Diffraction : Taking Light Apart

Teacher Guide

This suite of activities provides an opportunity for hands-on understanding of the phenomenon of **diffraction** of light. Astronomers use diffraction of light to disperse (or spread out) colors of light from astronomical light sources into a spectrum. The spectrum is then used to measure the physical characteristics of that source.

Science Standards

TEKS IPC:

Science concepts. The student knows the effects of waves on everyday life. The student is expected to:
(A) demonstrate wave types and their characteristics through a variety of activities such as modeling with ropes and coils, activating tuning forks, and interpreting data on seismic waves;
(B) demonstrate wave interactions including interference, polarization, reflection, refraction, and resonance within various materials;
(C) identify uses of electromagnetic waves in various technological applications such as fiber optics, optical scanners, and microwaves

TEKS Physics:

(8) Science concepts. The student knows the characteristics and behavior of waves. The student is expected to:
(A) examine and describe a variety of waves propagated in various types of media and describe wave characteristics such as velocity, frequency, amplitude, and behaviors such as reflection, refraction, and interference;
(B) identify the characteristics and behaviors of sound and electromagnetic waves; and
(C) interpret the role of wave characteristics and behaviors found in medicinal and industrial applications.

Prerequisites

Before doing this activity, students should already be familiar with concepts such as the electromagnetic spectrum, wavelengths of light, properties of waves (superposition, constructive and destructive interference, refraction, mechanical vs. electromagnetic waves), prisms & diffraction gratings, and basic trigonometry.

Materials Required

Per group:

- Diffraction Materials Card **Note that the card is incorrectly labeled – the last "hole" is 5000/cm*
    - available from several sources – see http://www.envisionlabs.com/optics.html
- Centimeter ruler and tape measure or meter stick
- Laser pointer
- CD disk - without a label on it

- Prism (for comparison)
- Scientific calculator

Entire Class:
- Incandescent light source

ideally a naked bulb >60W, with no shield around it, and unfrosted
- Fluorescent light source
- Strips of paper with dark lines separated 10cm apart (see section I)…can be substituted with strips of tape
- *optional: applets such as*
  - http://phet.colorado.edu/web-pages/index.html
  - http://id.mind.net/~zona/mstm/physics/waves/interference/waveInterference3/WaveInterference3.html
  - http://www.ngsir.netfirms.com/englishhtm/Diffraction.htm
  - http://perg.phys.ksu.edu/vqmorig/programs/java/makewave/olddouble/Slit.html
  - http://phet.colorado.edu/new/simulations/sims.php?sim=Wave_Interference

A. Engagement

Let's first consider diffraction. It's part of everyday life, in which waves of energy don't seem to move in straight lines.

1. Pick up a CD disk and look at the reflection of a light in it.

   a. In what way does it act like a mirror?

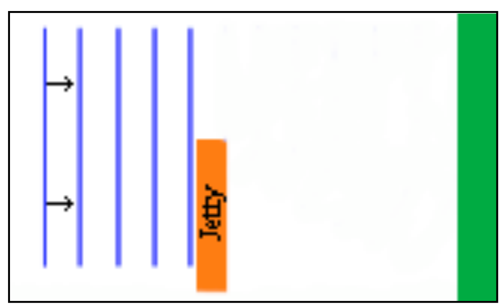
   You can see images of reflected objects, just like in an ordinary mirror

   b. In what way does it not act like a mirror?

   There are rainbow-like colors that seem to be coming from the light that are reflecting off the CD at odd angles.

   (We'll look more carefully at CDs later.)

2. Look at the picture of incoming ocean waves approaching a jetty.



a. Will the jetty block ocean waves entirely?

No.

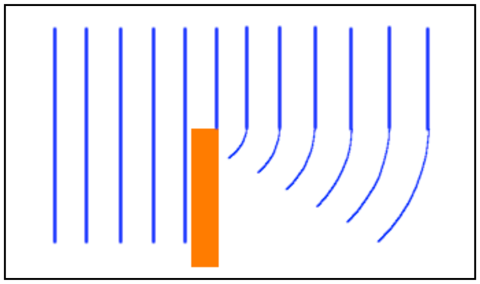
b. Does it make a sharp wave-shadow?

No.

c. Can waves get around the jetty?

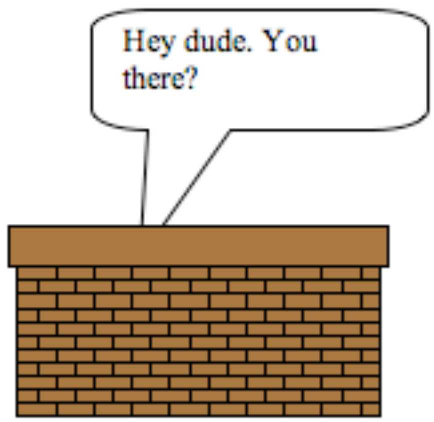
Yes, they can wrap around (diffract).

d. Make a sketch of how the waves behave when they hit an edge.



Here you may wish to have them compare their result to an applet such as
http://www.ngsir.netfirms.com/englishhtm/Diffraction3.htm

3. Your friend is on the other side of a wall. She calls to you. You can't see her, but you can hear her.



a. What type of wave is sound?
It's a mechanical wave (as opposed to an electromagnetic wave)

b. In what medium does sound wave travel?
Air (in this example).

c. Discuss why is it that you can hear her.
Students should appreciate that, in this case, sound didn't travel in a straight line. The sound must have been bent, like the water waves around a jetty. Now, they might also wonder if there was something else that the sound could have bounced off of.

OK, there's something a little strange going on, and we call it "diffraction". We're going to talk about diffraction as applied to light.

Explore

B. Refraction

We can disperse light into a spectrum using materials that bend different colors of light differently when the light travels through them (e.g. prisms, using the phenomenon of refraction). Do the following exercises and answer the questions.

