Chapter 24

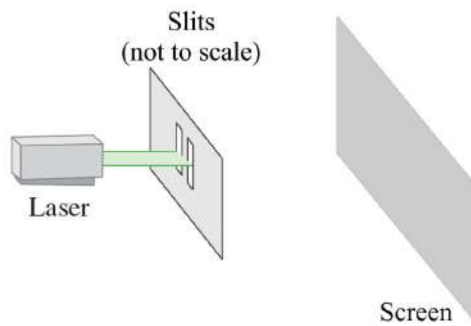
Wave Optics

24.1 Young's double slit experiment

24.1.1 Observe and explain

PIVOTAL ***Lab or class:*** *Equipment:* a plate with two closely-positioned very narrow slits, a laser pointer, a white screen.

a. Shine the laser beam at the slits so that light passing through the slits reaches the screen (see the figure on the right).



b. Draw a careful sketch of what you observe on the screen. Can your observation be explained using the particle-bullet model of light? The wave model of light?

c. Use Huygens' principle that you learned in Chapter 11 to explain the pattern on the screen.

24.1.2 Explain

PIVOTAL ***Class or lab***

In Activity 24.1.1, instead of seeing two thin bright lines (the images of the slits), you saw closely-spaced alternating bright and dark narrow bands of light—a bright band at the center with several less-bright bands on the sides. Why were there dark areas between bright areas? *Hint:* Is it possible for two bullets to arrive at the same location and cancel each other? Is it possible for two waves to arrive at the same location and cancel each other?

24.1.3 Reason and explain

***PIVOTAL* Class:** *Equipment per group:* whiteboard and markers.

Waves (of any type) are incident from the left side on a barrier with two small openings. Consider what happens on the right side of the barrier. According to Huygens' principle, these openings become wave sources. In the figure below, we represent the wave fronts leaving these sources with black and grey circles. The solid black lines represent wave crests, and the lighter gray lines represent the troughs beyond the slits at one instant of time.

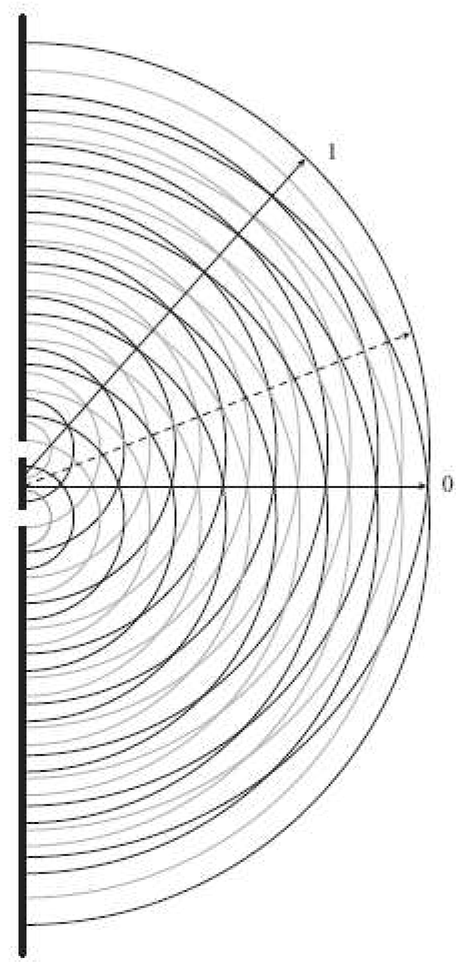
a. Describe what the crests might represent for each of the following types of waves: water waves, sound waves.

b. Indicate with the letters "dc" (double crest) places on line 0 that are equal distance from the wave sources (the openings) and where the crests add to form a disturbance that is twice as big as the wave amplitude from one source.

c. Indicate with the letters "dt" (double trough) places on line 0 that are equal distance from the sources and where the wave troughs add to form a negative disturbance whose magnitude is twice the amplitude of a wave trough from one source.

d. The sketch represents the positions of wave crests and troughs at one particular time. Suppose that these are water waves that are now propagating and that you stand in the water on the right side of line 0. What would it feel like as the alternating dc and dt points passed you?

e. What if the sketch represents sound waves that are now moving along the line described in part **d**. What would you hear?



f. What if these were light waves moving along the line described in part **d**. Would the light be bright or dim? Explain.

