Diffraction: Taking Light Apart

Student Guide

Engage

A. Waves

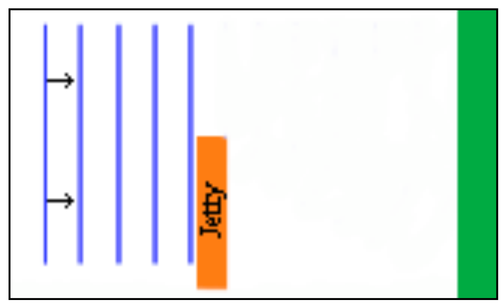
Let's first consider diffraction. It's part of everyday life, in which waves of energy don't seem to move in straight lines. Do the activity below and answer the following questions.

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?

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

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

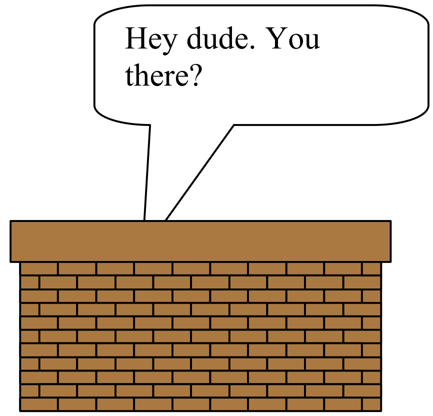


a. Will the jetty block ocean waves entirely?

b. Does it make a sharp wave-shadow?

c. Can waves get around the jetty?

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



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?

b. In what medium does sound wave travel?

c. Discuss why is it that you can hear her.

OK, there's something a little strange going on, and we call it "diffraction". Now we're going to look at some of the properties of light waves.

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.

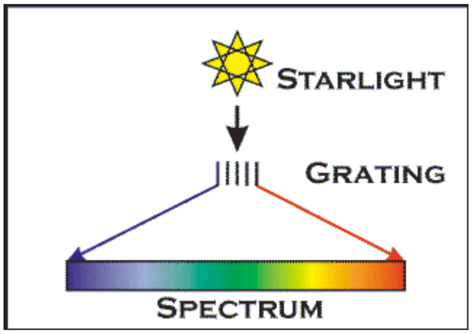
1. Hold the small prism with one finger at the top and one finger at the bottom. Position the prism 2 to 3 inches in front of your eye. Look through one side of it in the direction of the light source.

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

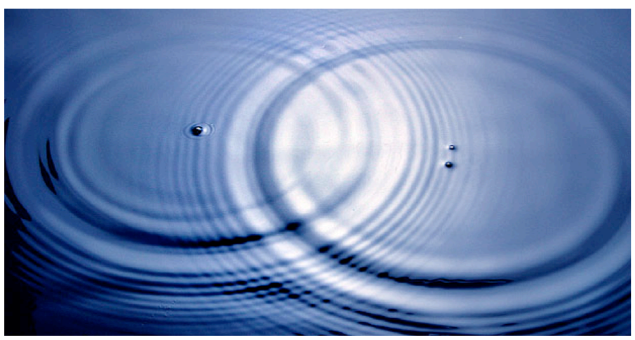
b. Next, view the fluorescent lamp in the classroom. Record your observations.

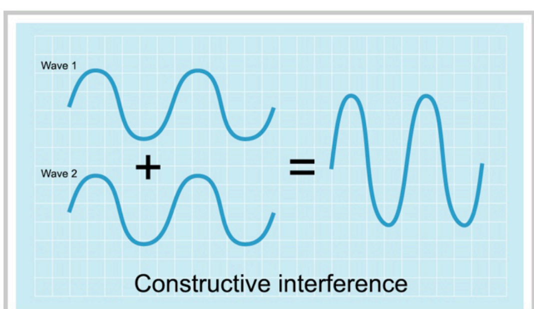
c. What differences and/or similarities did you observe in each light source when viewing through the prism?

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.