1. Hold the small prism with one finger at the top and one finger at the bottom. Position the prism 2 to 3 inches in front of your eye. Look through one side of it in the direction of the light source.

a. First, look at the incandescent lamp. Observe the colors that are visible as you view the lamp. Record your observations.

A rainbow of colors will be visible near the edges of the image of the light source.

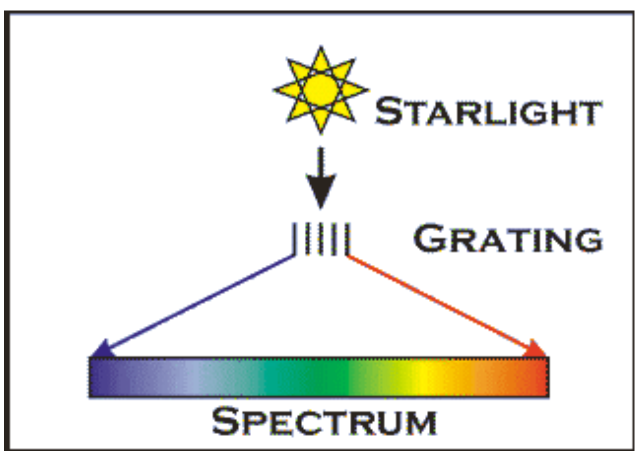
b. Next, view the fluorescent lamp in the classroom. Record your observations.

As in the previous case, a rainbow of colors will be visible near the edges of the image of the light source. But some parts of the spectrum will be brighter.

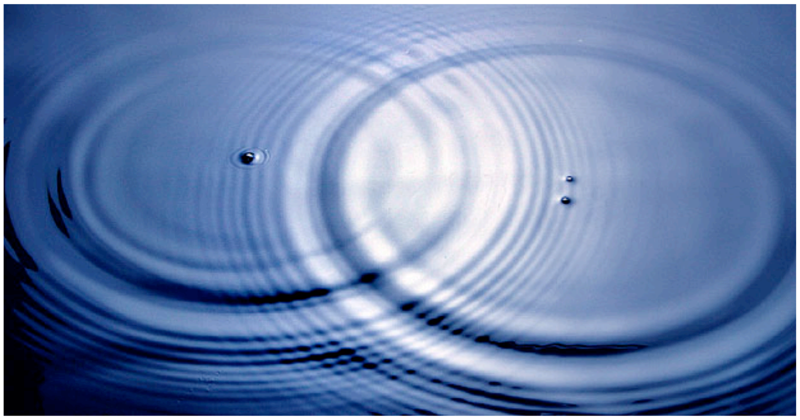
c. What differences and/or similarities did you observe in each light source when viewing through the prism?

A rainbow of colors will be visible near the edges of the image of the light source. But some parts of the spectrum will be brighter with the fluorescent bulb.

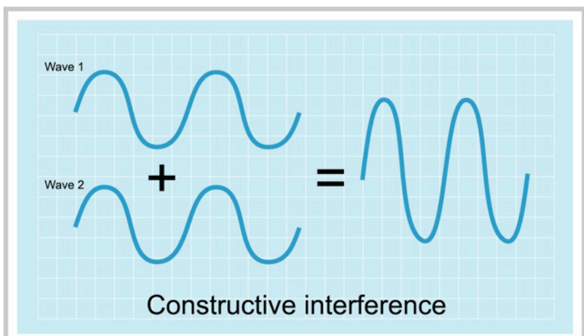
There are also materials that bend different colors of light differently because of a grid pattern on them (e.g. diffraction gratings – using the phenomenon of diffraction). Astronomers like to use the latter, rather than the former, because faint starlight doesn't have to pass through thick pieces of material, that is, some wavelengths that are absorbed in glass are reflected with a grating. Let's learn how these work.

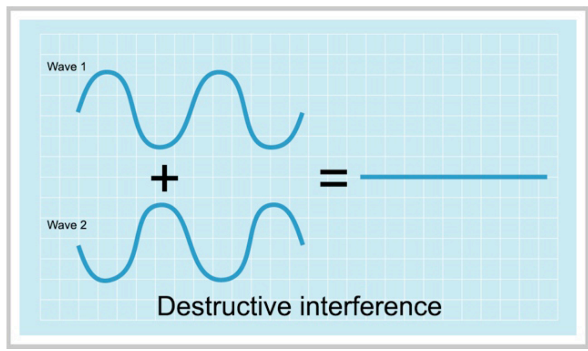


C. Some Background on Light as Waves



When waves from two sources cross, as in the picture above, they either reinforce each other (constructive interference) or cancel each other (destructive interference).





For light waves, there is no "higher" or "lower", like there is for waves in water. Rather, the wave is the direction of the electric field, and when an "up" pointing part of a wave hits a "down" pointing part of another wave, they cancel. For the purposes of this activity, we're going to think about light as traveling in ***plane waves****. That is, although light from a source, whether it be a star or a lamp, radiates outward in spherical waves, when you get far enough away, each peak and dip in the wave can be thought of as being in a plane, and we'll indicate that wave by parallel lines.*

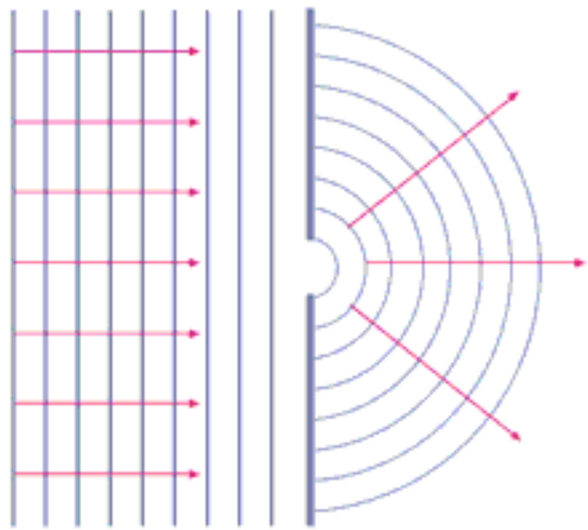
1. Differentiate between constructive and destructive interference.