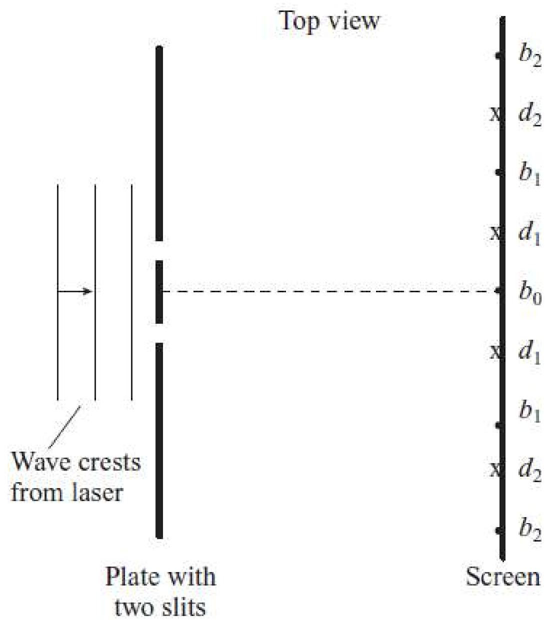
g. Would the same effect be observed along line 1 as along line 0? Explain.

h. What would you feel (water waves), hear (sound waves), or see (light waves) if you were located at the end of the dashed line between 0 and 1? Explain.

24.1.4 Reason and explain

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

In Activity 24.1.1, the light and dark bands produced on the wall by laser light passing through two narrow slits can be explained using the wave model of light. Consider the wave model and the two-slit phenomenon. Shine the light from a laser pointer onto two closely spaced slits. On a screen several meters to the right of the slits, you observe bright light bands at the positions of the dots shown in the figure below (b_0 at the center, and b_1 and b_2 bands at each side of the center). You see darkness, which we call dark bands, at the positions of the crosses (the d_1 and d_2 bands at each side of the center). *Note:* The separation of the bright and dark bands on the screen is exaggerated in this sketch.



a. Use Huygens' principle to explain why we can assume that the two slits are wave sources and the waves produced by them vibrate synchronously (they are said to be *in phase*).

b. Use the wave model of light to answer the questions below. Think about the distances from the two slits to a bright band or a dark band and about superposition of the waves coming from the two slits.

• Explain why the center b_0 band is bright.

• Explain why b_1 above the center bright band is bright.

• Explain why d_1 above the center bright band is dark.

• Explain why b_2 above the center bright band is bright.

• Explain why d_2 above the center bright band is dark.

24.1.5 Represent and reason

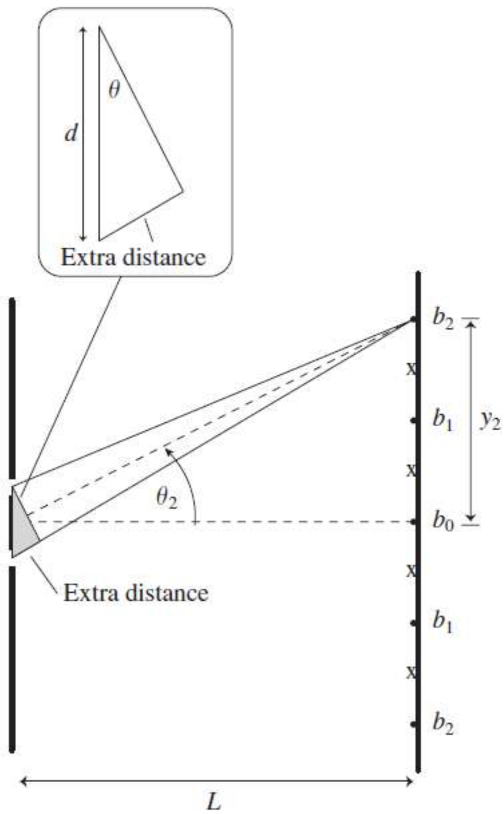
PIVOTAL ***Class:*** *Equipment per group:* whiteboard and markers.

