SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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National Science Education Standard: Physical Science

Interactions of Energy and Matter

a. Waves, including sound and seismic waves, on water, and light waves, have energy and can transfer energy when they interact with matter.

b. Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, X rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.

Teacher Materials

Learning Sequence Item:

1036

Wave Phenomena and the Electromagnetic Spectrum

March 1997
Adapted by: Bill G. Aldridge

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a. The Wave Model: Water Waves, Seismic Waves, Sound and Light. Many students are confused between the penumbra of shadows and the phenomenon of diffraction, so it will be important for them to understand shadows and the difference between those produced by point sources and those produced by extended sources. They should learn that light exhibits diffraction and therefore has wave properties. They should observe diffraction effects, understanding that they can be constructive or destructive (*Physics, A Framework for High School Science Education, p. 38*).

b. Photons, Electromagnetic Waves, Electromagnetic Spectrum. Students should have evidence that the entire E-M spectrum exhibits the characteristics of reflection, diffraction, interference, etc. (*Physics, A Framework for High School Science Education, p. 41*).

Contents

This micro-unit was adapted by **Bill G. Aldridge** (SciEdSol, Henderson, Nev.)

1036

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Science as Inquiry	Science and Technology	Science in Personal and Social Perspectives	History and Nature of Science
Shadows of Light **Activity 1** Shadows of Light: Another Look **Activity 2** Creating a Model to Explain Diffraction **Activity 3** Measuring the Wavelength of Light **Activity 4** Fuzzy Shadows **Assessment 1** An Eclipse of the Sun **Assessment 2** On the Head of a Pin **Assessment 3** Slinky Pulses **Assessment 4** What a Sound! **Assessment 6**	Listen to That Radio! **Assessment 5** How Close are Those Slits? **Assessment 7**		Creating a Model to Explain Diffraction **Activity 3**

Suggested Sequence of Events

Event #1

Lab Activity

1. Shadows of Light

Event #2

Lab Activity

2. Shadows of Light: Another Look

Event #3

Lab Activity

3. Creating a Model to Explain Diffraction

Event #4

Lab Activity

4. Measuring the Wavelength of Light

Event #5

Readings from Science as Inquiry, Science and Technology, Science in Personal and Social Perspectives, and History and Nature of Science

Suggested reading:

Aldridge, B.G., *What is Light and How Do We Explain It?* Arlington, Va.: National Science Teachers Association, 1996.

Assessment items are at the back of this volume.

Assessment Recommendations

This teacher materials packet contains a few items suggested for classroom assessment. Often, three types of items are included. Some have been tested and reviewed, but not all.

1. Multiple-choice questions accompanied by short essays, called justification, that allow teachers to find out if students really understand their selections on the multiple choice.

2. Open-ended questions asking for essay responses.

3. Suggestions for performance tasks, usually including laboratory work, questions to be answered, data to be graphed and processed, and inferences to be made. Some tasks include proposals for student design of such tasks. These may sometimes closely resemble a good laboratory task, since the best types of laboratories are assessing student skills and performance at all times. Special assessment tasks will not be needed if measures such as questions, tabulations, graphs, calculations, etc., are incorporated into regular lab activities.

Teachers are encouraged to make changes in these items to suit their own classroom situations and to develop further items of their own, hopefully finding inspiration in the models we have provided. We hope you may consider adding your best items to our pool. We also will be very pleased to hear of proposed revisions to our items when you think they are needed.

Science as Inquiry

Shadows of Light

What makes a shadow sharp or fuzzy?

Overview:

Your students have previously observed that light travels in straight lines when it is not interacting with something. There are other things about light that they have probably observed but may not have thought about. With the lights turned on in the classroom, what kinds of shadows are formed? Do objects in a well-lit room cast sharp shadows? Why? Or, why not?

In this activity students investigate these questions and find answers for themselves.

Materials:

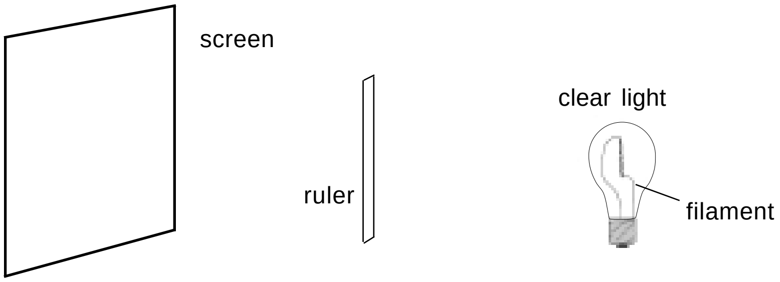
Per lab group:

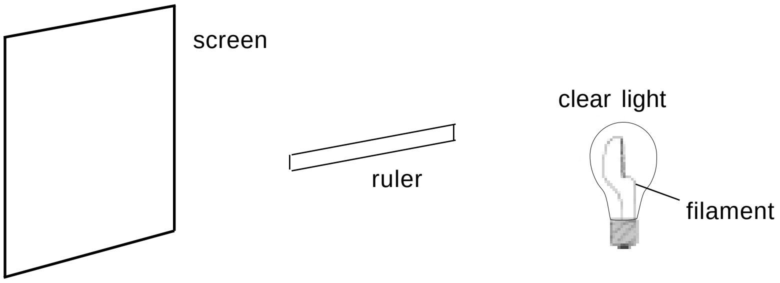
poster board to use as screen (large, white)
incandescent lamp with clear bulb (100–200 watts) and straight filament (no reflector)
incandescent lamp with clear bulb and straight filament that has been broken to expose filament
meter stick
ruler
filters, red and blue

Procedure:

Have students mount the light bulb in such a way that light from the filament travels directly to the ruler and other objects without being reflected by a floodlamp or other reflector. As they will examine light coming from the bulb in several orientations, they must be able to turn the bulb in various ways.