Constructive interference creates larger amplitudes, destructive results in smaller amplitudes.

At this point, you may wish to show an applet demonstrating interference such as http://id.mind.net/~zona/mstm/physics/waves/interference/waveInterference3/WaveInterference3.html

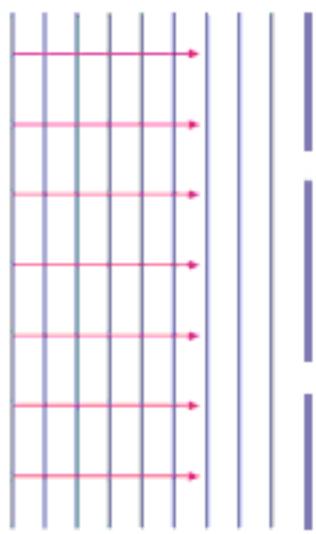
Just like the ocean waves bending around the jetty and the sound waves bending around a wall, light waves can diffract as well. Here is a sketch of how light waves behave when they pass through a small opening…

Light Source)))



2. Sketch how the waves would behave when they pass through two openings.

Light Source)))



Refer to the diagram on page 9 for the answer

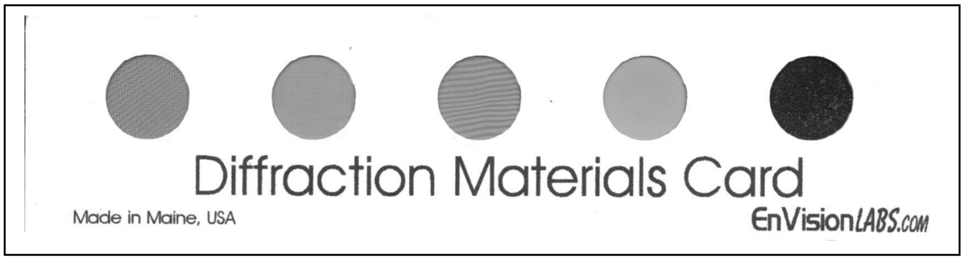
3. Imagine putting a screen somewhere beyond the two slits. Knowing that light waves interfere (constructively and destructively) with each other, what do you think will appear on the screen? (Draw or write your answer)

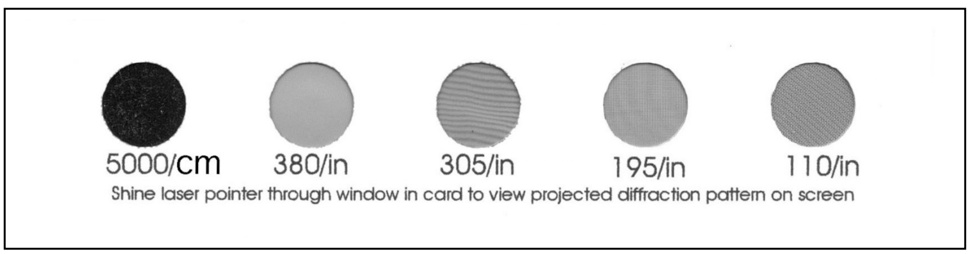
You may wish to show another applet now for the students to compare to their sketches, such as
http://www.ngsir.netfirms.com/englishhtm/Diffraction.htm
An applet for two openings is at

http://perg.phys.ksu.edu/vqmorig/programs/java/makewave/olddouble/Slit.html

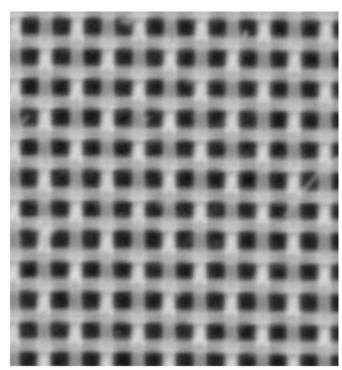
D. Diffraction Materials Card

Each team has been given a “Diffraction Materials Card”, which is a set of materials in five portholes that has lots of holes or slots in a regular pattern. Four of the five materials are fine wire screen (so the holes go in two directions, left/right and up/down). You can see through each porthole, some better than others!





Four portholes have fine wire screen in them. If you looked at them under a microscope (see below), it would look like the picture at right.



The 5000/cm porthole is a special acetate film that has on it a very fine set of parallel ripples embossed on one side. These make the equivalent of one-dimensional holes, or slots. (Astronomers would call them “slits”.) Sorry, you can’t see the slots in this acetate with your naked eye!

Now, the spacing of the holes (in the wire screen) and the slits (in the acetate) is indicated under each one (as in 380/in = 380 slits per inch). Seen from the front, the porthole at the far left has the coarsest spacing, and the one at the far right has the finest spacing.

E. Seeing Diffraction

LASER SAFETY – laser pointers are usually low power devices (~1 mW), but the beam they produce is very concentrated. Even the low power ones can cause permanent vision problems. DO NOT LOOK INTO THE BEAM.

1. Shine your laser through the different portholes, notice the image it creates on a nearby wall or screen. You can hold the laser close to the Diffraction Materials Card, but make sure the wall or screen is about a meter away.

a. Try them all out before drawing anything…then make a sketch of what you see from each one.

110/in	195/in	305/in

380/in	5000/cm

b. Qualitatively, how does the spot separation depend on mesh size?