Imagine that you shine a laser at a screen with two very narrow, closely-spaced slits, as in Activity 24.1.4. These two slits can be considered sources of light wavelets of the same wavelength vibrating in phase—produced by the same wave front arriving at the slits from the left. The figure below shows lines going from each of two slits to the second bright band (b_2) above the central bright band (b_0) on a screen. Dots represent the bright spots, and crosses represent dark spots.

a. Compare the extra distance that light travels from the lower slit to the b_2 bright band and the distance from the upper slit to that bright band. Express this difference in wavelengths of light. Remember that this is the second bright band.

b. How is the angle θ (shown in the inset) related to the angle θ_2 shown in the main part of the figure? Explain.

c. Refer to the triangle inset in the figure and to the results of Activity 24.1.4 to help you write an expression that relates the extra distance that light travels from the lower slit to the b_2 bright band and the distance from the upper slit to that bright band expressed through the wavelength λ, slit separation *d*, and the angle θ in the triangle. Here you need to make an important assumption/approximation that the triangle in the inset is a right triangle.



d. Write another expression that relates the angle θ_2 to the distance L from the slits to the screen and the distance y_2 from the b_0 central maximum to the position of the b_2 bright spot.

e. Generalize the two expressions developed in parts **c**. and **d**. so that they can be used to determine the angular deflection to the *n*th bright band. List all assumptions you made when constructing these two expressions.

24.1.6 Test your ideas

***PIVOTAL* Lab:** *Equipment per group:* a laser pointer, a set of double slits of known separations, a screen, and a ruler.

Design an experiment to test the relationships you devised in Activity 24.1.5. *Note:* Look at the laser's case; it may tell you the wavelength of the light it emits.

a. Sketch the experimental set-up.

b. Use the expressions devised in Activity 24.1.5 parts **d**. and **e**. to predict the outcome of the experiment.

c. List additional assumptions you made.

d. Perform the experiment, record the outcome, and compare it to the prediction.

e. Discuss whether the outcomes of the experiments support the expressions you devised in Activity 24.1.5 parts **d**. and **e**.

24.1.7 Reading exercise

Read Section 24.1 and answer Review Question 24.1.

