would the equipment need to be like to observe the bending of light as it goes through an opening?
LAB

LIGHT DIFFRACTION AND INTERFERENCE

INTRODUCTION

Isaac Newton was brilliant. It is said that he went from having a basic knowledge of college freshman math to being the most brilliant mathematician in the world in ... two years, and ... self-taught! In addition to his primary investigations of the physics of motion (three Laws of Motion and his development of the Universal Law of Gravity), he also investigated the physics of light. He believed there was adequate evidence to claim that the composition of light was that of particles (corpuscles, he called them) rather than waves – and so it was accepted. Well, not by everybody. Over a century later, Thomas Young, a physicist and a physician had a brilliant idea to absolutely solve the problem of the true nature of light. He figured that if light were a wave, then two identical sources of light, placed closely enough together, would have to form an interference pattern. The nodes, in this case, would be dark regions where the light from one source cancelled the light from the other source. So he brought a thin sliver of light up to a card with two holes spaced very closely together and then let the resulting light fall on a distant screen. Oh it must have been a glorious day and I know that he must have wished that Newton was still alive to see the very simple experiment that disproved Newton’s theory of light. Well, maybe Young didn’t have that kind of “rub your nose in it” personality, but I’m sure he was beside himself with excitement when he saw the alternating bright and dark spots on the screen onto which the light fell. And, I know that his immediate inclination was to calculate the wavelength of the light from the geometry of the interference pattern. You’ll do the same in this recreation of one of the most important experiments in historical optics. However, before the actual measuring of the wavelength of light, you will do a qualitative investigation of the diffraction and interference of light as it passes through single and multiple slits. At the conclusion of the qualitative portion, you should be able to predict how the diffraction and interference patterns change when any of the following conditions changes:

• The width of the openings changes.
• The distance between the openings changes.
• The number of openings changes.
• The wavelength of light used changes.

PURPOSE

• To qualitatively investigate the physics of single slit diffraction and multiple slit interference.
• To use the physics of wave interference patterns to calculate the wavelength of light.

Figure 6.11: Thomas Young’s visualization of two sources of light waves (A and B) interfering and causing characteristic antinodes (bright regions) and nodes (dark regions).
**INFORMATION**
Throughout this lab you will be viewing monochromatic (one color) light through a glass slide that has a variety of different openings. The diffraction or interference patterns will be projected onto your retina. Figure 6.12 shows the proper orientation to hold the slide as well as a legend that describes each of the types of openings.

![Image of diffraction patterns](image)

<table>
<thead>
<tr>
<th>Column A</th>
<th>Single slits going from wider to narrower.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column B</td>
<td>Top half is a double slit with increasing distance between slits. Bottom half is a single slit with decreasing width.</td>
</tr>
<tr>
<td>Column C</td>
<td>Multiple slits with different distances between slits.</td>
</tr>
<tr>
<td>Column D</td>
<td>1, 2, 3, 4, and 10 slits, all the same distance apart.</td>
</tr>
<tr>
<td>Column E</td>
<td>A single slit followed by double slits of the same thickness, but increasing distance apart</td>
</tr>
</tbody>
</table>

Figure 6.12: Interference/diffraction grating legend
PART 1: A QUALITATIVE INVESTIGATION OF SINGLE SLIT DIFFRACTION AND MULTIPLE SLIT INTERFERENCE
Throughout this part of the lab, you will be looking at light coming from a vertically oriented filament in an unfrosted light bulb. Place a red filter over whichever opening you use in order to make the light monochromatic.

1. **Single slits**: Look through opening A5. This is the narrowest single slit. Draw a careful diagram of the single slit diffraction pattern you see in the space below.

2. Now look alternately through openings A5 and A3. What are the similarities and differences in the patterns you see? What is the primary effect on the diffraction pattern when the slit is wider?

3. **Double slits**: Look through opening E2. This is the narrowest distance between two slits. Draw a careful diagram of the double slit interference pattern you see in the space below.

4. Now look alternately through openings E2 and E4. What are the similarities and differences in the patterns you see? What is the primary effect on the interference pattern when the distance between the slits is wider?

5. Compare the single slit diffraction pattern of A5 with the double slit pattern of E2. What are the similarities? What are the differences?

6. Now look through opening D2 and then through opening D5. D2 is a double slit. D5 consists of 10 slits, but they are all the same distance apart as the two in opening D2. What is the effect of changing the opening from a double slit to one with multiple slits?