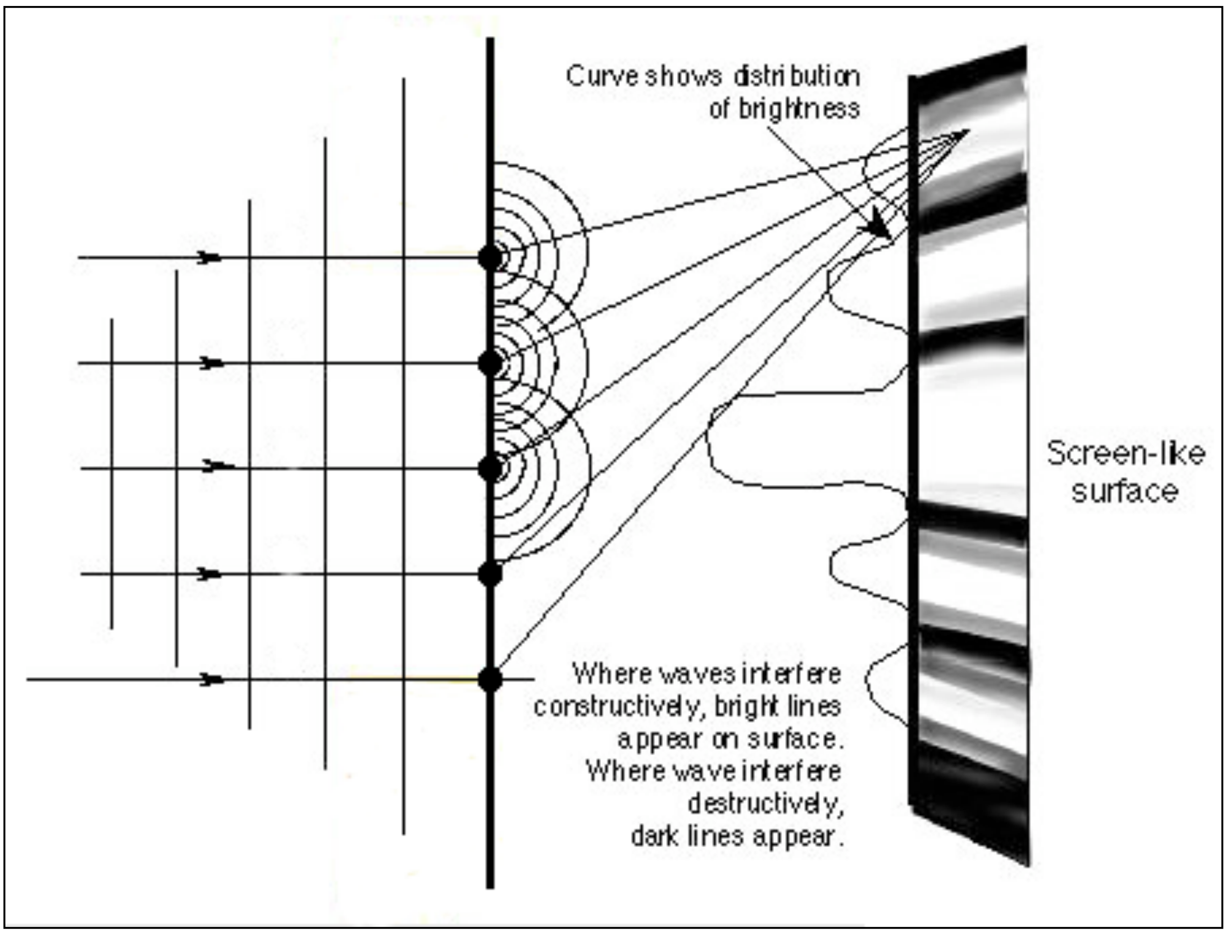
The finer the mesh (the more lines per inch) the farther apart the spots are spread out.

F. Measuring the Mesh

1. Look at the pictures of the portholes (see appendix A) and work out the hole spacing for yourself. Get your ruler, and start counting spots. Note that the size of each porthole is ½ inch. Don't count all the way across. Just do a quantitative estimate. Record your measurements. Then, convert your data to holes per inch. (Recall that 1 in = 25.4 mm, 1mm = 0.0394in)

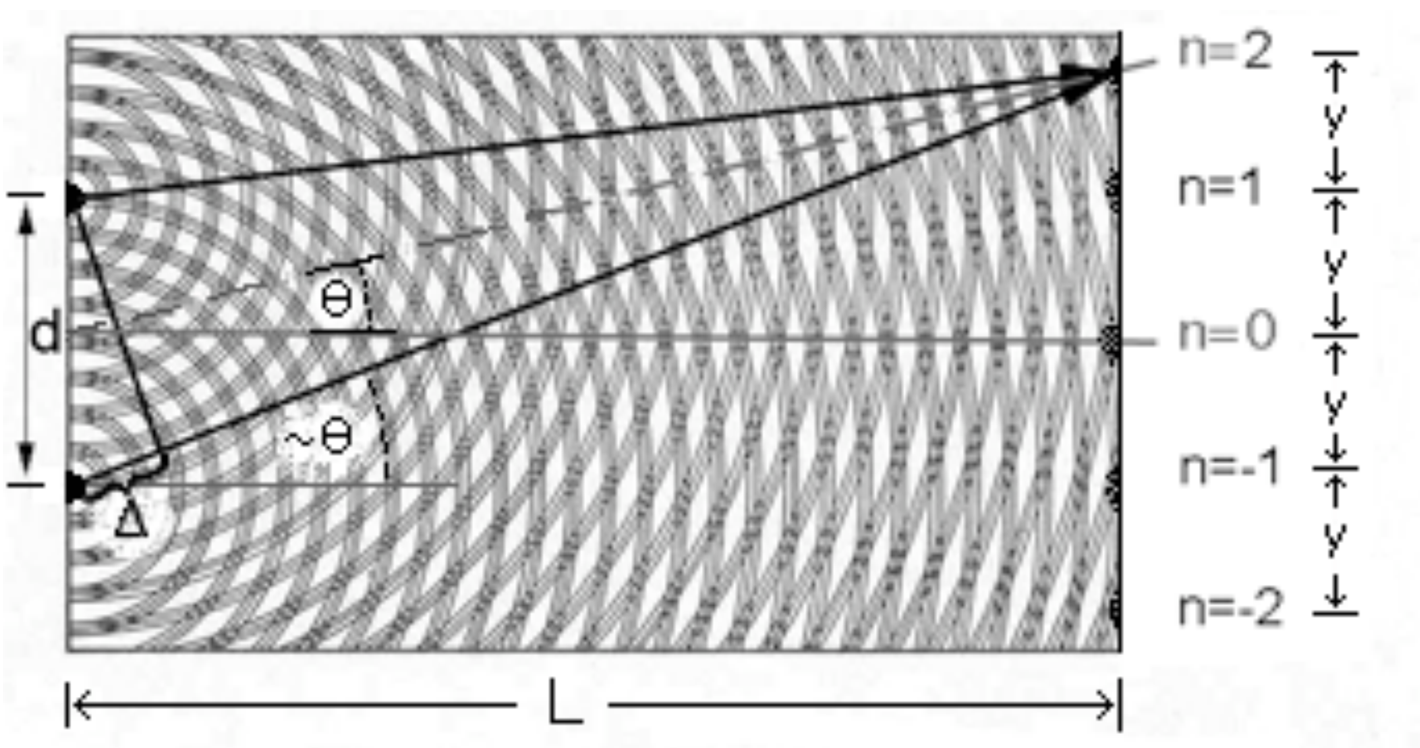
Porthole	Measured spacing "d" (millimeters)
110/in porthole	*0.23 mm*
195/in porthole	*0.13 mm*
305/in porthole	*0.0832 mm*
380/in porthole	*0.0668 mm*