24.2 Index of refraction, light speed, and wave coherence

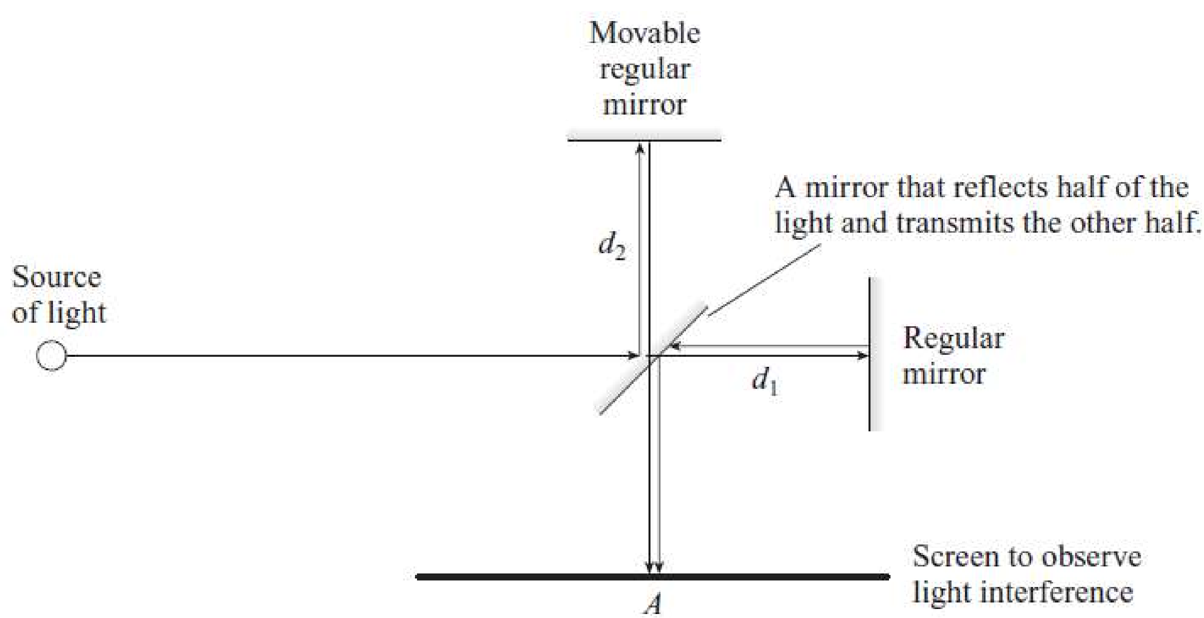
24.2.1 Reading exercise

Read Section 24.2 in the textbook and answer Review Question 24.2

24.2.2 Explain

Lab or class:

Examine the apparatus in the figure below to answer the questions that follow.



a. Explain why you see an alternating bright light and then a dark spot on the screen as the movable mirror is moved.

b. Explain how this apparatus can be used to determine if the speed of light in one direction is different from the speed of light in another direction.

24.3 Gratings: An application of interference

24.3.1 Observe and explain

PIVOTAL Lab: *Equipment per group:* laser, grating, meter stick.

The slit separation for double slits typically used in lecture demonstrations is about $0.5\text{mm} = 0.5 \times 10^{-3}\,\text{m}$. An apparatus called a *grating* has about 200 slits in 1 mm.

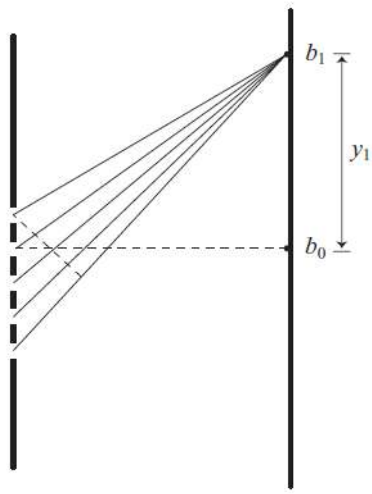
a. Determine the distance between the centers of the adjacent slits in such a grating.

b. Place the grating about 2 m from a white screen. Shine laser light through the grating and observe a set of bright dots on the screen. These dots are much farther apart than when you use a double-slit apparatus. Draw a diagram of the experimental situation and explain the phenomenon qualitatively.

24.3.2 Reason and explain

PIVOTAL Lab or class

In Activity 24.3.1, you found a large angular deflection to the first bright band. Suppose you have a five-slit grating with adjacent slits having a small slit separation. The position of the first b_1 bright band to the side of the central b_0 bright band for laser light passing through this grating is shown in the figure below. In terms of light wavelength, how do the distances from the second, third, fourth, and fifth slits to the first b_1 bright band compare to the distance from the first (bottom) slit to that bright band? Explain, and be specific.



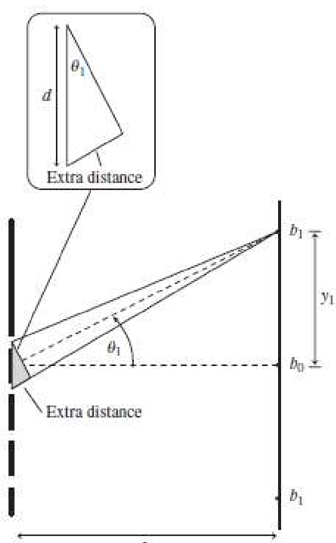
24.3.3 Derive

PIVOTAL ***Class:*** *Equipment per group:* whiteboard and markers.

