Chapter 24

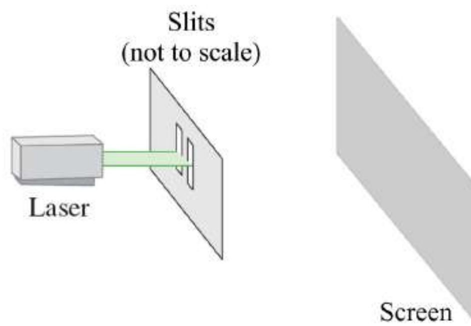
Wave Optics

24.1 Young's double slit experiment

OALG 24.1.1 Observe and explain

a. In the following video https://youtu.be/e55Er6-R10k

observe laser light first shining on two wide slits and then on two narrow slits.



b. Draw a careful sketch of what you observe on the screen in both experiments. Compare and contrast the results. Can the outcomes of these two experiments 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 in the second experiment with narrow slits. Is it possible for 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?

d. Read and interrogate text on pages 752-753 in the textbook and compare the textbook explanations with yours.

OALG 24.1.2 Reason and explain

In the figure below waves (of any type) are incident from the left side of 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.

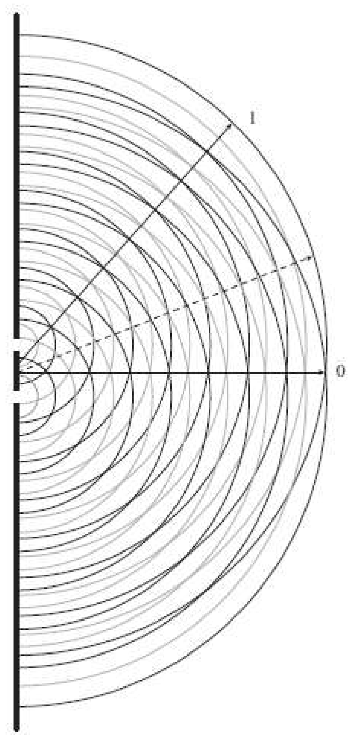
a. Describe what the crests might represent for each of the following types of waves: water waves, sound waves.

b. Indicate with the letters “dc” (double crest) places on line 0 where the troughs are both equal distance from the wave sources (the openings) and 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 where the troughs are both equal distance from the wave sources (the openings) and 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 at the 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?



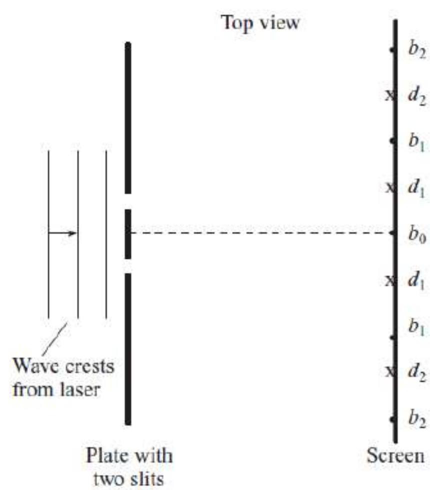
f. What if these were light waves moving along the line described in part **d**. Would the light be brighter or dimmer than incident light? Explain.

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.

OALG 24.1.4 Reason and explain

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.

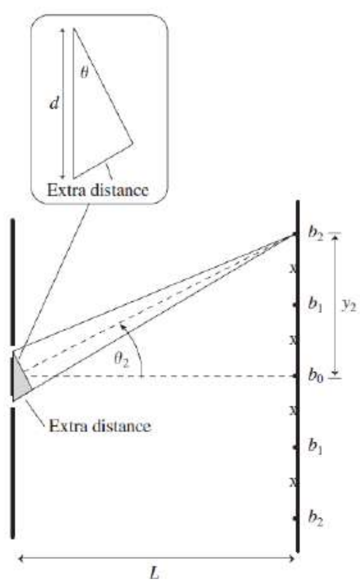
OALG 24.1.5 Represent and reason

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.

OALG 24.1.6 Test your ideas

a. Use the expressions that you devised in Activity 24.1.5, parts **d** and **e,** to predict what will happen to the bright spots on the screen when in the experiment described there the distance between the slits decreases. Will the bright bands be wider or narrower? Will the distance between the brightest parts of the bands increase, decrease or stay the same? Explain how you made your prediction

b. After you make your prediction, compare it to the outcome of the experiment in the following video: https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-experiment-video-55

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

OALG 24.1.7 Read and interrogate

Read and interrogate Section 24.1, pages 753-757 and answer Review Question 24.1 on page 757.

OALG 24.1.8 Practice

Answer Question 1 on page 778 and solve problems 1 – 4 and 7 on page 779 in the textbook.

24.2 Index of refraction, light speed, and wave coherence

OALG 24.2.1 Read and interrogate

Read Section 24.2 in the textbook and answer Review Question 24.2 on page 760.

OALG 24.2.2 Practice

Answer Questions 3, and 17 – 19 on page 778 and solve Problems 6, 8, and 9 on page 779.