G. Getting the Wavelength of Light using Diffraction



This diagram below shows how diffraction occurs through ‘slits’ (as opposed to the mesh ‘grids’ that are in the porthole). The general principles of diffraction and interference are the same in both cases.

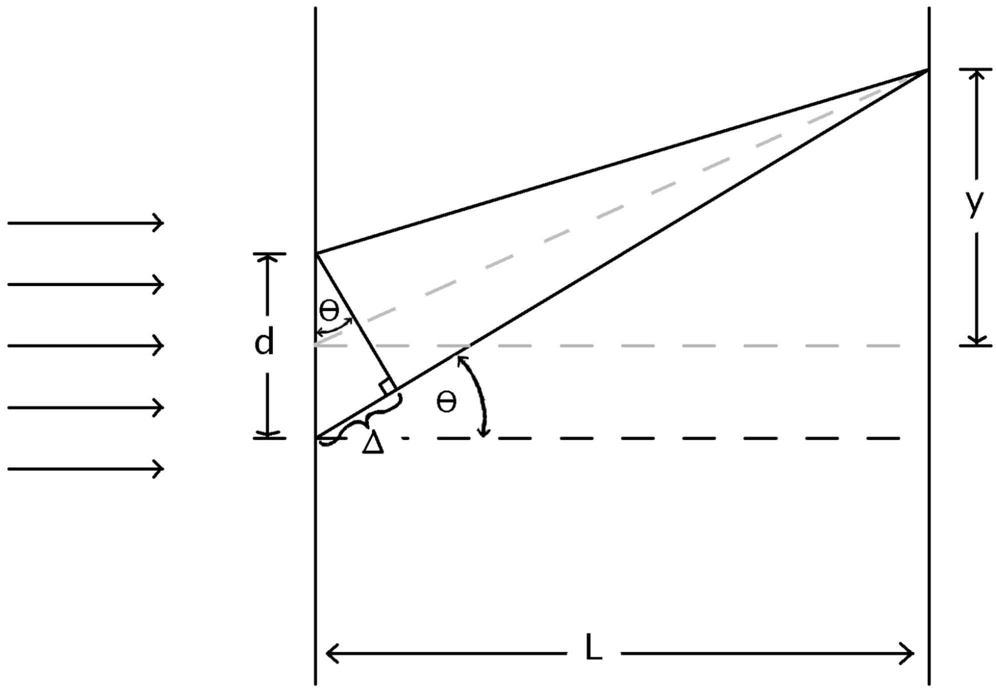
Knowing that the spots that we see through the portholes are caused by constructive interference, and knowing the size of the mesh that lets us see these spots, we can measure the length of the wave of the laser’s light. Of course, waves that we’re familiar with (like ripples on water, or waves in a Slinky that one shakes) are pretty long. Are peaks in the waves of visible light that far apart? Let’s find out…



1. In the diagram above, a plane wave from the left hits these two holes separated by a spacing “d”, and is diffracted to the right. A dashed line marks the path toward the n=2 spot, which is at an angle θ away from the central spot. The spots on the screen are separated by a spacing “y”. In this picture, the rings show the peak of the waves, and the separation of the rings is the wavelength λ.

a. In the diagram, looking at the places where the waves from the holes overlap and interfere constructively, how many spots are labeled across the screen at right?

