Diffraction: Seeing around corners

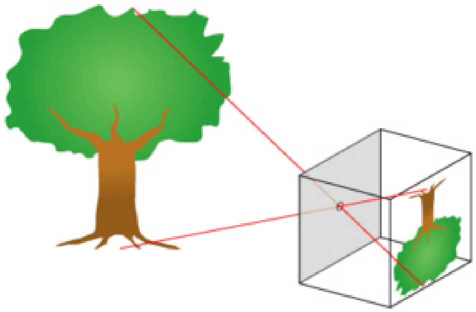
In Activity 1 we used a device called a diffraction grating to observe the spectra of several different sources of light. But how does the diffraction grating work? Why is it able to separate the colors of light? The short answer is that the diffraction grating works because light is a wave. But what does that mean? The next two Activities will provide the long answer. Between the extremes of radio and x-rays lies a narrow portion of the spectrum known as visible light. This band of radiation is the only portion of the electromagnetic spectrum to which our eyes are sensitive. Many of us are familiar with the essential colors of the visible spectrum through the band of colors (red orange yellow green blue purple) that we see when we look through a prism or at a rainbow. This visible spectrum provides us with much of our information regarding the external world.

So what is a wave?

First we need to be clear about what we mean when we talk about a wave. It is not as obvious as it might seem. The term wave refers to a disturbance that carries energy from one place to another without permanently moving any matter. For example, a quick snap of a telephone cord produces a pulse that will travel down the length of the cord. However, the cord itself is in the same position as before the wave was created, it hasn't moved across the room with the pulse.

If the telephone cord is moved up and down repeatedly, a series of pulses will be produced. This collection of up and down pulses, or crests and troughs, is called a periodic wave. Since most waves we will be discussing in this unit are periodic waves, we will simply use the general term "waves".

In taking about periodic waves there are two important terms that come up, wavelength and amplitude. All periodic waves have these two characteristics which are shown in Figure 1 above. The wavelength is the distance between two adjacent peaks or troughs (or any two identical points on the waveform). The amplitude of a point on a wave (amplitude of a crest or trough, for instance) is just the distance that point is away from the average value of the wave. When we refer to the amplitude of an entire wave, we usually mean the maximum value of the amplitude of the wave, that is, the height of a peak or the depth of a trough.



Modeling light: geometric optics

Dating back to ancient Greece, geometrical optics is by far the oldest model proposed for describing the behavior of light. Based on the assumption that light travels in straight lines, it handily explains shadow formation (Figure 2.a.) and the production of images by pinholes (Figure 2.b.). For centuries, geometrical optics has been successfully applied to problems associated with a wide range of optical devices including mirrors, lenses, microscopes and telescopes (Figure 2.c.).

As the above figures indicate, geometrical optics employs straight lines with arrows, known as rays, to indicate the path of light. Geometrical optics works well as long as the wave nature of light is of no concern, that is, when the dimensions of an object are considerably larger than the wavelength of light illuminating it. When this is not the case, light tends to “diffract” or spread into regions that would otherwise be in shadow.

Diffraction: a characteristic of all waves

We rarely take notice of our ability to hear around corners. We think nothing of having a conversation with someone who is not within in view. When listening to recorded music, we hear the low notes loud and clear even though the bass-producing “sub woofer” is hidden behind a piece of furniture.

Our ability to hear around corners really hasn’t as much to do with our ears as it does with a characteristic of waves known as diffraction. Diffraction is the bending of waves as they pass by obstacles or through openings. Diffraction becomes most pronounced when the size of the obstacle or opening is comparable to the length of a wave. Since sound waves have dimensions that are very close to the width of a chair or door, they bend a around and through household-size objects and openings with ease.

Diffraction effects are also observed with water waves. Figure 4, shows a water wave passing through a small opening in a barrier. Notice how the wave spreads out into regions on either side of the opening. Light, on the other hand, does not seem to bend around corners. We are all familiar with the shadows that are created when an object is placed in a beam of light. This result is often cited as proof that light travels only in straight lines.