Have students carefully observe the shadow of a ruler placed about 30–60 cm (1–2 ft) from the bulb, comparing the shadows produced by the long edges of the ruler with the shadows produced by the ends of the ruler. They should then slowly move the ruler farther and farther away from the





light source as they continue to make observations. Then, starting again with the ruler 30–60 cm from the bulb, they should move the ruler closer and closer to the bulb as they continue to make observations. Now students should change the orientation of the ruler to the filament from vertical to horizontal and repeat their observations. Have them describe the shadows carefully in each of these cases by drawing pictures. They should repeat all their observations using a red and then a blue filter placed between the bulb and the ruler.

Now have students rotate the bulb in various ways, and for each orientation again make observations, describing them carefully with drawings that show the filament, the ruler, the shadow, and the orientation of the filament to the ruler. For each these orientations of bulb and ruler, students should start with the bulb up close to the ruler and move the bulb backward away from the ruler, observing how the shadows change as this distance gets larger and larger. Have them measure the distance from the ruler to the screen and from the ruler to the bulb in each case.

Next have students measure the length of the bulb filament in a bulb that has been carefully broken so as not to damage the filament.

Students should also make careful observations of the shadows cast by other variously oriented objects, like their hands or fingers, using the light bulb. If possible, let them form shadows of the ruler and other objects using sunlight. They should also use red and blue filters with the sun as the light source.

From these observations your students should be able to explain why there are sharp and fuzzy shadows:

Background:

Sharp shadows are created by point sources, and fuzzy shadows are created by extended sources. Unfortunately, these terms are not simple. The sun, even though it is huge, can be considered a point source for casting shadows on a screen. But when the sun casts shadows of the moon on Earth, the shadows are not sharp (there is both a penumbra and an umbra.) The straight-filament lamp will cast sharp shadows of the edges of a ruler that is aligned with the filament length. This is because the width of the filament is so small, and the distances involved so much larger, that the width of the filament serves as a point source. But the edges of the ruler at right angles to the filament have light coming to them from all along this extended source. Thus, unless the ruler is placed very close to the screen, or the source is distant, the shadows of these edges will be fuzzy (there will be a penumbra).

When students first observe diffraction, they are confused between diffraction and the penumbra effects of extended sources. These two effects are vastly different, and fuzzy shadows are several orders of magnitude larger than the effects of diffraction.

Answers to Student Questions:

Question 1. When the bulb is close to the ruler, and the ruler is aligned with the bulb filament, what do the shadows of the ends of the ruler look like? What do the shadows of the long edges of the ruler look like? How do the shadows change as the distance from the ruler to the bulb is made larger and larger? When you place a red filter between the bulb and the ruler what happens to the shadows? When you use a blue filter what happens to the shadows?

Question 2. When the bulb is close to the ruler, and the ruler is aligned at right angles with the bulb filament, what do the shadows of the ends of the ruler look like? What do the shadows of the long edges of the ruler look like? How do the shadows change as the distance from the ruler to the bulb is made larger and larger? When you place a red filter between the bulb and the ruler what happens to the shadows? When you use a blue filter what happens to the shadows?

Answers: When the bulb is close to the ruler, both the long edges and the ends of the ruler produce sharp shadows regardless of the alignment of the ruler with the bulb filament. When the ruler is moved outward away from the screen, the edges of the ruler at right angles to the filament "see" an extended source; therefore, the edges cast fuzzy shadows. These shadows are the same when either a red or blue filter is used. This observation is important because diffraction effects *do* change with color of light.

Question 3. For any orientation, what do the shadows of the ends and long edges of the ruler look like when the shadows are cast by sunlight? When a red or blue filter is used with sunlight, do the results change?

Answer: These shadows will be very sharp in sunlight, and it will make no difference whether the light is red, white, or blue. Again, were this diffraction, it *would* make a difference which color was being observed.

Question 4. When shadows cast from some source are sharp, the source is said to be a *point source*; when the shadows cast are fuzzy, the source is said to be an *extended source*. Based on your observations and in your own words, explain what these two terms mean. How can an extended source be made a point source without changing the size, shape, or intensity of that source?

Question 5. The dark part of a shadow is given a name. It is called the *umbra* of the shadow. The fuzzy part of a shadow, from the area of full darkness through the fuzziness to the area of no shadow, is also given a name. It is called the *penumbra* of the shadow. Draw light rays from various parts of the filament of the light bulb to show how an umbra and penumbra are formed. Describe what is happening to make the light intensity in the penumbra change from its darkest edge to the area of no shadow.

Answers: Students should be able to show how different parts of the light source produce their own shadows, and how this effect occurs from the umbra to the edge of the penumbra. Ray diagrams are very helpful.

Question 6. How does the production of an umbra or penumbra relate to the color of light? Is the penumbra the same size? Is the umbra the same size? Except for the color of light striking the screen, does the color of the light have anything to do with the shape, form, or size of the shadows that you have observed?

Answer: There is no color effect whatsoever on the size of the penumbra or umbra or on their locations. This point is very important in considering the difference between diffraction and the effects of extended sources.

Question 7. From your measurements of the distances from the screen to the ruler and from the ruler to the light bulb filament, and using your measurement of the length and thickness of the filament, what ratio comparison best indicates when a sharp shadow will be formed? What are the conditions on these ratios?