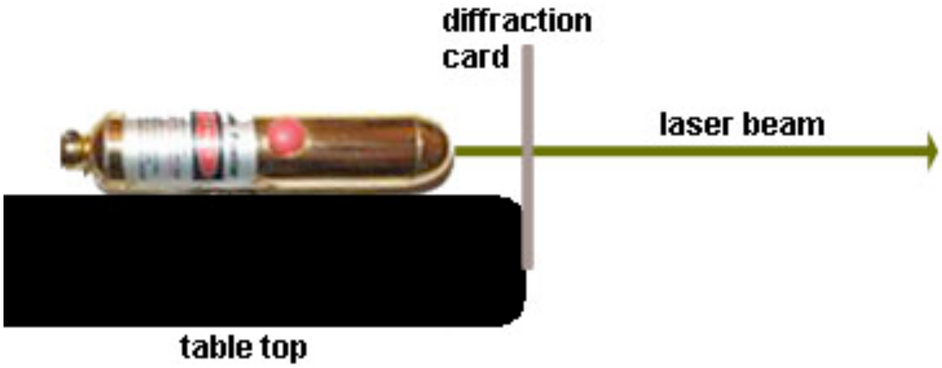
b. Which do you think is the bright spot? *The middle spot*



c. For L >> d, you can use the above approximation of θ. The beam (holes-to-spots) angle should be understood to be identical, by similarity, to the angle opposite Δ and adjacent to d. Derive the Grating Equation $n\lambda = d \sin \theta = \Delta$ either using trigonometry or "small angle approximation" where $\sin \theta \sim \theta$ in radians $\sim y/L$. (Hint: Determine the ratio of the corresponding sides of two similar triangles.)

$$n\lambda = d \sin \theta = \Delta$$

H. Measuring the Wavelength of the Laser Light



Use a laser pointer to do a more quantitative analysis of diffraction. Take the diffraction card with the five portholes and tape it to the side of a tabletop as shown above, so that the portholes are just above the surface of the tabletop. Place the laser on the surface so that the beam can shine through the portholes with the 380/in mesh. Shine the beam perpendicular to a wall. You might put a spring clip on the laser pointer both to hold the button down and to keep it from rolling. Record your observations.

1. Put a white piece of paper on the wall as a screen that is big enough to show the spot separation, and carefully mark where the spots are on the paper.

Measure y – the separation of the spots
Measure L – the distance from the grating to the screen (the piece of paper)

Using the value of d you measured for that piece of mesh, calculate the wavelength of the laser. Remember that

$$\tan \theta = y/L$$

and that (with a separation of a single order difference such that n=1)

$$n \lambda = d \sin \theta$$

Measure the wavelength (λ) of the laser accurately. Yes, it's OK to use the small angle approximation, in which $\sin \theta \sim \tan \theta = y/L$.

a. What answer did you get for the wavelength? Show your work.

Any where between 100 and 1500 nanometers (10^{-9} meters) is a good result. The correct wavelength for red light is around 650 to 700 nanometers.

b. How consistent are the wavelengths of different laser pointers?

The answers may vary a lot, depending mostly on measurement errors.

c. Try this experiment with the CD, in which the laser beam is held nearly perpendicular to the surface of the CD. It may be helpful to reflect the laser beam off of the CD instead of trying to shine it through (CDs can show diffraction either way). Using the wavelength that you discovered in the previous question (red light has a wavelength of about 650 – 700 nm), figure out the groove spacing "d" on the CD.

The actual value is 1,600 nanometers, or 1.6 x 10^{-6} *meters.*

d. On a diffraction grating (like one on the card) what would the spot distribution look like if the spacing of the wires that make the mesh were twice as wide in one direction as in the other?

The spots would be more or less spread apart horizontally compared to vertically.

3. Have a partner slowly move an edge of the Diffraction Card across the front of the laser. Go to the wall or a screen, which should be many meters away, and watch the spot carefully. Does it get cut off uniformly? Compare this spot with the previous unobstructed spot of the laser.

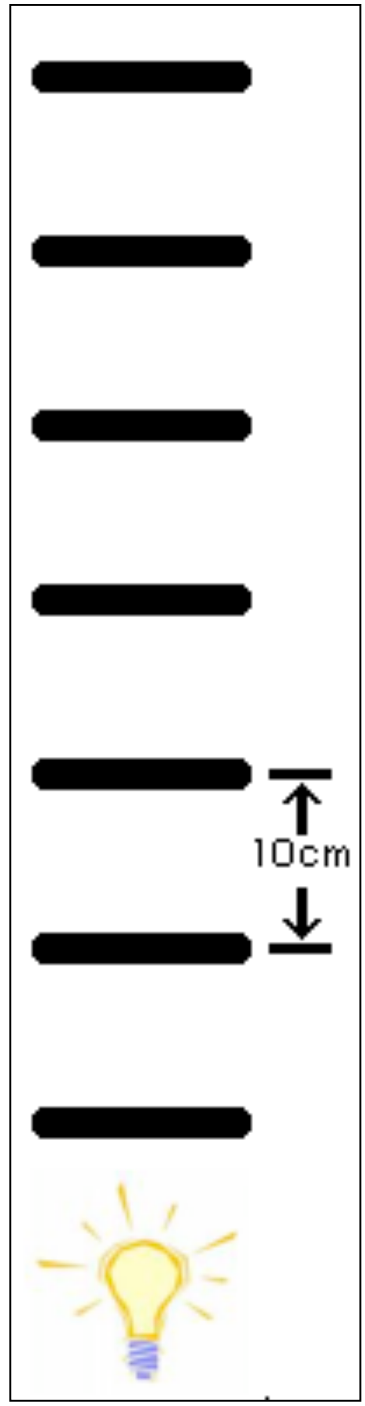
If done correctly, you can see faint light that is bent away from the main beam in the form of spikes on the otherwise round spot.

4. Use the laser to look at the acetate (5000/cm) grating more carefully. As noted, the grating is a set of ripples embossed on one side. Can you use the laser to tell which side? (Hint: use reflection)

The side with the ripples embossed on it will reflect a diffraction pattern (spots).

I. Measurement of Diffraction with the Eye

1. On a wall of the room, make marks (perhaps taping up inch-wide strips of paper or tape that contrast well with the color of the wall) at approximately 10 cm intervals. Put the incandescent lamp near the bottom, so you end up with a wall that looks like this.



a. Hold one of the portholes over one eye and look at the incandescent lamp, perpendicular to the wall. Keep the other eye open and unblocked. Record your observations.