7. Finally, look through opening C3. This opening has 80 very closely spaced slits. Then replace the red color filter with a green filter and look again through opening C3. The green light has a wavelength that is smaller than that of the red light. What is the effect of using a smaller wavelength on the resulting interference pattern?
PART 2: A CALCULATION OF THE WAVELENGTH OF LIGHT

1. Look at the light bulb through opening C3. You should see consecutive color spectrums. These are the antinodes of a visible light wave interference pattern.

2. Now place the red color filter over the same opening. You should now see a series of bright red antinodes (Figure 6.13).

3. Place the slide on the edge of the lab table and while one partner is viewing the interference pattern have the other partner place two light colored pencils or pens in line with the central antinode (the light bulb filament) and an antinode on either side of the light bulb filament (see Figure 6.14).
   - The antinode chosen should be as far away from the central antinode as possible.
   - Place the pencils slightly behind the light bulb so that the light shines on them.
   - When looking at the pencils through the slide you will notice there are three images of each pencil. Choose the center image as your marker (the other two are diffracted images of the actual pencil).
   - Note the order of the maxima that you have chosen

4. Measure $L$ from the slide to the pencil marking the non-central antinode (Figure 6.15).

5. Measure the distance between the pencils, $x$. This measurement is notoriously prone to experimental error so you should trade places with your partner to make sure you both get the same values.

6. Do two more trials with the red light.

7. Repeat the instructions above for green light.
DATA

<table>
<thead>
<tr>
<th>Color</th>
<th>(L) (m)</th>
<th>(x) (m)</th>
<th>(\sin \theta)</th>
<th>(m)</th>
<th>(\lambda) (m)</th>
<th>(\lambda) average (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td></td>
<td></td>
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<tr>
<td>Green</td>
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</table>

CALCULATIONS (SHOW ALL WORK)

(Note that the distance “d” between slits in the opening C3 is \(3.26 \times 10^{-3}\) cm).

1. Calculate the wavelengths for:
   a. red light

The conventional unit for wavelength is the nanometer (nm). \(1\ \text{nm} = 1 \times 10^{-9}\ \text{m}\). Express your average wavelengths in nanometers.
2. Which color of light is seen closest to the central antinode? Why?

3. What is the necessary condition for the path-length difference between two waves that interfere:
   a. constructively
   b. destructively?

4. For which part of the electromagnetic spectrum would a picket fence (with space between the pickets about 10 cm) make a good diffraction grating? Explain why. (You may want to look up the wavelengths of various waves in the electromagnetic spectrum.)

5. (Honors Physics only) Ask me which of your wavelength calculations is the most accurate. Then use this color and your calculated wavelength to calculate the number of openings in the pattern directly above the center pattern on the slide. Note that the patterns all have the same width and the number of openings in each pattern is a multiple of five.

Thomas Young (1773-1829)

You could call Thomas Young a quick learner – he learned to read at age two. He had a keen interest in mathematics, foreign languages, and of course, physics. He made significant contributions to each of these fields during his lifetime.

As a medical doctor in London, Young turned his focus to optics and light. Working with fellow physicist Hermann von Helmholtz, Young published a fundamental theory of color, which is now called the Young-Helmholtz Theory. The theory is based on the assumption that there are three major color sensations – red, green, and blue, and likewise three different groups of cones in the retina. Other colors are seen when the cone cells are stimulated in different combinations.

Continuing his study of optics, Young considered the nature of light. He developed the double slit experiment to prove the wave theory of light. He used his new wave theory to explain the colors of thin films (like bubbles) and calculated the wavelengths of the seven colors recognized by Newton. His wave theory also explained why light waves are transverse, rather than longitudinal as once thought.

After his work on optics, Young returned to the study of languages, with a particular interest in Egyptology. He studied the Rosetta Stone and succeeded in providing a nearly perfect translation. This was a major contribution in deciphering the ancient Egyptian language.

(Biography by Alex Altman, Class of 2005)
1. Two slits are 0.010 cm apart. Monochromatic light is directed through the slits. The 3rd order (m = 3) bright lines are 12.5 mm apart are seen 0.40 m from the slits. What is the wavelength and color of the light?

2. Red light, having a wavelength of 650 nm is directed through two slits separated by 0.0330 mm. The distance from the slits to a wall where the interference pattern is formed is 2.35 m. What is the distance between the two 2nd order bright lines?