24.3 Gratings: An application of interference

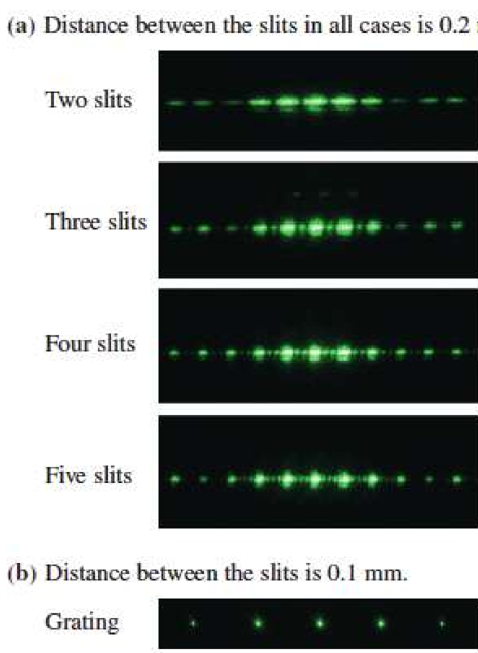
OALG 24.3.1 Observe and explain

The figure below shows the patterns on the screen when green laser light passes through several different assortments of slits and finally through a grating – a plate of glass with a total of about 30 slits (as many as fit inside a laser beam which is about 3 mm wide). Observe the differences in the patterns on the screen as the number of slits increases and as the distance between the slits increases.

a. Explain why for the same slit separation the width of the bright bands decreases with the increasing number of slits.

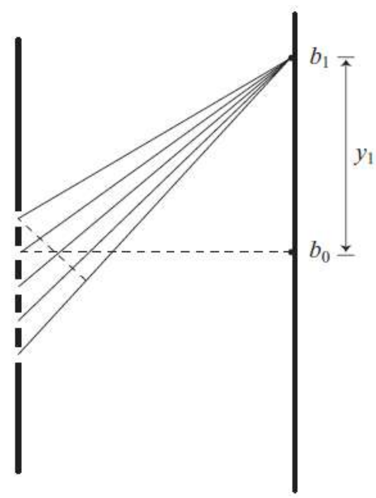
b. Explain why when we both decrease the slit separation and increase the number of slits (such as in a grating) the bright bands become very narrow and they are spread farther apart.

c. If you have trouble devising an explanation, read and interrogate textbook pages 760-761.



OALG 24.3.2 Reason and explain

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.

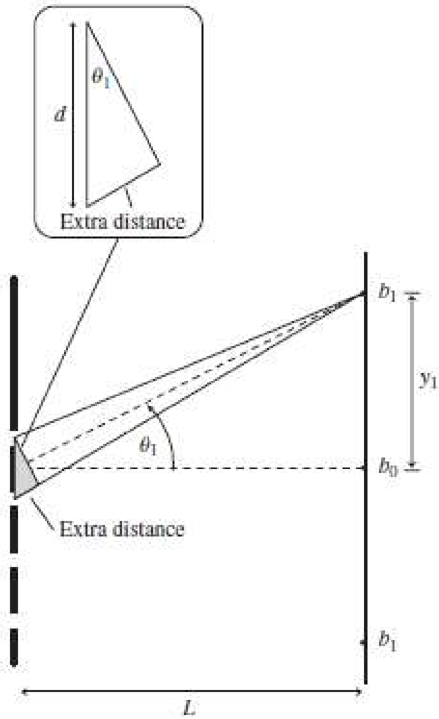


OALG 24.3.3 Derive

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.

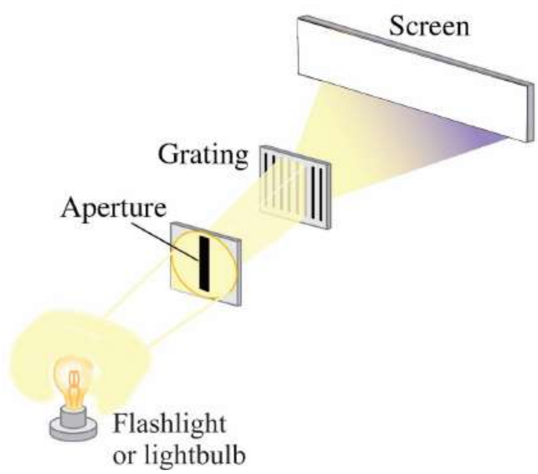
b. Devise a mathematical expression that relates the angular deflection θ_1 to the first bright band on the screen to the distance L of the grating from the screen and the distance y_1 of the first bright band from the central maximum b_0 on the screen in the figure below.



c. Read and interrogate Quantitative exercise 24.3 on page 761 in the textbook.

OALG 24.3.4 Test your ideas

Imagine that you have a flashlight, a small vertical aperture, and a grating with the greatest number of slits/mm that is available. The set-up is shown on the figure below. Use what you learned about gratings to predict what you will see on the screen when you turn the flashlight on.



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

b. Describe the pattern in terms of color location.

c. Write an explanation for the pattern.

d. Compare your prediction to Figure 24.12 on page 762 in the textbook. Does the figure predict the same patters on the screen that you do?

