SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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Learning Sequence Item:

1036

Wave Phenomena and the Electromagnetic Spectrum

March 1997
Adapted by: Bill G. Aldridge

Contents

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

Science as Inquiry

Shadows of Light

What makes a shadow sharp or fuzzy?

Overview:

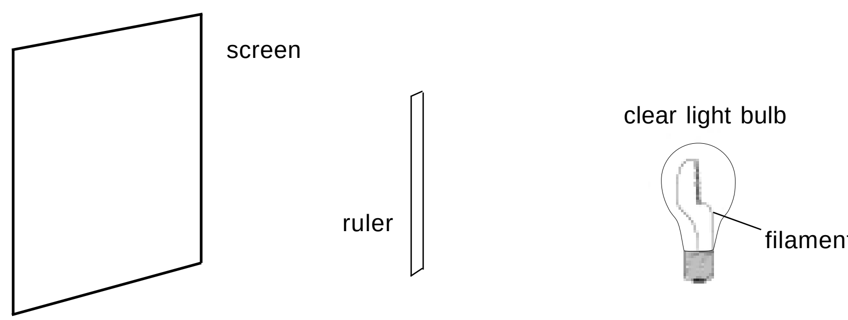
You have previously made observations that show that light travels in straight lines when it is not interacting with something. There are other things about light that you have probably observed but may not have thought about. With the lights turned on in this room, what kinds of shadows are formed?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

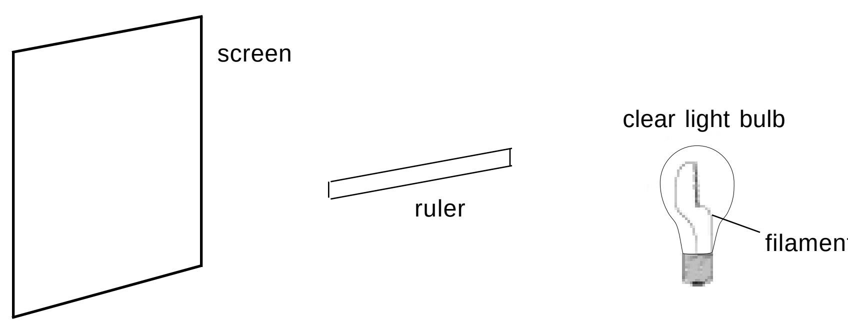
In this activity you'll investigate these questions and find answers for yourself.

Procedure:

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

Place the ruler about 30–60 cm (1–2 ft) from the bulb in a vertical position. Look carefully, comparing the shadows produced by the edges of the ruler with the shadows produced by the ends of the ruler. Slowly move the ruler farther and farther away from the light source as you continue to make these same observations. Then, starting again with the ruler 30–60 cm from the bulb, move the ruler closer and closer to the bulb as you continue to make observations. Now change the orientation of the ruler to the filament from vertical to horizontal and repeat your observations. Describe the shadows carefully by drawing pictures. Next,





repeat these same observations using a red and then a blue filter placed between the bulb and the ruler.

Now rotate the bulb in various ways, and for each orientation again make observations. Is there any orientation of the filament that gives sharp shadows? Is there any orientation that gives fuzzy shadows? Describe these orientations 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, 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. Measure the distance from the ruler to the screen and from the ruler to the bulb in each case.

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

Finally, make careful observations of the shadows cast by other variously oriented objects, like your hands or fingers, using the light bulb. If the sun shines in your room, form shadows of various objects using sunlight. Try red and blue filters with the sun as the light source.

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

Questions.

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?

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?

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?

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?

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.

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?

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?

Science as Inquiry

Shadows of Light: Another Look

For very small objects, what happens to the shadows?