3. Monochromatic light passing through two slits separated by 0.012 cm falls on a screen 2.0 m away, producing the pattern to the right. What is the wavelength of the light?

4. If the light used in the problem above is directed through a different pair of slits, the pattern to the right forms on the same screen 2.0 m away. What is the distance between this pair of slits?
THIN FILM INTERFERENCE

THIN FILM INTERFERENCE is responsible for the colors seen in the thin film of oil on a wet parking lot, or in the pastel colors seen when viewing a soap bubble in strong light. Optical engineers have long used this wave phenomenon to coat optical devices with thin films that will selectively reflect or transmit particular colors of light. Thin film interference is exactly what the name implies. It is classic two-source interference, except that the sources producing the waves are not bobbers in water, or slits allowing light through, but the top and bottom of the film that light is passing through. Let’s use the example of the thin film of oil on the water of the parking lot. As light strikes the top surface of the oil, some of the light will reflect off this top surface and some of the light will refract into the oil film. The light refracting into the oil will encounter the bottom of the film, where a portion of it will reflect. The reflected light from the bottom of the film can now rejoin the reflected light from the top of the film. So the original light coming down to the film has been converted into two separate beams; the interference occurs between these two beams. The beam reflecting off the bottom of the film travels a greater distance as it approaches your eyes, so now it’s out of step with the light reflecting from the top of the film. The amount that it’s out of step depends on how thick the film is. For light striking the film in a direction parallel to the normal, the two “sources” of light are out of step by twice the thickness of the film (one for the path down into the film and one for the reflected path up through the film). Now, since different colors of light have different wavelengths, if the two reflections of light are out of step they will be out of step differently for different colors. For example, if the film thickness is just right to give constructive interference for red light, at that point in the film you would see red. If the film thickness is just right to cause destructive interference for green light you would see the absence of green (magenta) in that part of the film.

This is the essence of thin film interference. However, it is more complicated than this. The interference also depends on the relative refractive indices at each of the two surfaces. That effect probably isn’t as obvious as the difference in path length due to film thickness. Recall, the type of reflection at the boundary of two wave media (inverted or upright) depends on the relative rigidity of the new medium. In the case of light reflecting at the boundary between two transparent substances, the index of refraction determines the rigidity. When light travels from a lower to a higher index of refraction, there is an inverted reflection (see Figure 6.17). So a wave crest would be reflected as a trough, creating a phase shift of one-half wavelength. Now if the light encounters a higher index of refraction at both the top and the bottom of the film, then both waves experience a phase shift and there is therefore no relative shift (they’ve both changed by one half wavelength). Encounters with a lower index of refraction produce an upright reflection (crests reflect as crests) and therefore, no phase shift. So the only time these reflections become an issue is when one is phase shifted and the other is not.
Now we're almost ready to predict what color a particular film will preferentially reflect (or restrict from reflecting). Perhaps the desire might be to calculate the proper thickness for a film to have in order to reflect a particular color. There are varieties of equations that will do the work for you, but it is best to approach this conceptually:

1. Find phase difference due only to types of reflections at each surface. (See Figure 6.17)

   Look at the relative indices of reflection at each of the surfaces. If the change is from lower to higher index of refraction at both surfaces, or from higher to lower index of refraction at both surfaces then move on – there will be no relative phase shift due to reflections. Any change in path length for the two beams of light will have to come from the film thickness alone. If, however, there is a change from higher to lower index of refraction at the top surface and the opposite at the bottom surface or a change from lower to higher index of refraction at the top surface and the opposite at the bottom surface, then there will be a one-half wavelength phase change between the two beams. You must keep this information in mind for later.

2. Determine wavelength of light within the film.

   This was not mentioned before, but, because of refraction, the wavelength the light has in empty space is not the wavelength it will have within the film. Thus, the calculation for film thickness must account for this issue. To calculate the wavelength within the film, consider that on each side of the film boundary, the frequency of the light must be the same:

   \[
   f_{\text{vacuum}} = f_{\text{film}} \Rightarrow \frac{v_{\text{vacuum}}}{\lambda_{\text{vacuum}}} = \frac{v_{\text{film}}}{\lambda_{\text{film}}}
   \]

   \[
   \Rightarrow \lambda_{\text{film}} = \lambda_{\text{vacuum}} \frac{v_{\text{film}}}{v_{\text{vacuum}}} = \frac{v_{\text{film}}}{c} = \lambda_{\text{vacuum}} \frac{1}{n} = \frac{\lambda_{\text{vacuum}}}{n}
   \]
3. Decide film thickness based on the desire for constructive or destructive interference.