OALG 24.3.5 Read and interrogate

Read and interrogate subsections "White light incident on grating" and "Spectrometer" in Section 24.3 and answer Review Question 24.3 on page 764.

OALG 24.3.6 Practice

Answer Questions 4 – 6, and 9 on page 778, and Problems 10 – 14 on page 779 in the textbook.

24.4 Thin-film interference

OALG 24.4.1 Observe and find a pattern

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 the 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, a soap skin should form that covers the whole cup opening. Now, carefully turn the cup in a horizontal position (as shown in the photo below) 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 longer lasting 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.

c. Read and interrogate Section 24.4 in the textbook and answer Review Question 24.4 on page 768.

OALG 24.4.2 Practice

Answer Questions 21 and 22 on page 778, and solve problems 19 – 22 and 27 and 29 on page 780 in the textbook.

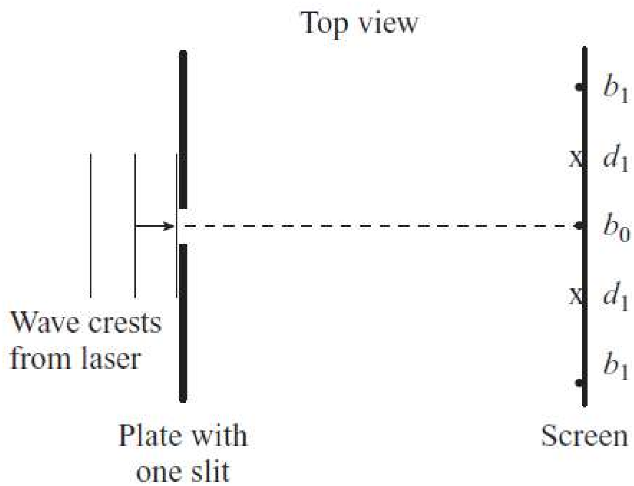
24.5 Diffraction of light

OALG 24.5.1 Observe and explain

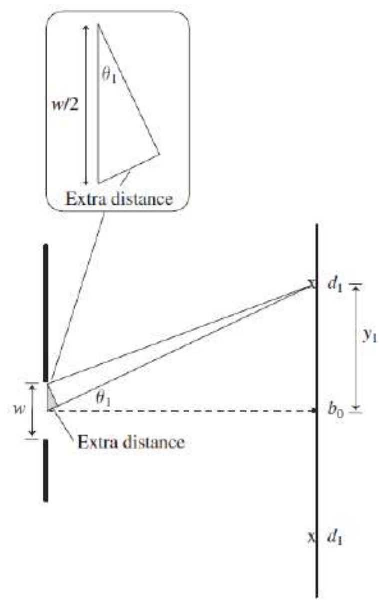
In previous activities involving two or more slits, we used very narrow slits and considered them to be point-like wave sources. In the following video one of the two slits in a double slit experiment is slowly covered https://youtu.be/3po3Y3okCpU. Observe the changes in the patterns on the screen and suggest an explanation. *Hint:* what would a pattern look like if each slit were infinitely thin as we assumed in al previous experiments?

OALG 24.5.2 Derive

In this experiment we will use a single slit, which is rather narrow but not as narrow as the slits in double-slit experiments. What happens when 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.

d. Compare the expression you wrote in part **b** with Equation 24.6 on page 771 in the textbook. How are they different?

OALG 24.5.3 Test an idea

Equipment: 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?

OALG 24.5.4 Read and interrogate

Read and interrogate Section 24.5 in the textbook and answer Review Question 24.5 on page 772.

OALG 24.5.5 Practice

Answer Questions 23 and 25 on page 778 and solve Problems 33-35 on page 780 in the textbook.

24.6 Resolving power

OALG 24.6.1 Read and interrogate

Read Section 24.6 in the textbook and answer Review Question 24.6 on page 774.

OALG 24.6.2 Evaluate and reconcile

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?

OALG 24.5.3 Practice

Answer Question 26 on page 778 and solve Problems 36 – 39 on page 780.

24.7 Skills for applying the wave model of light

OALG 24.7.1 Regular problem

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.	

OALG 24.7.2 Represent and reason

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.

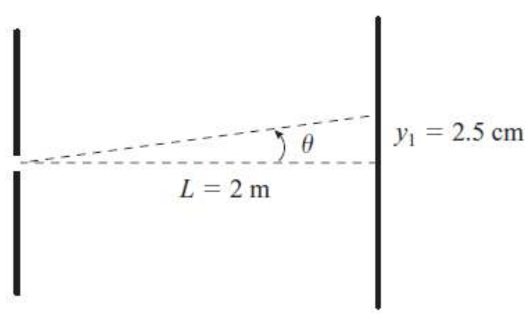
b. Determine the fringe separation if the slit separation is doubled and everything else remains unchanged.

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.

OALG 24.7.3 Evaluate the solution

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:

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

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

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

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

b. Provide a corrected solution if there are errors.

OALG 24.7.4 Regular problem

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).

OALG 24.7.5 Design an experiment

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.

OALG 24.7.6 Practice

Solve Problems 44, 45, 48, 61, 62, 67 and 71 on pages 780 – 782 in the textbook.