Overview:

In Activity 1 you observed shadows cast by both extended sources and point sources. You 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)

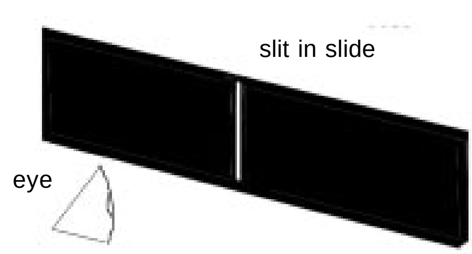
You also observed that the shadows were the same size regardless of whether the light was white, red, or blue.

You saw that sharp shadows are formed by point sources and fuzzy shadows are formed by extended sources. When there are fuzzy shadows, the dark part is called an umbra and the fuzzy part is called a penumbra. You saw that a penumbra is darkest at its boundary with the umbra and becomes successively less dark as you move outward on the screen to where you see no shadow. You learned that a penumbra is produced because different parts of the extended source, from the full source to an edge of the source, 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 you will use your own eye retina. Painted microscope slides with vertical slits will provide the shadows. As you look at the light bulb through these narrow openings, shadows are formed inside your eye on the retina. You will then "see" these shadows, just as you saw them on the screen.

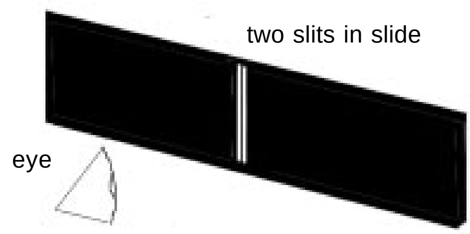
Procedure:

After your teacher has darkened the room, place the slide with one slit next to your eye and look through the opening at the filament of the light bulb. The slit should be oriented vertically with the filament. Describe what you observe.

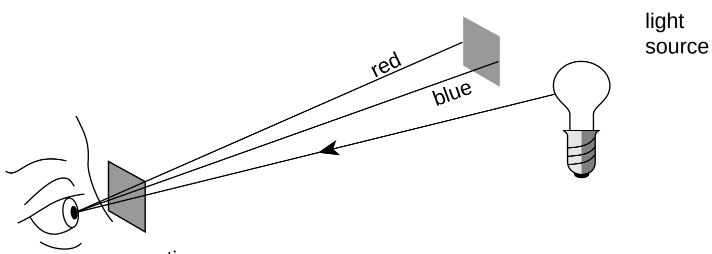


Look carefully for colors. If you do not see any, try to find a slide with a narrower slit. If you do see colors, where are they? In your notebook, carefully draw what you observe, indicating where the colors, if any, appear. What you have observed is given a name; it is called a *diffraction* pattern.

Now look at the light source using a slide with two slits. What do you observe?



To observe this phenomenon better, especially the colors, you have been given a grating. It is actually a piece of transparent material on which there are thousands of very closely spaced slits. Hold the grating close to your eye and look through the grating at the light source. What do you observe now? Look at the first band of color to the left, as shown in the figure below.



Questions:

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?

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

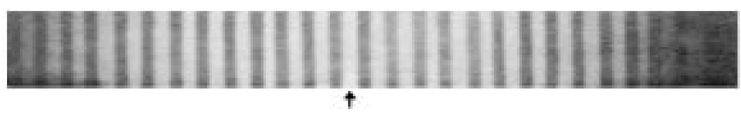
Science as Inquiry/History and Nature of Science

Creating a Model to Explain Diffraction

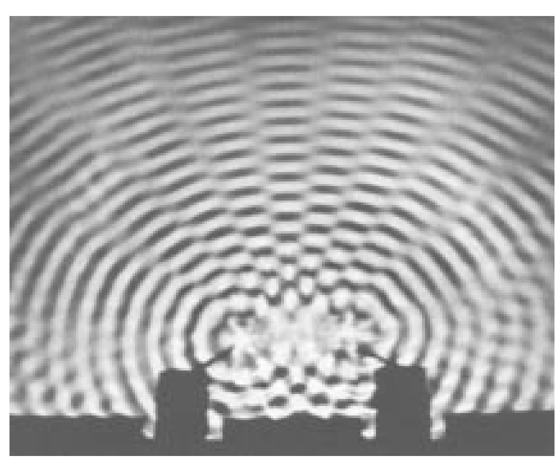
Can we create a model or theory that explains why light forms diffraction patterns?