> *VERY IMPORTANT! Students will find that the array of spots won't be of equal brightness. Some will be very faint, and some will be very bright. Ignore that difference. But the spacing of the spots in each direction is a constant.*
>
> *Why are they like that? Suffice it to say that if all the holes were very small, they would all appear about the same brightness. What you're seeing is a superimposed interference pattern from the fact that the holes are finite sized.*

2. Now walk toward and away from the wall until the spots line up with the marks on the wall. For some gratings (especially the 5000/cm mesh size), the spot is such a stretched out rainbow that you'll have to measure one particular color.

a. Use the tape measure or meter stick to get the distance to the wall (L) where the spots line up with the marks for each grid. Fill out the table below with the "d" lengths you measured for the mesh, and your estimated errors for each measurement.

porthole	d (mm)	L (cm)	θ	$\lambda = d \sin \theta$ (mm)
5000/cm	0.0020			
red light				*~700*
yellow light				*~570*
blue light				*~475*
380/in	*0.0668*			
305/in	*0.0832*			
195/in	*0.13*			
110/in	*0.23*			

Astronomers use more convenient units than for the wavelength of visible light.

10000 Ångstroms = 0.001 mm
1000 nanometers = 0.001 mm
1 micron = 0.001 mm

b. What did you find as a rough wavelength of yellow visible light?

In Ångstrom?
In nanometer? *Students should do accurate conversions*
In micron?

c. How many times "longer" is red light than blue light?

Roughly 1½ times as long

d. How does the wavelength of visible light compare to the "spacing" (d) of the "diffraction gratings" in the Diffraction Card?

It is much smaller (thousands of times smaller)

e. How does the wavelength of light compare to other things?

- size of a carbon atom (~2 Ångstroms)
- size of a water molecule (~2 nanometers)
- thickness of a human hair (~50 microns)
- size of a paramecium (~200 microns)
- size of an E-Coli bacterium (~1 micron)
- wavelength of middle C in air (~130 cm)
- wavelength of a disturbance in water (~few meters)

J. Using Diffraction to Explore Compact Disks

1. Take a CD and, in the same way that you did for the diffraction Card, look <u>through</u> it at the bright light. Record your observations.

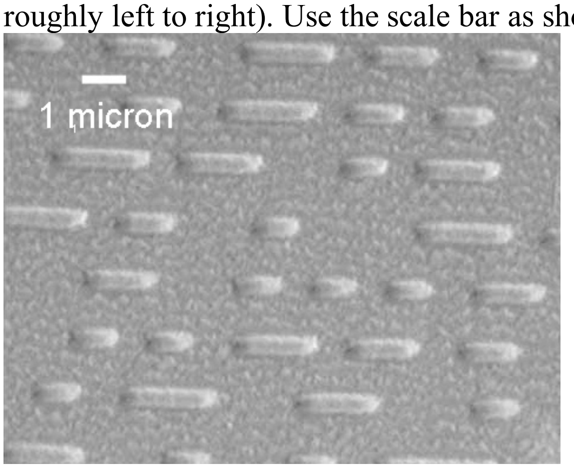
a. Does the diffraction "spot" you see through the CD have an angle that is similar to that of any of the five "diffraction gratings" you experimented with above?

It is somewhat similar to the 5000/cm

b. Can you estimate "d" for the CD using this method? How far apart do you think the tracks are on a CD?

The actual value is 1,600 nanometers, or 1.6 x 10^{-6} meters.

c. Compare your estimate for "d" with the electron microscope picture of a CD shown below, which shows the data bits represented as "pits" or segments on the groove tracks (which run roughly left to right). Use the scale bar as shown where 1 micron = 0.001 mm = 1,000 nm.



d. CDs are written with 650 nm (red) light beams. Is that consistent with the picture above?

Yes, the pits are on the correct scale

e. What are the physical limits for data storage on an optical disk? Calculate this using the 12 cm disk diameter, single side storage, and a writing beam that uses red light.

Students should divide the area of the disk by the area of the smallest spot (0.65^2 square microns). They will get almost $30x10^9$ that, in principle, is the number of "bits" of data one could fit on the disk. A byte is 8 bits, so this would suggest that one could fit about 4 gigabytes on the disk. In fact, a CD can hold only about 500 megabytes. The difference is clear by looking at the picture above. The bits are not packed very efficiently in a CD. See below.

Explain

K. Astronomical Applications of Diffraction Gratings

1. Use a CD to look at the incandescent lamp in reflection directly with your eye, and find the main spot. Why do you think astronomical reflection gratings have slots that are straight lines and not circles as in a CD?

Circles are not as accurate, they produce hard-to-measure diffraction spectrums

2. If the highest precision gratings are ones where the light hits a lot of grooves, why can't we make a grating with d very small, so we can put a lot of grooves onto a small grating? Use the grating equation.

Students should understand that as d gets smaller than λ, sin θ gets to be larger than 1, whereupon the grating won't produce a spectrum!

3. By the same token, what can we say about the sizes of gratings that would be used in the infrared part of the spectrum (longer wavelength), compared with those that we would use in the visual part of the spectrum?

Students should know that infrared light wavelengths are much larger than visual light wavelengths. As a result, the groove separation d has to be proportionally larger. But if you need a certain number of grooves on a grating, that grating has to be proportionally larger to hold them!