Consider the situation depicted in Activity 24.3.2.

a. Devise a mathematical expression that relates the angular deflection θ_1 to the first bright band, the wavelength λ of the light, and the separation d of adjacent slits. You might want to review what you did in Activity 24.1.5.

b. Devise a mathematical expression that relates the angular deflection θ_1 to the first bright band on the screen to the distance L of the grating from the screen and the distance y_1 of the first bright band from the central maximum b_0 on the screen in the figure below.



24.3.4 Test your idea

Class: *Equipment per group:* gratings, laser, screen, meter stick.

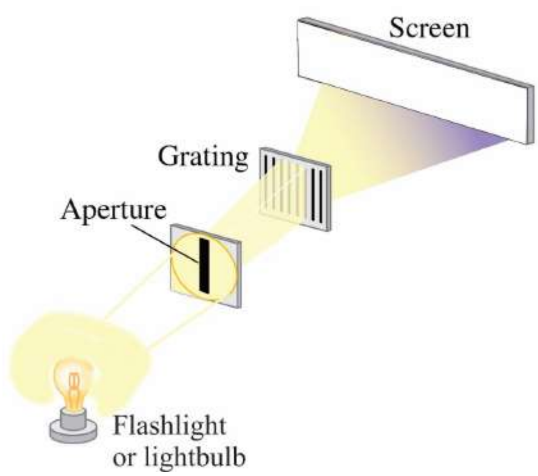
a. Use the expressions that you devised in Activity 24.3.3 to predict how an increase in the number of slits per millimeter in the grating (for example, 400 slits per mm instead of 200) should affect the separation of the bright dots on the screen, assuming you use the same laser as in the previous activities. Perform the experiment and compare the outcome to your prediction.

b. Use the explanations that you devised in Activities 24.3.2 and 24.3.3 to predict how an increase in the total number of slits without changing the number of slits per unit length should affect the separation of the bright dots on the screen, assuming you use the same laser as in the previous activities. Create an experiment that you can perform to check your prediction. Then perform the experiment and record the outcome. Was it consistent with your prediction?

24.3.5 Observe and find a pattern

PIVOTAL Class: *Equipment per group:* gratings, laser, screen, meter stick, flashlight, vertical aperture (width of about 2 mm).

Repeat the experiment in Activity 24.3.4, but this time instead of a laser, use a flashlight, small vertical aperture and a grating with the greatest number of slits/mm that is available. Build a set-up shown on the figure below and answer the questions that follow.



a. Sketch the experimental set-up.

b. Use colored pencils to draw the pattern you observe on the screen.

c. Describe the pattern in terms of color location.

d. Write an explanation for the pattern.

24.3.6 Design an experiment

Use the apparatus from Activity 24.3.5 to design an experiment to determine the wavelengths of different colored light coming from an incandescent lightbulb.

a. Sketch the experimental set-up.

b. List the quantities you will measure.

c. Summarize the mathematical procedure you will use to calculate wavelengths. Then calculate the wavelengths.

d. List representative calculated wavelengths of the different colored light.

24.3.7. Reading exercise

Read Section 24.3 and answer Review Question 24.3.

24.4 Thin-film interference

24.4.1 Observe and find a pattern

PIVOTAL ***Lab or class:*** *Equipment per group:* cup or mug with dark inside, shallow plate, sheet of white paper, bright light or flashlight, soap bubble solution (keep it in an open container for a day).

Pour some soap bubble solution into a shallow plate. Rub the rim of the cup with a soap bubble solution and then turn the cup upside down onto the plate. Slowly lift the cup, first on one side and then the whole cup. If you do it right, the soap skin should form that covers the whole cup opening. Now, carefully turn the cup in a horizontal position and place it on the sheet of paper. Aim the light to the paper in front of the cup. Watching from above, observe the light that reflects from the soap skin. Vary your position until you see colored stripes that reflect from the soap bubble. Observe the development of the soap bubble until it pops. Repeat the experiment several times. In particular, focus on the long living bubbles.

a. Describe the change of colors of the soap skin and compare them to the rainbow colors. Are they the same or different?

b. Describe your observations of the top of the soap skin, right before it pops.