However, when the shadow cast by a small object is examined carefully, light is found to exist in regions that should be in shadow. First observed in the seventeenth century, this phenomenon demonstrates that light does not necessarily travel in straight lines but rather bends, just as other waves do, when it passes close to the edge of an object or through a small opening.

As is the case with sound or water waves, optical diffraction only becomes noticeable when the dimensions of the barrier or opening are comparable to the wavelength of light, or around one micrometer -- one one-thousandths of a millimeter. For this reason, the diffraction of light is usually overlooked in our daily lives. However, there are examples of optical diffraction all around us. In fact, you might say that diffraction is almost at your fingertips.

To observe diffraction effects using your fingers, view a light bulb through the opening between your index and middle fingers. As you bring your fingers together, you should see that the light spreads out and a pattern of bright and dark lines appears. Notice what happens to the diffraction pattern as you squeeze your fingers together, reducing the width of the slit.

As we age, we begin observing what appear to be little creatures as we look at plain background such as blank wall or a blue sky. Possessing shapes reminiscent of tiny amoebas and paramecia, “floaters” are produced when light diffracts around tiny bits of vitreous gel or other errant cells suspended in the vitreous humor. These diffraction patterns are ultimately projected onto the retina, the light-sensitive part of the eye.

Common Examples of Diffraction

A number of nature’s creatures, besides humans, take advantage of the diffraction of sound. Owls, for instance, are able to communicate across long distances due to the fact that their long-wavelength hoots are able to diffract around forest trees and carry farther than the short-wavelength tweets of song birds. Scientists have recently learned that elephants send out infrasonic waves of very low frequency to communicate over long distances to each other.

Sometimes nature has found it advantageous to limit diffraction effects. Bats use high frequency ultrasonic sound waves with wavelengths smaller than the dimensions of their prey. Instead of diffracting around the prey, these sound waves will reflect off small animals and allow the bat to hunt using nature's sonar.

Designers of home entertainment equipment take advantage of diffraction to simplify speaker systems. Modern sound systems often consist of three speakers: two speakers to produce mid and high range frequencies and a single low frequency "sub woofer." Diffracting around objects in the room, long wavelength sounds emanating from the sub-woofer seem to be coming from every direction and cannot be located. Sounds produced by the sub-woofer will not be blocked even if the speaker is behind a chair or under a couch. This allows the sub woofer to be placed where it can be heard, but not seen. Because of the directionality of higher frequency sounds, their sources must be placed directly in plain view, in front of the listener.

Like all waves, electromagnetic waves diffract. The wavelengths of AM radio signals are roughly 1000 times greater than those of FM. This greatly enhances AM signals ability diffract around obstacles that tend to block FM signals. As a consequence, AM radio stations can often be received hundreds of miles from the transmitting tower whereas the range of FM broadcasts is more limited.

CONCEPTS behind MANIPULATION OF LIGHT

Diffraction is the bending of waves as they pass by obstacles or through openings. Diffraction becomes pronounced when the size of the obstacle or opening is comparable to the wavelength. In some cases, light may pass through openings with dimensions much smaller than the wavelength of light.

Diffraction of Waves

2 ACTIVITY

Make a data table with space to record:

- title of stations you visit
- observations made at each station
- answers to questions posed at each station

Gather these materials for your group:

- all neccesary materials should be at the stations

Think about these questions as you do the activity:

What types of waves have you observed in this lab?

Do all of the waves you observed exhibit diffraction?

What seem to be the important parameters in detremining the amount of diffraction you observe?

This activity is divided into four separate parts.

Part A. Diffraction of Water Waves

Procedure

Record all of your observations when following these steps.

1. Place a wood block upright in the center of the ripple tank. With the dowel rod parallel to the length of the wood block, gently roll the dowel rod forward. Observe the wave as it encounters the wood block.
2. Using as many wood blocks as necessary, form a barrier across the center of the ripple tank. Once the barrier has been constructed, remove one wood block, leaving an opening in the center. With the dowel rod parallel to the barrier, produce a straight wave. Watch as the wave passes through the opening.
3. Using the arrangement of wood blocks used in step 2, reduce the width of the opening to half its original size by sliding all the wood blocks inward. The gaps formed between the ripple tank wall and the end wood blocks should not affect the outcome of the experiment. Observe a wave as it passes through the narrower slit.