Answer: This is a very difficult question for all but your most highly motivated and capable students. Not only does it require that they set up similar triangles to see relationships, they must then use these with inequalities instead of equalities. The result of those efforts is the inequality

(length of source)/(length of object) << (distance of source to object)/(distance of object to screen)

Adapted from: none

Science as Inquiry

Shadows of Light: Another Look

For very small objects, what happens to the shadows?

Overview:

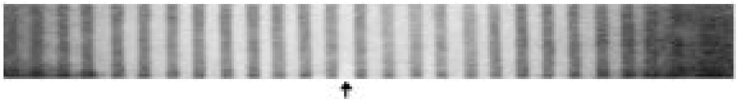
In Activity 1 your students observed shadows cast by both extended sources and point sources. They learned that a point source is one for which the ratio of the size (length or radius) of the source to the size (length or radius) of the object forming the shadow must be much smaller (at least 100 times smaller) than the ratio of the distance from the source to the object to the distance from the object to the screen. When this condition is *not* met, then the source is an extended source. As an inequality, this condition is as follows:

(length of source)/(length of object) << (distance of source to object)/(distance of object to screen)

Students also observed that sizes of shadows are the same, regardless of whether the light is white, red, or blue. They saw that sharp shadows are formed by point sources and fuzzy shadows are formed by extended sources. They learned that when fuzzy shadows are formed, the dark part is called an umbra and the fuzzy part is called a penumbra. They saw that a penumbra is darkest at its border with the umbra and becomes successively less dark as it moves outward on the screen to where there is no shadow. They learned that a penumbra is produced because different parts of the extended source, from the full source to an edge of the source, together form the shadow,

Now, what if we make the object casting the shadow very small? Do we still see the same kinds of shadows? Are they still umbras and penumbras? For this investigation, we cannot use an external screen. We need to have the object casting the shadow very close to the screen to see the effects. For the screen each student will use his or her own eye retina. Painted microscope slides with vertical slits provide the shadows.

Students look at the filament of the light bulb through the narrow openings on the slide, and shadows are cast on the retina. Students then "see" these shadows, just as they saw them on the screen. The reason you cannot just shine light through the slit onto a screen is that the light is not intense enough (unless it is a laser). Of course, what the students will observe is diffraction, with alternating bright and dark bands, as well as some fringe color if they look carefully (see figure below).



Materials:

Per lab group (four students):

lab slides, painted flat black on one side, with 1 narrow slit made by razor blade, 4
lab slides, painted flat black on one side, with 2 closely spaced narrow slits, 4
incandescent lamp with clear bulb and vertical filament, with holder and no reflector
diffraction gratings, 4

Procedure:

Prior to class, prepare two microscope slides for each lab group. Each slide should be painted flat black on one side. With a razor blade, cut one very narrow vertical slit into the paint of the first slide. Cut two closely spaced slits into the paint of the second slide. Only you or a trusted aide should do this, as it is very easy to cut oneself. Do not cut slits while holding the slide in your hand!

First have students use the slide with one slit. Darken the room and have students place the slit next to one eye and look at the filament of the light bulb oriented vertically with the slit and describe what they observe. If they do not see any colors, have them try a slide with a narrower slit. They should record their observations carefully, indicating where any colors appear. Make sure they have made the observations before you tell them the name of the phenomenon; it is called a *diffraction* pattern.

Now have students use a slide that has two slits. Again, they should look at the light source and record their observations. The reason for using a slide with two slits is that it will lead students to the use of a grating with multiple slits. Also, it is easier to understand the derivation for the equation that gives wavelength using double slits rather than single slits. They may not see much difference in intensity of the bands using two slits rather than one, but they will see a difference with the grating.

To observe diffraction better, especially the colors, students should now use a diffraction grating. It is actually a piece of transparent material that has thousands of very closely spaced slits. Have them hold the grating close to an eye and look through the grating at the light source. They should look at the first-order bright band on either side of the central maximum. Then have them record what they observe.

Background:

This activity enables students to see the alternating bright and dark bands produced by diffraction of light. Since the bands alternate, it cannot be penumbras that they are observing. This is clear evidence that light does not always travel in straight lines. Light not only bends, it somehow does so in a way that produces these alternating bright and dark bands. A particle model cannot account for these observations.

When students look carefully through the slits on the slides, they will observe color fringes on the edges of the bright bands, with red on the outward side with respect to the central maximum and blue on the inward side. Note that this is the opposite effect than that observed with a prism, where blue is bent more than red.

The diffraction grating greatly enhances the intensity and separation of the bright and dark bands. Indeed, the bright bands are widely separated with a 7,500 line/cm grating. In this case, the entire bright band is separated by color, creating the visible spectrum.

Answers to Student Questions:

Question 1. In your experiment using the slide with a single slit, the width of the slit was about 0.2 mm and the distance from the slit to the retina in your eye was about 40 mm. Assuming that the light source filament width was 2 mm and the distance from the filament to the slit was 10 meters (10,000 mm), compare the ratios in the expression:

(width of source)/(width of object) << (distance of source to object)/(distance of object to screen)

Remember that your eye retina is the "screen." Should the "shadow" on your retina have been sharp or fuzzy? Even if these ratios made it possible, could shadows have accounted for the alternating bright and dark bands? And what about the colors?

Answer: The 'source width to object width' ratio is 2 mm/0.2 mm = 10. The 'source-to-object distance to object-to-screen distance' ratio was 10,000 mm/40 mm = 250. Since 10 is much less than 250, we would expect there to be very sharp shadows.

Question 2. Given what you have observed, and your answer to Question 1, does light travel in straight lines in situations with narrow slits?

Answer: These observations provide direct evidence that when light interacts with very small single or multiple slits, light no longer travels in straight lines. Furthermore, other things happen when light travels through slits that a particle theory cannot account for.