24.4.2 Reading exercise

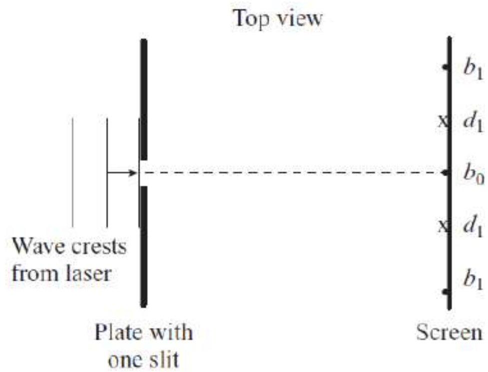
Read section 24.4 in the textbook and answer Review Question 24.4.

24.5 Diffraction of light

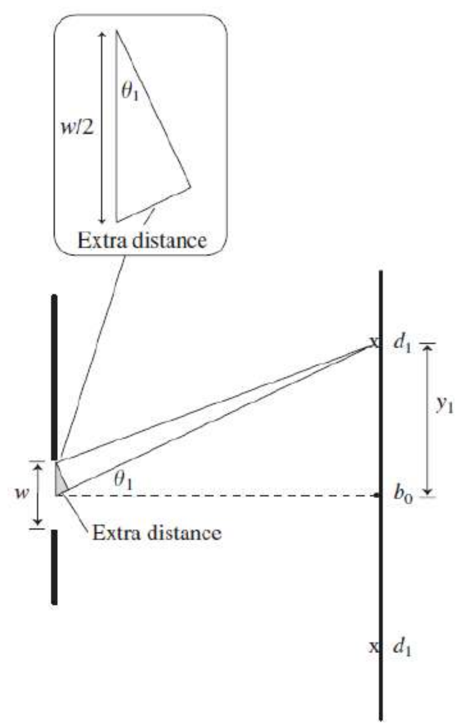
24.5.1 Derive

PIVOTAL ***Class:*** *Equipment per group:* whiteboard and markers.

In previous activities involving two or more slits, we used very narrow slits and considered them point-like wave sources. What happens if a single slit blocks the monochromatic light beam? Imagine that a wave approaches a single slit from the left (see the figure below). The opening is about the same width as the wavelength of the wave. We observe on a screen to the right of the slit a bright band of light in the center $\left(b_0\right)$ and alternating dark and bright bands on each side of the center bright band (d_1 and b_1 in the figure—there are usually more than one dark and bright band on the sides).



a. To understand the location of the first dark band (d_1) on the screen, divide the slit in half. What condition is necessary for a wavelet from a point at the top of the top half of the slit to interfere *destructively* at d_1 on the screen with a wavelet from the top of the bottom half of the slit opening? Explain (see the figure below)



b. Write an expression that relates the slit width *w*, the wavelength of the light λ, and the angle θ_1. Refer to the illustration.

c. If you consider a wavelet produced a little lower in the top half of the opening and another the same distance lower in the bottom half of the opening, will they also interfere destructively? Explain. Can we say that if the condition in part **a.** is satisfied, a wavelet from each point in the bottom half of the single slit interfere destructively with a wavelet from each point in the top half of the slit? Explain.

24.5.2 Test your idea

***PIVOTAL* Lab:** *Equipment per group:* hand-held laser, screen, a set of slits of a known width, meter stick.

Use the relationship derived in Activity 24.5.1 to predict the width of the central maximum on a screen placed about 1 m away from the slits of known widths.

a. Sketch the pattern on the screen for the narrowest slit.

b. Sketch the pattern on the screen for a medium-width slit.

c. Sketch the pattern on the screen for the widest slit.

d. Calculate the distance between the dark bands on each side of the central maximum for each slit.

e. Sketch the pattern on the screen for the widest slit.

24.5.3 Test an idea

Lab: *Equipment per group:* hand-held laser, sewing needle, screen, ruler.