Interpretation of the Data and Reflections

1. Does a wood block stop the wave from entering the region behind the wood block or does some of the wave spread into that region?
2. Do you observe any bending of the wave at the edges of an opening formed by wood blocks?
3. Compare your observations in step 3 with those in step 2.

Begin today! No matter how feeble the light, let it shine as best it may. The world may need just that quality of light which you have.

Henry C. Blinn
Shaker Elder

Part B. Diffraction of Light Through Openings

Procedure

Record all of your observations when following these steps.

1. Look at the showcase lamp through the narrow gap formed by holding your index and middle tightly together. Observe how the light is affected by passage through the opening.
2. Hold the aluminum foil containing a pinhole very close to your eye. Look through the pinhole at a distant light source (Note: Never look directly at the sun.) Observe the effect the pinhole has on the light passing through it.
3. View the light source through small (<1 mm) holes of different sizes and shapes.

Interpretation of the Data and Reflections

1. How are the diffraction patterns produced by the various openings the same? How are they different?
2. Try to explain variations in the observed diffraction patterns.

Part C. A Closer Look at Diffraction (optional)

Procedure

1. Find the site http://surendranath.tripod.com/Applets/Optics/Slits/SingleSlit/SnglSltApplet.html
2. Set the light source control to red. With the slit width set at its maximum value, observe and sketch the resulting diffraction pattern produced by the slit.
3. Slowly decrease the slit width and observe changes in the diffraction pattern. Describe the observed changes and sketch the diffraction pattern when the slit has been reduced to half and approximately one tenth its original width.
4. Set the width of the slit to approximately one half its maximum value. Slowly change the color of light emitting by the source. Starting with red light move through orange, yellow, green and blue and observe any changes in the diffraction pattern.

Interpretation of the Data and Reflections

1. How is the amount diffraction affected when the wavelength (color) is held constant and the slit width decreases from its maximum to minimum value?
2. How would you describe the relationship between wavelength (color) and diffraction effect when the slit width is held constant?

Part D. Diffraction through Subwavelength Opening

Instructions for using this simulation can be found at http://www.freewebs.com/northwestemp/Single%20Slit%20Write%20Up.html

1. First make a prediction based on what you have observed in the previous parts of this activity about what will happen when you pass 450 nm light through different width slits. Justify your predictions.

a. 900nm b) 500 nm c) 400 nm d) 200 nm e) 40 nm

2. Using the simulation of light passing through a single slit, observe the diffraction of 450 nm light when the width of opening is:

a. 900nm b) 500 nm c) 400 nm d) 200 nm e) 40 nm

3. Now repeat with a larger wavelength, around 650 nm.

4. As an optional step, try a few different parameters of your own choosing to see if there is a sharp cutoff of transmitted light, or if it is a gradual process.

Interpretation of the Data and Reflections

1. How well did your predictions match up with what you observed? Explain any differences.
2. Describe how the amount of light passing through the opening is affected by the width of the slit and the wavelength of the light.
3. Is there a particular point at which the amount of light passing through the slit drops sharply, or is there a gradual decline? Is it different for the different wavelengths?

Part E. Diffraction of EM waves through a single slit, version 2, metal – Computer simulation (optional)

1. Using the simulation of a light wave passing through subwavelength openings in a metal foil, observe the diffraction of 450 nm light when the width of opening is:

a) 500 nm b) 400 nm c) 200 nm d) 100 nm e) 40 nm

2. Try again, but set the button at the top of the simulation to "ideal conductor." Record your observations

Interpretation of the Data and Reflections

1. Describe how the amount of light passing through the opening is affected by the width of the slit and the width of the wall.
2. What happens for slits much smaller than the wavelength of light? Is there a particular slit width for which something different happens?
3. How are your results in this section different from your results in Part D? What was the difference between using gold (Au) and a perfect conductor?