This is the most deductive part of the whole calculation. Make sure it makes sense.

a. If the idea is to see a particular color in a thin film, then there must be constructive interference for that particular color. You want the phase shift between the two beams to be a whole wavelength (actually any number of whole wavelengths). If there has already been a phase shift due to types of reflections, then the extra path length taken by the beam inside the film must be a half wavelength, meaning that the film thickness must be a half wavelength (because the light must go down to the bottom of the film and then back up again). If there has not been a phase shift due to reflections, then the extra path length taken by the beam inside the film must be a whole wavelength, meaning that the film thickness must be a half wavelength.

b. If the idea is to see the absence of a particular color in a thin film, then there must be destructive interference for that particular color. You want the phase shift between the two beams to be a half wavelength (actually any odd number of odd half wavelengths). If there has already been a phase shift due to types of reflections, then the extra path length taken by the beam inside the film must be a whole wavelength, meaning that the film thickness must be a half wavelength. If there has not been a phase shift due to reflections, then the extra path length taken by the beam inside the film must be a half wavelength, meaning that the film thickness must be a quarter wavelength.

Example

Light falls on a film of gasoline (n = 1.40) that is floating on a puddle of water (n = 1.33). Find the minimum thickness of the film in a spot that looks red (λ = 630 nm)?

Solution:

• Identify all givens (explicit and implicit) and label with the proper symbol.
  - It doesn’t say what medium the light is coming from as it passes into the oil, so we must assume that medium is air (n₁ = 1.0)
  - The thin film is the gasoline (n₂ = 1.40)
  - The oil floats on water (n₃ = 1.33)
  - The wavelength of light in the air = \( \lambda_{\text{air}} = \lambda_{\text{vacuum}} = 630 \text{ nm} \)
• Determine what you’re trying to find.
  The sense of “spot that looks red” suggests that you’re looking for film thickness that produces constructive interference for red light.
• Use the three-step process to find the film thickness.
  1. Find phase difference due only to types of reflections at each surface.

At the top surface the light goes from \( n = 1.0 \) to \( n = 1.40 \). At the bottom surface the light goes from \( n = 1.40 \) to \( n = 1.33 \). Since the transitions are opposite (lower \( n \) to higher \( n \) followed by higher \( n \) to lower \( n \)) there is a one-half wavelength phase shift due only to the types of reflection.

2. Determine wavelength of light within the film.

\[ \lambda_{\text{film}} = \frac{\lambda_{\text{vacuum}}}{n} = \frac{630\text{ nm}}{1.40} = 451\text{ nm} \]

3. Decide film thickness based on the desire for constructive or destructive interference.

The desire is for constructive interference, meaning the two waves are out of phase by one full wavelength. Since the different reflections have the two waves already out of phase by one-half wavelength, the one that travels through the film must travel an additional extra half wavelength. This is possible if the film thickness is one-quarter wavelength.

\[ \text{film thickness} = \frac{\lambda_{\text{film}}}{4} = \frac{451\text{ nm}}{4} = 113\text{ nm} \]
QUESTIONs AND PROBLEMS
THIN FILM INTERFERENCE

1. A soapy water film \((n = 1.33)\) is in a plastic loop out in the sun. A portion of the film reflects all but the green light \((\lambda = 550 \text{ nm})\). What is the minimum thickness of the film in that portion?

2. A plastic thin film \((n = 1.37)\) with a thickness of 212 nm is placed on the lenses of a pair of sunglasses. If you looked at someone wearing these sunglasses in full sunlight, what color would the lenses be?

3. If you take the wand of a soap bubble maker and hold it so that the plane of the soapy water is vertical, there are colored bands containing each color of the spectrum from violet through red. Then they repeat themselves several times until the bottom of the soapy water in the wand. Explain the occurrence of the colored bands as well as why they repeat themselves.

4. If the wand in the previous question is held vertically for a long enough period of time, the color disappears from the bands at the top of the wand and then finally the film breaks. Explain the disappearance of the colors at the top of the wand.
5. A soap film is deposited on the surface of some glass (n = 1.50). A portion of it appears red ($\lambda = 6.00 \times 10^{-5}$ cm in a vacuum) when viewed from a right angle in white light. Determine the smallest non-zero thickness for that portion of the soap film if its index of refraction is 1.40.