Adapted from: none

Teacher Sheet

Science as Inquiry/History and Nature of Science

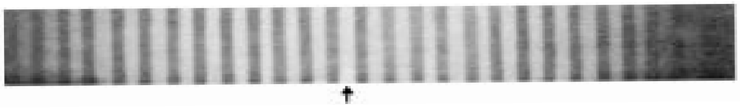
Creating a Model to Explain Diffraction

Can we create a model or theory that explains why light forms diffraction patterns?

Overview:

In Activity 1 your students learned how shadows are formed, and how point sources and extended sources cause fuzzy or sharp shadows. In Activity 2 they looked at light passing through narrow slits, for which shadows should have been sharp but instead appeared fuzzy. But there was no simple penumbra or umbra. Instead, when they looked at the straight filament of a light bulb through a single slit, what they observed were the alternating light and dark bands shown in Figure 1.

Figure 1



The arrow shows the location of the bright band that corresponds to the filament. This is the image that appears on the retina of the eye. To the right and left of this central bright band are alternating light and dark bands. And, although not evident in this black and white illustration, there are fringes of color at the edges of the light bands. The bands to the left of the central bright band have red fringes on their left and blue fringes on their right. On the other side of the central band, the blue fringes are on the left and the red fringes on the right. These observations are quite unexpected if light travels in straight lines. If light does not travel in straight lines in these situations, then we need to modify our model of light to account for these new phenomena.

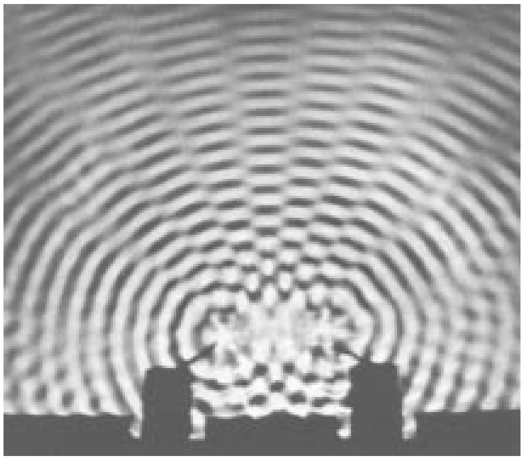


Figure 2

When Thomas Young first observed double-slit patterns, he wondered how he might explain this strange phenomenon. He thought about the alternating bands of light and dark and saw a connection between these alternating bands and the kinds of alternating bands of waves he had seen on ocean water near inlets or jetties. He wondered if light behaved like a wave, and if so, could he explain diffraction using a wave model? Figure 2 shows the water wave pattern produced by two small balls bouncing up and down on the surface of water. Notice the alternating bands and the lines of undisturbed water. The bouncing balls produce circular waves at a regular rate, and these waves move outward. Waves from the ball on the left and waves from the ball on the right appear to interact with each other to produce regions of undisturbed water and regions of larger waves.

This is the sort of thing Young had observed on ocean waves, and he sought to account for light diffraction in the same way. He reasoned that lines of undisturbed water are where crests of waves meet troughs and cancel each other out. Where crests meet crests, or troughs meet troughs, the waves become larger in amplitude, adding together to make a higher wave or a deeper wave.

This concept can be better understood by considering the simple movement of pulses on a toy called a Slinky®. The first "slinky" was probably a curled bit of steel produced when cylinders were cut to make automobile engines. Possibly a curious machinist wanted to make one of these coils as long as possible. Later the coils were made into toys for children. The Slinky® is an excellent device to study the motion of waves or pulses.

Materials:

Per lab group (four students):

Slinky® (large)
heavy paper or cardboard, 2 small folded pieces
compasses for creating concentric circles, 4
poster board for concentric circles, 4 large sheets
straightedges, 4

Procedure:

This activity requires that one person hold one end of a Slinky® while another person holds the other end. Each person produces a pulse from his or her end and watches it move down the Slinky®. This will require some practice.

A third student should place a folded piece of paper next to the Slinky® at about the midpoint between the two students holding the ends. The paper must be so close to the Slinky® that it will not allow either pulse to pass. One student then sends a pulse down one side of the Slinky®, while the other sends a pulse down the other side (Figure 3). Students are to see if they can make the two pulses cross each other at precisely where the piece of paper is marking the midpoint. If they are successful, the two pulses will add to zero amplitude and will pass the paper, leaving it undisturbed. This is called *destructive interference*.

Figure 3

Next have students place a folded piece of paper at the midpoint, but far enough away from the Slinky® that one pulse is not big enough in amplitude to reach the paper. Have them try again to send pulses at the same time, but now on the same side of the Slinky® (Figure 4). The goal is to have the pulses reach the center at the same time. When this happens, the two pulses add, forming a pulse with an amplitude twice the size of each pulse. Being large enough, this pulse should knock the paper away from the Slinky®. This phenomenon is called *constructive interference*.

Figure 4

An examination of the pattern produced by the two point sources shows that constructive interference occurs whenever the path difference is an integral number of wavelengths, and that destructive interference occurs whenever the path difference is a half-integral number of wavelengths. This principle of path differences is of fundamental importance in science.

Background:

This activity is intended to help students understand the principle of superposition of waves. The ideas learned are fundamental and important.

As you may know, Fourier analysis is a mathematical way of breaking down periodic wave shapes of any kind into a sum of simple sinusoidal waves. Since a sine wave is much easier to use in mathematical expressions, Fourier analysis is used extensively in electronics.

Fourier synthesis is the inverse procedure to Fourier analysis. Fourier synthesis allows us to take various sinusoidal waves and add them together to see what the overall result looks like. Basically, it is a matter of taking two or more waves that impinge at a certain point at a certain time and adding their amplitudes. Then, at that same point, the amplitudes are added for whatever length of time one wants. If the impinging wave is periodic, then the additions only have to be done for one period, and the complete wave form is known.