Babinet's principle states that the diffraction pattern of a complementary object is the same as that of an object itself. For example, a slit in a screen produces the same diffraction pattern as a screen the same size as the slit; a hair will produce the same diffraction pattern as a slit of the same width as the hair.

Discuss using Babinet's principle to predict the difference in the patterns on a screen produced by laser light shining on a strand of your hair and then shining on a thin sewing needle. Explain your prediction. Perform the experiment and record the outcome. Did the prediction match the outcome of the experiment?

24.5.4 Reading exercise

Read Section 24.5 in the textbook and answer Review Question 24.5.

24.6 Resolving power

24.6.1 Reading exercise

Read Section 24.6 in the textbook and answer Review Question 24.6.

24.6.2 Evaluate and reconcile

***PIVOTAL* Class:** *Equipment per group:* whiteboard and markers.

Jade learned about the resolving power of optical devices and the Rayleigh criterion. She decides to test these ideas using a conventional camera. She draws on a paper two 4-mm diameter black spots, with their centers 7 mm apart. She fixes the paper on the window and places a tripod with a camera 8.5 m away from the window. Then she performs the following three experiments.

Experiment 1: Jade takes a photo of the paper with black spots, using the camera in the normal way (see the photo below):

The exposure time of the photo was 1/200 s.

Experiment 2: Jade covers the camera's front lens with aluminum foil in which she makes a 1 mm-diameter hole. The hole is on the optical axis of the lens. Then she takes the photo below:

The exposure time was 1 second. All other settings were the same as in Experiment 1.

Experiment 3: Jade covers the camera's front lens with aluminum foil in which she makes a 0.7 mm-diameter hole. The hole is on the optical axis of the lens. Then she takes the photo below:

The exposure time was 3 second. All other settings were the same as in Experiment 1.

a. Observe carefully all three photos and describe differences and similarities between them.

b. Jade argues that the differences between the photos can be explained using the Rayleigh criterion. Do you agree or disagree with her? Explain your answer using quantitative arguments. Indicate any assumptions that you made.

c. Frances (a friend of yours and Jade) says, after seeing Jade's photos, "I am confused. When we studied the pinhole camera, we found out that the smaller the hole diameter, the sharper the image. But the outcome of Jade's experiments are exactly opposite." How you will help Frances to reconcile what she learned?

24.7 Skills for applying the wave model of light

24.7.1 Regular problem

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

Light of wavelength 540 nm from a green laser is incident on two slits that are separated by 0.50 mm; the light reaches a square screen 50 cm × 50 cm that is 1 m away from the slits. Describe quantitatively the pattern that you will see on the screen. Complete the table that follows.

Sketch and translate • Visualize the situation and sketch it. • Translate givens into physical quantities.	
Simplify and diagram • Decide if the small-angle approximation is appropriate. • Represent the situation with a ray diagram showing the path of light waves from the two slits to the screen.	
Represent mathematically • Describe the diagram mathematically.	
Solve and evaluate • Solve the problem and decide if the answer makes sense.	

24.7.2 Represent and reason

Class: *Equipment per group:* whiteboard and markers.

Monochromatic light passes through two slits and then strikes a screen. The distance on the screen between the central maximum and the first bright fringe at the side is 2.0 cm.

a. Sketch the situation. Translate the givens into physical quantities.

b. Determine the fringe separation if the slit separation is doubled and everything else remains unchanged.

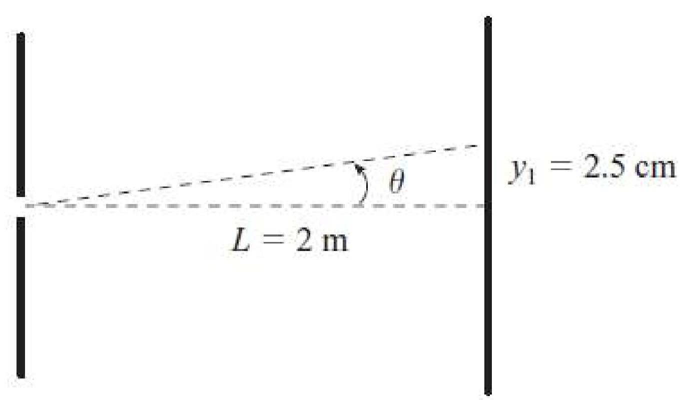
c. Determine the fringe separation if the wavelength is doubled and everything else remains unchanged.

d. Determine the fringe separation if the screen distance is doubled and everything else remains unchanged.