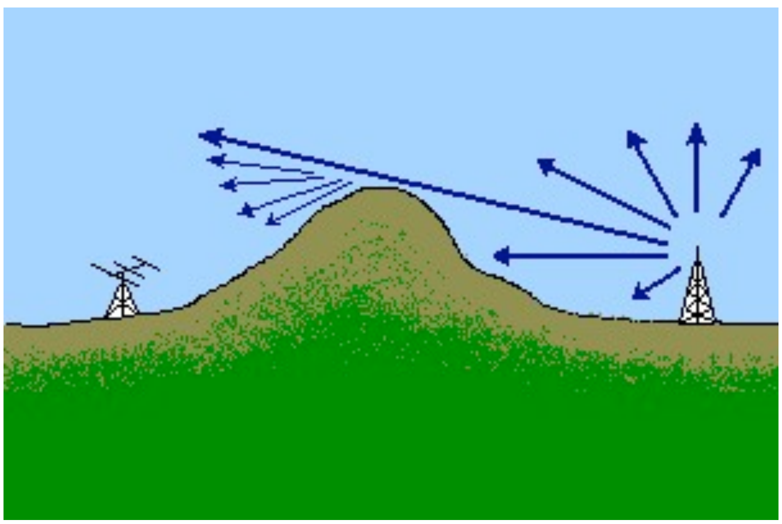
*******THIS IS THE END OF THE STUDENT GUIDE MATERIALS*******

EXTRA INFORMATION FOR THE TEACHER…

See Annex Slide 7

Diffraction is more of an everyday phenomenon than you might realize. While visible light has such a short wavelength, nothing much interesting happens unless you're looking VERY close to the edge, longer wavelengths have larger scale effects. Radio waves are such longer wavelength light waves, and diffraction is important for us using them.

It is commonly understood that we can receive radio transmission without being in the line of sight of the transmitter. An important factor in this is diffraction, which bends some of the radio waves around obstacles. This is not just important for hills (see below), but in cities with buildings all around us. You already thought about this in the engagement activity, when we thought about how sound travels around obstacles!



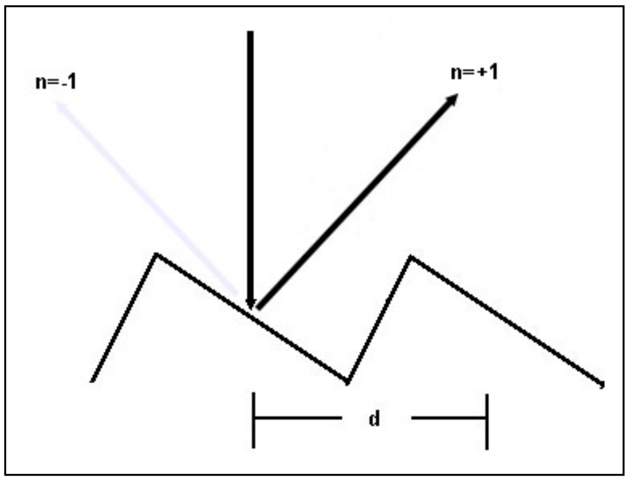
More on Astronomical Applications of Diffraction Gratings

Astronomers use diffraction gratings routinely to produce spectra of astronomical objects. You should understand that if you went outside and held one of our gratings up to a star, there would be spectra off on each side. But stars are so faint, and the spectra are the dispersed light from the faint star, so the spectra would be much too faint to see with the eye. (You could do it for the Sun, though!)

Astronomers use some special grating engineering to be able to take spectra of very faint stars and galaxies.

First, they use telescopes to collect a lot of light, and make these faint objects look brighter.

Second, they use reflecting surfaces for gratings, rather than transmissive surfaces. This is because even for transparent substances like our acetate 5000/cm grating, some light is still absorbed in the acetate. Even if we could make a very, very fine mesh, you can see that such a mesh would actually block a lot of the light. How do you make a reflective diffraction grating? Well, it's a lot like the light reflected off of a CD!

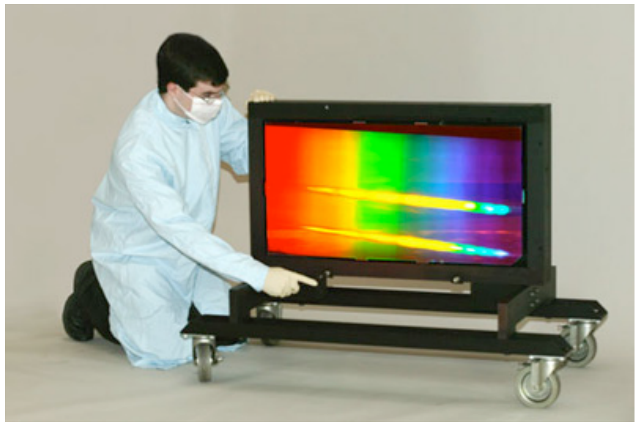


Unlike a CD though, astronomical reflection gratings have slots that are straight lines, and not circles. They are coated with a highly reflective material, to avoid losing light.

Thirdly, there is a strategy to put as much of the diffracted light as possible into one spot (n, or "order"). That's a strategy called a "blazed" grating, where the grating is made with reflective facets that aim at the order you want to enhance.

The figure above shows two "slots" of a blazed grating, where the surface (usually of glass) is etched or grooved with facets at an angle. These "slots" aren't really holes, like we used with the mesh, but are like individual mirrors that act like slots. Astronomers call them "grooves". This grating above naturally reflects incoming light in the direction of the +1 order of the grating, so that order will naturally be a lot brighter than the other orders, and the starlight that hits it won't be spread out as much among different orders.

The precision with which a grating works depends on the number of grooves that the light from the celestial object hits. The more grooves it hits, the more precise the spectrum will be, and the more detail astronomers can see in the spectrum. The most sophisticated astronomical gratings can have a million or more "grooves" or facets, all precisely parallel to each other, and precisely the same distance apart. One such reflective diffraction grating is shown in the picture below.



Ruling a piece of glass like this – essentially scraping it in a very precise way millions of times, is a very difficult and expensive proposition!

For most purposes, a groove spacing is chosen that is on the order of the wavelength that is going to be studied.

History Note:
See < http://www.jhu.edu/~jhumag/0400web/02.html> for a note about early astronomical diffraction gratings.. More detail is at:
The Controlled Ruling of Diffraction Gratings by George R. Harrison

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