Your students have looked at one of the simplest of Fourier syntheses, the addition of two pulses of equal amplitude. When the two pulses overlap, the resultant wave pulse is the *algebraic* sum of the two pulses. So if you take the amplitude of one pulse on one side of the Slinky® as positive, a pulse on the other side of the Slinky® has negative amplitude. If pulses are on the same side of the Slinky®, their sum is then twice the amplitude of one pulse. If the pulses are on opposite sides of the Slinky®, their sum is zero—they cancel out.

In the real world, amplitudes are seldom equal, so the sum will not be twice as great nor will the two waves cancel out entirely. But if two waves have nearly the same amplitude, as they do in the case of double-source interference on water surfaces or in double-slit interference of light, then there will be essentially dark bands alternating with bright bands.

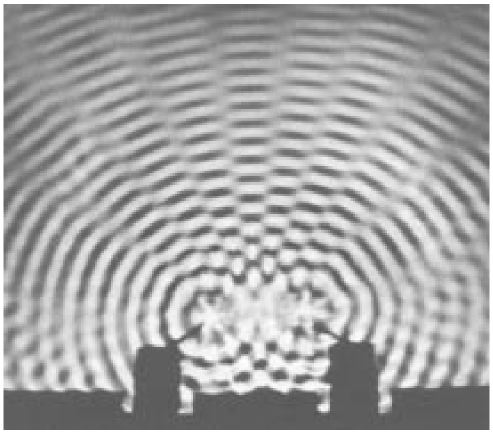
Answers to Student Questions:

Question 1. When two pulses traveling in opposite directions and on *opposite sides* of a Slinky® reach a point where they cross each other, what happens? What is the amplitude of each of the pulses before they cross? What is the amplitude of the resulting pulse at the instant the two pulses cross each other?

Answer: Students should relate height of the pulse to amplitude. If the floor is composed of square tiles, they can use them to estimate the size of the pulse. They should see that as these two pulses cross, the amplitude of their sum is zero.

Question 2. When two pulses traveling in opposite directions on the *same side* of a Slinky® reach a point where they cross each other, what happens? What is the amplitude of the resulting pulse at the instant they cross each other?

Answer: When two pulses cross on the same side of a Slinky®, their amplitude is twice that of each pulse.



Question 3. When two pulses or waves add together to form a wave or pulse equal to the sum of the two separate waves or pulses, the waves are said to *interfere constructively*. When the two waves cancel each other out, or when one subtracts from the other when they are not the same size, the waves are said to *interfere destructively.* In the first case it is called *constructive interference*; in the second case it is called *destructive interference*. If the diffraction patterns that you observed with a single slit, double slits, and a diffraction grating can be explained with a wave model, then we must find a way to determine the conditions under which these two kinds of interference occur.

The figure above shows waves on the surface of water being produced one after another by little balls bobbing up and down at the same frequency. Each bright circle surrounding a ball is a wave crest, and each dark circle is a wave trough. The distance between two consecutive bright circles—the distance between two consecutive crests—is the wavelength of the water wave.

Suppose that the lines of calm water correspond to the dark bands in a diffraction pattern and that the bright lines of wave crests and deep troughs correspond to the bright bands in a diffraction pattern. Then, if light behaves like water waves to form a diffraction pattern, we should be able to determine a condition for this to occur.

To find a condition for the bright lines of wave crests, count the number of waves from one of these bobbing balls out to some bright crest and then count the number of waves from the other bobbing ball to the same bright crest. How do these distances, expressed in wavelengths, relate? Do the same for several bright crest lines at several distances from the sources.

Next, determine when a line of undisturbed water occurs by counting wave crests and/or wave troughs from each of the two sources to the same point. If you have difficulty finding the crests or troughs, use a compass to make your own overlapping circles on paper. Now see if you can answer the following questions: What is the condition for constructive interference? What is the condition for destructive interference?

Answer: Students will need to carefully examine the figure of water waves, or their compass-drawn concentric circles, about two points. Then they can easily see where two circles cross and where one circle crosses the midpoint between two circles from the other "source."

Students have learned that two waves can add together to form a wave with a larger amplitude, which is called *constructive interference*, or they can cancel each other out, which is called *destructive interference*. When students examine the circular wave crests produced by two sources producing water waves at the same frequency or, equivalently, concentric circles from two centers located close to one another, they will discover that constructive interference occurs whenever the path difference from the two sources to this point of observation is 1, 2, 3, 4, . . . , or any integral number of wavelengths. When the path difference is 1/2, 3/2, 5/2, . . . , or any half-integral number of wavelengths, there is destructive interference.

Adapted from: none

Science as Inquiry

Measuring the Wavelength of Light

If light behaves like a wave, what are its wavelengths?

Overview:

In Activity 3 students learned that two waves can add together to form a wave with a larger amplitude—constructive interference—or they can cancel each other out—destructive interference. When they examined the circular crests of water waves from two sources that produce waves at the same frequency, they observed that constructive interference occurred whenever the path difference from the two sources was 1λ, 2λ, 3λ, 4λ, . . ., or any integral number of wavelengths (λ is the symbol used for wavelength). When the path difference was (1/2)λ, (3/2)λ, (5/2)λ, . . ., or any half-integral number of wavelengths, destructive interference was observed.

To apply a wave model to light, we must see if these conditions lead us to expressions for the wavelengths of light. If we make such observations, and we find the alternating bright and dark bands meet these conditions, then the wavelength we assign to a certain light can provide us with a wave model of light.