Overview:

In Activity 1 you learned how shadows are formed, and how point sources and extended sources cause fuzzy or sharp shadows. In Activity 2 you 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 you looked at the straight filament of a light bulb through a single slit, what you observed were the alternating light and dark bands shown below.



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.



When Thomas Young first observed double-slit patterns like those you saw, he wondered how he might explain this strange phenomenon. When we want to explain something using a model, we often relate it to other things we have seen or experienced. This is what Young did. He thought about the alternating bands of light and dark that he had observed and saw a connection between these alternating bands and the kinds of alternating bands of waves he had seen on water near inlets or jetties. He wondered if light behaves like a wave, and if so, could he explain diffraction using a wave model? The figure here shows the wave pattern produced by two small balls bouncing up and down on the surface of water. Note 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.

Procedure:

This activity requires that one person hold one end of a Slinky® while another person holds the other end. Then each person can produce a pulse from his or her end and watch it move down the Slinky®. This will take some practice.

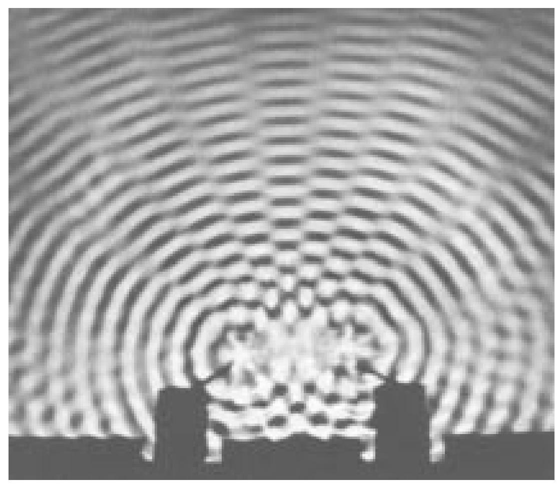
To start the experiment, place a folded piece of paper next to the Slinky® at about the midpoint between the two persons holding the ends. Place the paper so close to the Slinky® that it will not allow either pulse to pass. One person should send a pulse down one side of the Slinky®, while the other sends a pulse down the other side. They should try to make the two pulses cross each other right where the piece of paper is marking the midpoint. If the Slinky® hits the paper, replace it until the two pulses pass each other at the midpoint without disturbing the piece of paper.

Next, 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. Two of you should try again to send pulses at the same time, but this time on the same side of the Slinky®. The goal is to have the pulses reach the center at the same time. When this happens, what do you observe?

Questions:

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?

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?



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?

Science as Inquiry

Measuring the Wavelength of Light

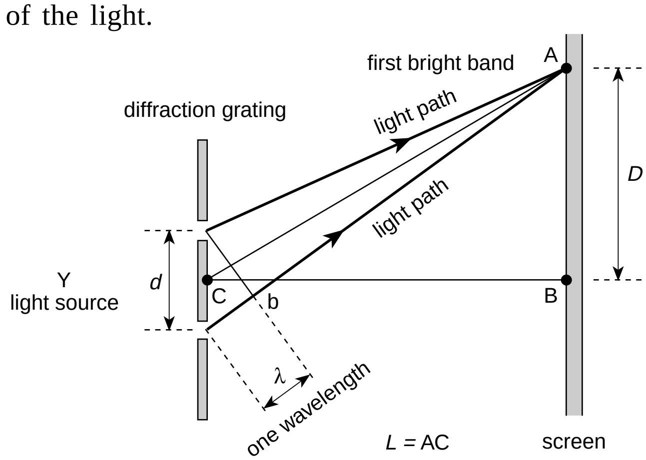
If light behaves like a wave, what are its wavelengths?