6. How thick should be the coating of a material with an index of refraction of 1.35 on a piece of flat glass (n = 1.55) if you want it to be an anti-reflection coating for blue light ($\lambda = 450$ nm)?

7. A transparent film (n = 1.40) with a thickness of $1.10 \times 10^{-7}$ m is deposited on a glass lens (n = 1.55) to form a non-reflecting coating. What is the wavelength of light (in vacuum) for which this film has been designed?

8. A certain transparent substance has an index of refraction of 1.35. What is the thinnest film coating of this substance on glass (n = 1.50) for which destructive interference of green light (500 nm) can take place by reflection? The glass and film are in air.
Polarized Light

Take a trip to the sunglass store and you’ll see an array of sunglasses ranging from barely tinted to so dark that no one could ever see your eyes behind the lenses. There are mirrored and colored lenses, UV-blocking lenses and … polarizing lenses. These are the most misunderstood types of sunglasses. You can’t get especially dark or light ones. These lenses always block exactly 50% of incoming light. This is due to the phenomenon of wave polarization. If you take two sets of polarizing lenses, one right in front of the other, and then rotate one pair by 90° you will block 100% of the incoming light (see Figure 6.21)!

The ability of two polarizing sunglass lenses to block 100% of the light striking them gives further evidence that sound does not have a monopoly on interesting wave behavior. The fact that light can be polarized means that it is not only a wave, but it must be transverse. Polarized light provides the technology for those realistic 3-d movies and it means that sunglasses can be produced to allow the transmission of 50% of normal light, but 0% of the light reflected from surfaces that causes glare. Finally, it gives the person with no artistic talent the opportunity to create beautiful art. Or perhaps it simply pushes the definition of what art is and who is the artist to a new and broader realm. The “art” produced with polarized light is compelling enough to force us to reckon with the question of whether art is a function of the artist, the artist and the medium, or perhaps … just the medium?

Conventional light (from a light bulb candle, or the Sun) is unpolarized. It’s like the light coming off the surface of this page. Light is a transverse wave, so if you could see the actual wave trains, they would look like a rope being shaken to make a transverse wave. Looking sideways at the wave would look like this:

This wave is moving to the right, but if you rotated it 90° so that it was coming out of the paper toward you, it would look like this:

Notice that the plane of vibration is vertical. Naturally occurring light is made up of waves that have random planes of vibration. This type of light is called unpolarized. A beam of unpolarized light coming out of the paper toward you can be visualized like this:

Figure 6.18: Unpolarized light is made up of transverse waves that vibrate in more than one plane of polarization.

If the vibration is in only one plane, the light is called polarized. A beam of polarized light coming out of the paper toward you might look like one of these:

Figure 6.19: Polarized light is made up of transverse waves that vibrate in only one plane of polarization.

For the remainder of this discussion, imagine the unpolarized light as having two planes of vibration (vertical and horizontal) and moving to the right across the page. The arrow represents the vertical plane of vibration and the dot represents the the horizontal plane of vibration.

There are three methods to polarize light: by Selective Absorption, by Reflection, and by Double Refraction (also known as Birefringence).
POLARIZATION BY
SELECTIVE ABSORPTION

Selective absorption is what polarizing sunglasses do. A selective absorber is a transparent material in which long organic molecules have been stretched out, all in the same direction. Light vibrating in the direction of the stretch is absorbed and turned to heat. The remaining 50% of the light, all vibrating perpendicular to the plane of the stretched molecules, passes through the absorber, yielding a polarized beam (see Figure 6.20).

Figure 6.21 shows two polarizing sunglass lenses, each with their selective absorbing directions rotated 90° with respect to the other. Selective absorbers absorb all the light vibrating in one plane of vibration and allow all the light to pass through if it vibrates in a plane rotated by 90°. This is how two polarizing sunglass lenses rotated at 90° relative to each other can block all light incident on them.

The special glasses you have to wear to see the 3-d effect at 3-d movies are selective absorbers. However, unlike sunglasses that use selective absorbers, these 3-d movie glasses have the two lenses rotated at 90° with respect to each other. When you put them on and watch the movie, you’re actually watching two movies being projected at the same time, with the images overlapping each other. Each of the movie projectors projects polarized light, but the planes of vibration for each beam are rotated at 90°. This way, the light from each movie goes into only one eye. When the films are made, the shots are taken from a slightly different perspective. It’s just like when you view anything with both eyes open. Each eye sees its own slightly different perspective, allowing you to perceive the three dimensionality of whatever you look at. The 3-d glasses give you the same effect because each eye sees its own movie, from a different perspective.