Suppose that we shine light from a laser pen—light of a single red color—through a diffraction grating. Figure 1 below shows how that light passes through an adjacent pair of the thousands of slits on the grating. We have chosen a bright band of red light on one side of the central bright band, and have set the condition that the path difference from the two slits must be one wavelength of the light.

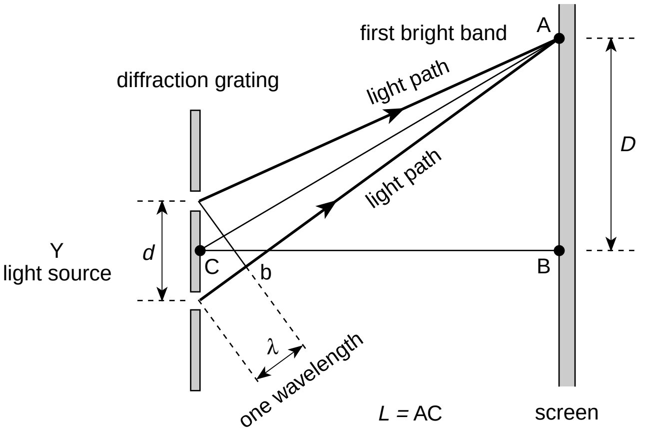


Figure 1

When the distance CB is great enough, the triangle formed by the two slits and point b is similar to the triangle ABC. From geometry we know that when two triangles are similar, corresponding sides have the same ratio. This allows us to set up an equation where we set these two ratios as equal. In this case, the ratio 'one wavelength/separation of the two slits' must equal the other ratio of corresponding sides of triangles 'distance from point B to point A along screen/distance AC.'

Using symbols, we would have the ratio

$$\lambda/d = D/L,$$

where D is the distance along the screen from the center maximum to the first bright band, L is the distance from that bright band back to the grating, d is the distance between two adjacent slits on the grating, and λ is the wavelength of the light. We can find the wavelength then as

$$\lambda = d(D/L).$$

Materials:

Per lab group:

laser pen (red light)
diffraction grating and holder
incandescent lamp with clear bulb and straight vertical filament, no reflector
spectrum tubes and spectrum power supply (optional)
poster board (large, white) to use as screen

Procedure:

Have students place a diffraction grating into a holder on a long flat tabletop. The screen should be placed so that it is precisely one meter away from the grating. Students then shine the light from the laser pen beam through the grating onto the screen. They should have the laser pen mounted so that the light beam is fixed and does not move. Make sure that they have the grating lines oriented so that the diffraction pattern produced by the grating is to the left and right of the center spot on the screen (instead of being up and down from that spot).

Students should carefully measure the distance from the center spot to the center of the first bright spot on one side of the central spot. This is distance D in the equation. They then measure the distance from that first bright spot to the center of the grating. This is the distance L in the equation (Figure 2). To get distance d they need to calculate the distance between two slits. Many gratings have 7,500 lines/cm. You will need to tell them the number of lines/cm for their gratings. If there are 7,500 lines/cm, then the distance between lines must be (1/7,500) cm, or d = 0.000133 cm.

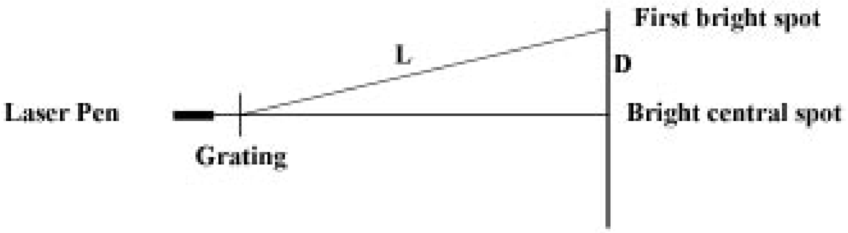


Figure 2

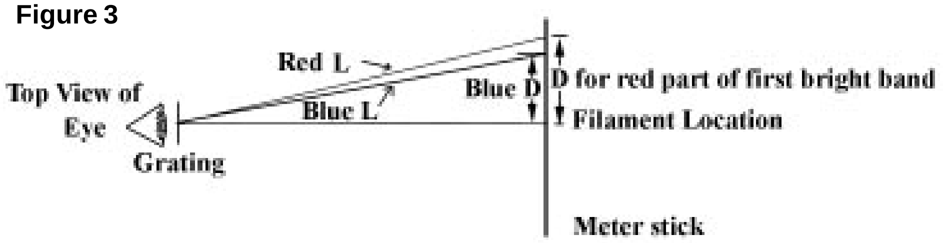
Using the correct value for d for their gratings, students should calculate the wavelength of the red laser light. Many laser pens have the wavelength marked on them. Students should look for that wavelength and compare it with the value just measured.

What about the light from the filament of a clear incandescent bulb? If one were to form a light beam and pass it through the grating, the result would be too dim to see on the screen. Instead, one can use his or her own retina as a screen. The same kinds of measurements can be used to determine the wavelengths of the different colors of light.

Have students mount the grating at the edge of a tabletop so that they can place one eye up against the grating. They should place the light bulb at the other end of the tabletop with the filament aligned with the slits of the grating (Figure 3). Then one lab partner holds a meter stick directly above and at right angles to the light bulb filament as another student looks through the grating. As the student looks at the light source through the grating he or she will see the first bright bands of color, one on each side of the central maximum.

The lab partner holding the meter stick should carefully measure the distance from the center of the light bulb filament to the red part of the first band of color that the student looking through the grating sees. They then measure the distance from that location to the center of the grating. These are the values of D and L needed in the equation for wavelength. Next, students should make the same measurements for the purple color in the bright band. They will get slightly different values for D and L. They might do the same for other colors of light in that bright band.