Overview:

In Activity 3 you 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 you examined the circular crests of water waves from two sources that produce waves at the same frequency, you 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 $(1/2)\lambda$, $(3/2)\lambda$, $(5/2)\lambda$, . . ., 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. The figure below 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.



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

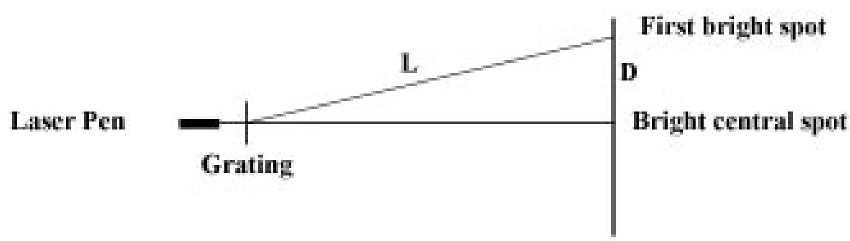
$$\lambda/d = D/L,$$

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

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

Procedure:

Place the diffraction grating into a holder on a long flat tabletop. Place the screen so that is precisely one meter away from the grating. Now shine the beam from the laser pen through the grating onto the screen. Have the laser pen mounted so that the light beam is fixed and does not move. Make sure the grating lines are 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).



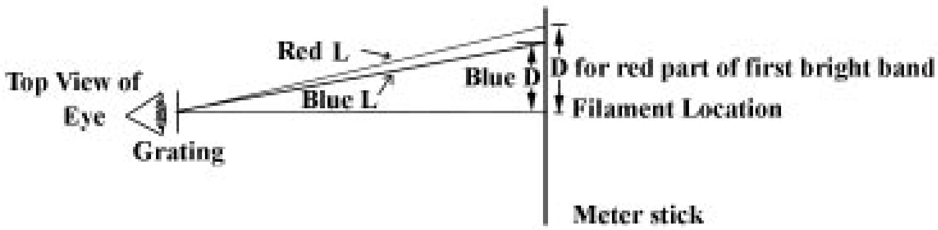
Carefully measure the distance from the central spot to the center of the first bright spot on one side of the central spot. This is distance D in the equation. Then measure the distance from that first bright spot to the center of the grating. This is the distance L in the equation (Figure 2). To get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

Use the correct vaue for d for your grating and calculate the wavelength of this red light. Many laser pens have the wavelength marked on them. Look for that wavelength and compare it with the value you just measured. Knowing the wavelength of the laser pen, you can use it to determine the separation of lines on the grating.

What about the light from the filament of a clear incandescent bulb? If you were to form a light beam and pass it through the grating, the result would be too dim to see on the screen. Instead, you can use you own retina as a screen. You will find that you can make the same kinds of measurements to determine the wavelengths of the different colors of light.

Mount the grating at the edge of the tabletop so that you can place one eye up against the grating. Place the light bulb at the other end of the tabletop with the filament aligned with the slits of the grating. Have a lab partner hold a meter stick directly above and at right angles to the light bulb filament as you look through the grating. As you look at the light source through the grating you will see the first bright band of color.

Have your lab partner carefully measure the distance from the center of the light bulb filament to the red part of the first band of color that you see. Then measure the distance from that location to the center of your grating. These are the values of D and L you need in your equation for wavelength. Next, make the same measurements for the purple color in the bright band. You will get slightly different values for D and L. You might do the same for other colors of light in that bright band.



If your lab has spectrum tubes, make measurements of the different colors of light from various gaseous elements like hydrogen, helium, or neon. Or make measurements of neon if you can find a neon sign somewhere.

Questions:

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?

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?

3. What other wavelengths did you measure?

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.

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.