Figure 6.20: A selective absorber is a transparent material in which long organic molecules have been stretched out, all in the same direction. Light vibrating in the direction of the stretch is absorbed and turned to heat. The remaining 50% of the light, all vibrating perpendicular to the plane of the stretched molecules, passes through the absorber.

Figure 6.21: Selective absorbers absorb all the light vibrating in one plane of vibration and allow all the light to pass through if it vibrates in a plane rotated by 90°. This is how two polarizing sunglass lenses (selective absorbers) rotated at 90° relative to each other can block all light incident on them.
**POLARIZATION BY REFLECTION**

Polarization by reflection occurs naturally when light strikes any surface. The light vibrating horizontally tends to be reflected from the surface and the light vibrating vertically tends to be refracted into the surface. This is usually only a partial polarization though. However, the reflected and refracted rays are completely polarized if the angle between them is 90°. This occurs perfectly when the angle of incidence is at what is called Brewster’s angle (see Figure 6.22).

This natural polarization is why polarizing sunglasses are so effective at blocking glare. Glare light is light that is reflecting off some surface, like a still lake or the trunk lid of the car in front of you. Now since this glare light has been anywhere from partially to fully polarized, and its plane of vibration is horizontal, then a pair of polarizing sunglasses can be especially effective at blocking this light. As long as the lenses are oriented to absorb all light vibrating in a horizontal plane, up to 100% of the glare light will be taken out. Figure 6.23 illustrates this phenomenon.

You can tell if a pair of sunglasses is truly polarizing by simply tilting your head as you look at a surface. The amount of light coming through conventional sunglasses will be the same in any orientation, but if the lenses are polarizing, then you will get a strong change in intensity if you rotate your head by 90°.

Figure 6.22: Polarization by reflection occurs naturally when light strikes any surface. The light vibrating horizontally tends to be reflected from the surface and the light vibrating vertically tends to be refracted into the surface. This polarization is 100% when the angle between the reflected and refracted rays is 90°. This occurs when the angle of incidence is at “Brewster’s angle.”

Figure 6.23: The effectiveness of blocking glare light using polarizing lenses.

Light reflects off a surface, causing a glare. However, the glare consists of rays primarily polarized horizontally. The polarizing sunglasses have their orientation set to block rays polarized horizontally, thus blocking nearly all the glare. The polarizing sunglasses oriented in the opposite direction now block hardly any of the glare. This is how it would appear if you walked with your head tilted 90°.
**POLARIZATION BY DOUBLE REFRACTION**

Polarization by **double refraction** occurs naturally in some crystals (like calcite). The double refracting substance has two different indices of refraction, one for the light with a vertical plane of vibration and another for the light with a horizontal plane of vibration. This causes an incident beam of light to separate into two separate and polarized refracted beams of light (see Figure 6.24).

You know that when two selective absorbers are oriented at 90° with respect to each other, all light is blocked. An interesting property of double refractors is that when they are placed in between two such selective absorbers, light is able to pass through in the area where the double refractor is located. This becomes a useful way to identify double refractors, especially for substances that are not natural double refracting.

Some materials (many plastics) will become double refracting if their structure is stressed. This can be used to analyze the structural weaknesses in a proposed building, bridge, or car if a scale model of the structure is constructed and then placed under various types of stress (see Figure 6.25). If the scale model is viewed while in between two 90° oriented selective absorbers, not only will light pass through, but the points of greatest stress will be prominent and produce *Interference Colors*. These interference colors are more than useful. Many artists have seized the opportunity to exploit the beauty of these interference colors, which can be quite compelling.

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*Figure 6.24: Polarization by double refraction occurs naturally in some crystals (like calcite). The double refracting substance has two different indices of refraction, one for the light with a vertical plane of vibration and another for the light with a horizontal plane of vibration. This causes an incident beam of light to separate into two separate and polarized refracted beams of light.*

*Figure 6.25: Two selective absorbers have their absorption axes rotated at 90° relative to each other. This blocks all light from passing through except where the broken pieces of protractor are located. This property of double refractors is useful for analyzing structural stress. (Photo by Charlotte Simmonds, Class of 2006).*