Figure 3



Background:

The fundamental relationship that path differences must be integral for constructive interference is basic to this measurement application. There is more involved, however. The two sources must be temporally coherent. That is, they must be "in phase." If two sources are out of phase, or if the phase varies, then the lines of constructive interference will move all over.

If you are uncertain about the number of lines/cm in your gratings, you may want to use a grating with a known wavelength of light (either the laser pen or a spectrum tube) to calibrate your gratings. The relationship

$$\lambda = d(D/L)$$

is, of course equivalent to

$$n\lambda = d(\sin \varphi), \quad \text{where } n = 1, 2, 3, 4, 5, \ldots,$$

where φ is the angle formed by a normal to the grating (and normal to the screen) and the ray from the grating to the screen, and where values of n correspond to the order of bands from the central maximum.

In this derivation, students have to be convinced that the rays of light from the two slits are so far from the screen that they are essentially parallel. You can show that by drawing these lines carefully on the chalkboard over a great distance.

Additional Activity:

If your lab has spectrum tubes, have students make measurements of the different colors of light from various gaseous elements like hydrogen, helium, or neon. Or, if they can find a neon sign somewhere, have them use it to make measurements.

Since the Thomson model of the atom would have light from sources like neon or helium as continuous, the existence of line spectra, as students see with the spectrum tubes, is very important. Also, the fact that each element has its own spectrum allows one to determine the elements present in any source of light. For example, helium was discovered on the sun before it was discovered on Earth. Certain lines were observed in the sun for which no comparable element was known to exist on Earth. Later, when helium gas was found on Earth, it was put into a discharge tube and its light analyzed. Lines of light were found that were identical to those previously observed on the Sun. Thus, because of the universality of natural law, we were able to find an element in a star before we found it on Earth.

Answers to Student Questions:

Question 1. What was the value of the wavelength of light from your laser pen? How did this compare with the value given by the manufacturer?

Answer: Typically these values are in the range of 670–680 nm. You may need to explain that a nanometer is 10^{-9} meters.

Question 2. What value did you get for the wavelength of red light from the incandescent bulb filament? What value did you get for the blue or purple part of that light?

Answer: The red wavelength should be somewhere around 700 nm and the purple somewhere around 400 nm.

Question 3. What other wavelengths did you measure?

Answer. The most prominent lines from neon, argon, helium, sodium vapor, etc., can be found in the *Handbook of Chemistry and Physics*. You may want to look these up or you may want to measure some yourself. Better still would be to get student data and find the best in terms of errors.

Question 4. Suppose that you had an intense source of light from an incandescent source like a light bulb, and that you had a grating that would produce intense enough light on a screen that you could see it. There is such a grating—a *reflection grating*. What could you use to see if there is any invisible "light" beyond the red that is visible to your eyes? What could you use to see if there is any invisible "light" beyond the purple that you are able to see? If you had such detectors, you could measure these wavelengths too.

Answers. To detect infrared radiation you could put a temperature sensor like a sensitive thermometer or a thermistor in the region just beyond the deepest visible red. You should get an increased reading. To detect ultraviolet light, you could put some sort of material that will respond to these wavelengths just beyond the visible purple light. (You might direct some of the EM radiation through a hole and into a darkened chamber onto a screen consisting of a phosphor material that emits visible light when struck by ultraviolet light.)

Question 5. Suppose you wanted to see if sound produced diffraction patterns by using a loudspeaker that produced a pure tone of a certain frequency and a large sheet of fiberboard with a couple of slits in it. You could then move to the other side of the board and move around to see if there are alternating loud and silent bands. The wavelength of sound at 440 Hz is about 76 cm. Describe the experimental arrangement, including the size of the slits, their separation, and the distance you would need to move for L and for D.

Answer. This would take a pretty big arrangement. With a 76-cm wavelength, you would need two slits separated by at least five or six wavelengths, or at least 500–600 cm. The slits need to be at least two wavelengths. Thus, with slits 1.5 meters each, separated by about six meters, the sound from one huge loudspeaker (or from two speakers in phase) would come through and interfere, producing an interference pattern. At 30 meters from the slits and 3.8 meters from the central maximum, you would hear a first-band maximum.

Adapted from: none

Science as Inquiry

Fuzzy Shadows

Item:

A clear incandescent light bulb has a vertical filament (with respect to the base of the bulb). Suppose that you hold the light bulb so that light moves off the end of the filament toward a ruler 50 cm away. Suppose that the ruler is held 10 cm from a screen. What do the shadows of the long edges of the ruler look like? Are there penumbras? What about shadows off the edges of the ends of the ruler? Are there penumbras?

Answer:

Since the light comes off the end of the filament, it is responded to as a point source by the ruler. The shadows will all be sharp. There will be essentially no penumbra, either off the long edges or off the ends of the ruler.

Science as Inquiry

An Eclipse of the Sun

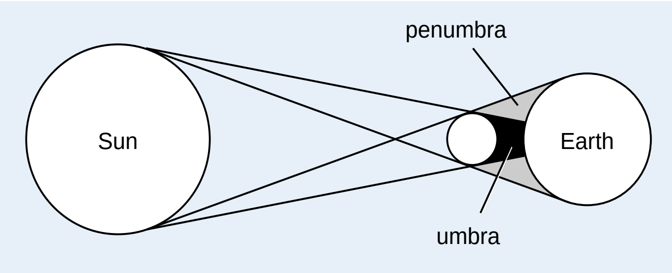
Item:

When the moon eclipses the sun, a shadow of the moon is produced on Earth. Draw a diagram that shows how that shadow appears and label different parts of the shadow. Draw ray diagrams from the sun to the moon and to Earth, showing how that shadow is formed.