24.7.3 Evaluate the solution

Class: *Equipment per group:* whiteboard and markers.

The problem: Determine the width of a hair that, when irradiated with laser light of wavelength 630 nm, produces a diffraction pattern on a screen with the first minimum 2.5 cm from the central maximum, as shown below. The screen is 2.0 m from the hair.



Proposed solution: A hair is a very thin obstacle in the path of light; the light bends around it and produces a diffraction pattern on the screen. According to Babinet's principle, the pattern will be similar to that formed by light passing through a single narrow slit whose width is the same as the width of the hair. Thus, we can use the expression for the angular deflection to the first minimum to relate the angular width of the central maximum to the width of the hair. Because the angular deflection is small, the sine and tangent of this angle give the same result:

$$\sin\theta_1 = \tan\theta_1 = y_1/L$$

$$w\sin\theta_1 = n\lambda \quad \text{for} \quad n = 1$$

$$w = \frac{\lambda}{\sin\theta_1} = \frac{\lambda y_1}{L} = \frac{\left(630\times 10^{-9}\right)(2)}{(2.5)} = 504\times 10^{-9}\ \text{m}$$

a. Identify any missing elements or errors in the solution.

b. Provide a corrected solution if there are errors.

24.7.4 Regular problem

Class: *Equipment per group:* whiteboard and markers.

A reflection grating reflects light from adjacent lines in the grating instead of allowing the light to pass through slits, as is the case with the so-called transmission gratings we have been studying. Interference between the reflected light waves produces *reflection maxima*. The angular deflection of bright bands, assuming perpendicular incidence, is calculated using the same equation as the angular deflection of transmitted light through a regular grating. White light is incident on the wing of a Morpho butterfly (whose wings act as a reflection grating).

a. Explain why you see different color bands coming from the wings of the butterfly when white light shines on the wings.

b. Red light of wavelength 660 nm is deflected in first order (n = 1) at an angle of 1.2°. Determine the distance between the adjacent reflecting lines on butterfly's wing.

c. Determine the angular deflection in first order (n = 1) of blue light (460 nm).

24.7.5 Design an experiment

Lab or class: *Equipment:* On request.

You have probably noticed that stars have different colors—some are white, some are yellowish, and some are reddish. Does this mean that stars of a red color do not emit any blue light? Astronomers use an instrument called a *spectrograph* to analyze the color composition of starlight. The central mechanism of a spectrograph is a grating. Design a simple version of a spectrograph, an apparatus that will allow you to separate different colors of light emitted by a lamp on your desk (that emits light very similar to the light emitted by many stars) and will also allow you to measure the wavelengths of these different colors. Draw a picture of the apparatus and explain how it works.

24.7.6 Design an experiment

Lab: *Equipment per group:* a laser pointer, a screen, and a meter stick.

Design an experiment to determine the thickness of an individual strand of your hair using a laser pointer.

a. Describe the design, the procedure, and the assumptions that you make.

b. Perform the experiment, record the measured quantities, and calculate the width of a piece of hair. Then measure the hair strand with a caliper and decide whether the result you obtained with the first method agrees with the second.

24.7.7 Estimate

Class: *Equipment per group:* whiteboard and markers.

Assume that Earth, its structures, and its inhabitants are all decreased in size by the same factor. *Estimate* the decrease required so that the first-order diffraction dark band of 500-nm light entering a typical room window is at 90° (the central bright band would light most of the room). Explain all aspects of your calculations and the assumptions that you made.