Answer:

There is both an umbra and a penumbra. Earth acts as a huge screen, so the shadow covers only a very small portion of Earth, which is visible only to people who are at that location.

The diagram would appear as follows:



Science as Inquiry

On the Head of a Pin

Item:

Suppose that you make a tiny hole in a black sheet of paper at the end of a closed box. Then suppose that you allow light from the sun to strike the black paper so that sunlight covers the hole and the sun's rays are at right angles to this black surface. Finally, suppose that there is a screen inside the box at the opposite end. What will be observed on that screen?

Answer:

There will be a diffraction pattern on the screen, with a bright spot in the center of the screen. This bright spot will be surrounded by alternating bright and dark bands. This pattern on the screen will be many times larger than the hole in the black paper at the other end of the box.

Science as Inquiry

Slinky Pulses

Item:

A Slinky® has been stretched a distance of 10 meters. Persons at each end send pulses simultaneously toward each other. One person sends a pulse having an amplitude of 20 cm, and the other person sends a pulse having an amplitude of 30 cm. If the pulses are on the same side of the Slinky®, what is the amplitude at the instant they cross each other at the midpoint? If the pulses are on opposite sides of the Slinky®, what is the amplitude when they cross?

Answer:

On the same side, the two pulses add, so the pulse would be 50 cm in amplitude as they cross. When on opposite sides of the Slinky®, the pulses still add, but algebraically. This means that we find the difference and assign the sign of the larger in absolute value. Thus, the amplitude is 10 cm. The 20 cm pulse canceled 20 cm of the 30 cm pulse, leaving 10 cm.

Science and Technology

Listen to that Radio!

Item:

Mary is driving across Kansas toward Colorado and is listening to the radio. She hears FM stations as well as AM stations from all over Kansas and eastern Colorado. When she gets into the mountains west of Denver she discovers that she can still hear the AM stations from Colorado and Utah quite well, even during the daytime hours, but she cannot hear any of the FM stations from cities even as close as Denver. Why is this?

Answer:

The AM signals are about 1,000 kHz in frequency, with a wavelength of 300 meters. Thus, with such a long wavelength, the AM radio waves can diffract—bend—around the mountains so that Mary can listen to those stations. The FM signals are about 100 MHz in frequency, meaning that the wavelength is only 1% as long, or about 3 meters. Such short wavelengths will not diffract around such large things as mountains. Thus Mary cannot listen to the FM stations. Also, at night the AM signals are bounced (refracted) off the ionosphere, and even more AM signals can be heard. FM signals are not refracted enough to return to Earth.

Science as Inquiry

What a Sound!

Item:

Two children are experimenting with sound. They have two garden hoses. One hose has an overlapping extension that allows it to me made longer just by sliding the top hose over the inner hose. Suppose that the hose of fixed length is 20 meters long and the other hose has a length that can be varied by as much as 5 meters. Thus, this hose can be 20 to 25 meters in length.

When the two hoses are both 20 meters, one child plays one tone on a harmonica next to both hose openings. The other child listens at the other end and hears the sound through both hoses. Suppose that the sound has a wavelength of 0.6 meters. How far would the extendable hose have to be lengthened at the far end so that the child would hear no sound when the two hoses were joined so that the sounds from each hose came together at that end? How far before the sound became loud again?

Answer:

The path difference for destructive interference would be 1/2 wavelength. So the hose would have to be lengthened at the far end 0.6 m/2, or 0.3 m, or 30 cm. For the sound to be made loud again the hose would have to be lengthened by 1 wavelength, or 0.6 meters, or 60 cm.

Science and Technology

How Close Are Those Slits?

Item:

Suppose that you are given a very high-quality diffraction grating, but you do not know how many lines per cm it has. You carefully set up an arrangement whereby you look at the light from a sodium vapor source. The brightest line by far from this source is at 588.995 nm. There is a another line very close to this line that is only half as bright at 589.5924 nm. You carefully measure D and L for the first bright maximum beyond the central maximum for the brightest of these two lines. Your results are $D = 36.81$ cm and $L = 100.00$ cm. How many lines/cm does this grating have?

Answer:

Using the equation, $\lambda/d = D/L$, and solving for d, we have $d = \lambda(L/D)$. In this case this gives us $d = 588.995$ nm (100 cm/36.81 cm), or 1,600 nm for the slit width. This would be 0.0001600 cm. This is the number of cm per slit. If we want the number of slits per cm, we take the reciprocal of this number, or 1/(.0001600 cm), and this gives us 6,250 lines/cm.

Consumable Materials

Item	Quantity per lab group	Activity
heavy paper or cardboard	2 small folded pieces	3
poster board (large, white) to use as screen	1 sheet	1, 4
poster board (to draw concentric circles on)	4 sheets	3
notebook and graph paper	—	all

Nonconsumable Materials

Item	Quantity per lab group	Activity
compasses (to draw concentric circles)	4	3
diffraction grating and holder	1	4
diffraction gratings (7,500 lines/cm)	4	2
filters	1 red, 1 blue	1
incandescent lamp with clear bulb (100–200 watts) and straight filament (no reflector)	1	4
incandescent lamps with clear bulb (100–200 watts) and straight filament (no reflector)	2	1, 2
lab slides painted black with one slit	4	2
lab slides painted black with two slits	4	2
laser pen	1	4
meter stick	1	1
ruler	1	1
Slinky® (large)	1	3
spectrum tubes and power supply (optional)	1	4
straightedges	4	3

Key to activities:
1. Shadows of Light
2. Shadows of Light: Another Look
3. Creating a Model to Explain Diffraction
4. Measuring the Wavelength of Light