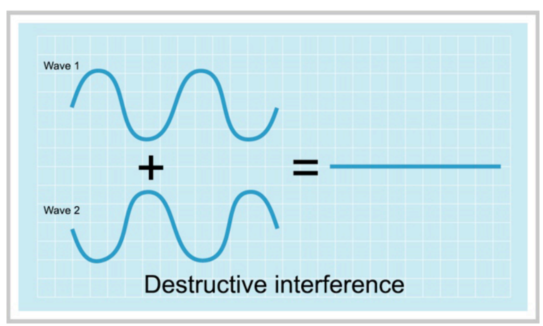


C. Some Background on Light as Waves





Light appears brighter

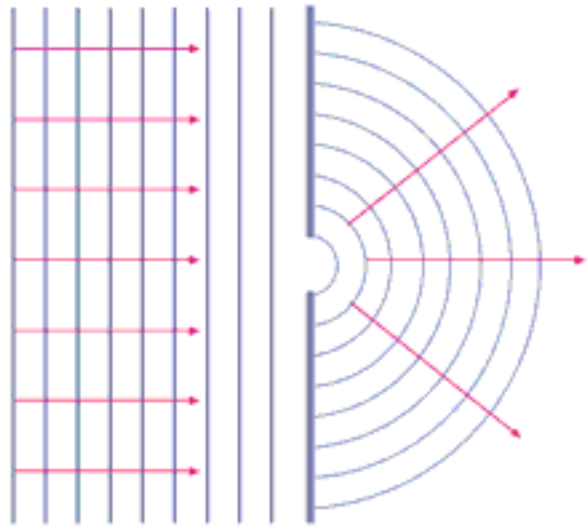


No light is visible

1. Differentiate between constructive and destructive interference.

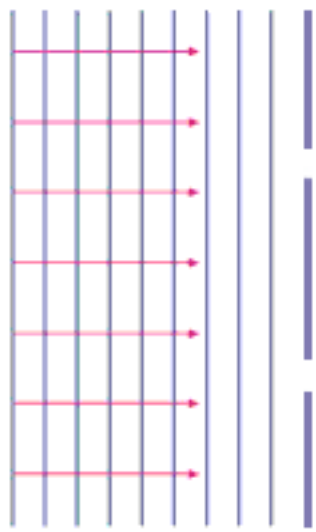
Just like the ocean waves bending around the jetty and the sound waves bending around a wall, light waves can diffract as well. Here is a sketch of how light waves behave when they pass through a small opening…

Light Source)))



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

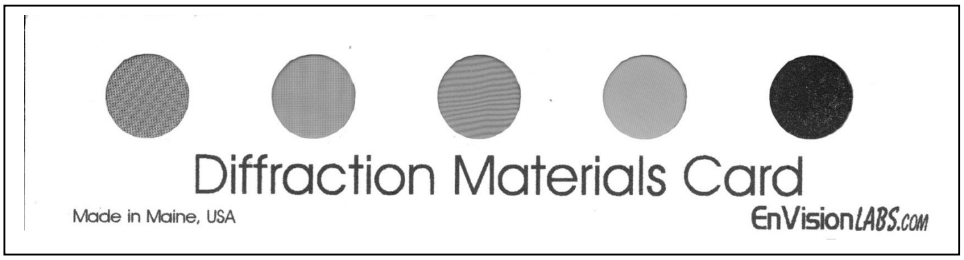
Light Source)))

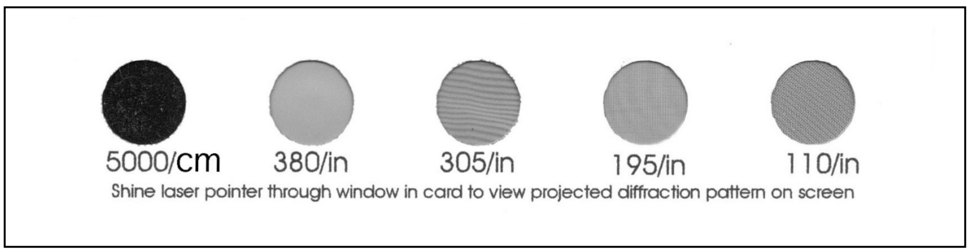


3. Imagine putting a screen somewhere beyond the two slits…Knowing that light waves interfere (constructively and destructively) with each other, what do you think will appear on the screen? (draw or write your answer)

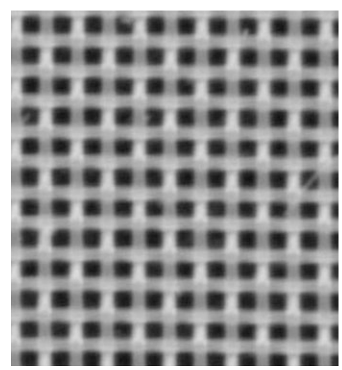
D. Diffraction Materials Card

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 at least 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

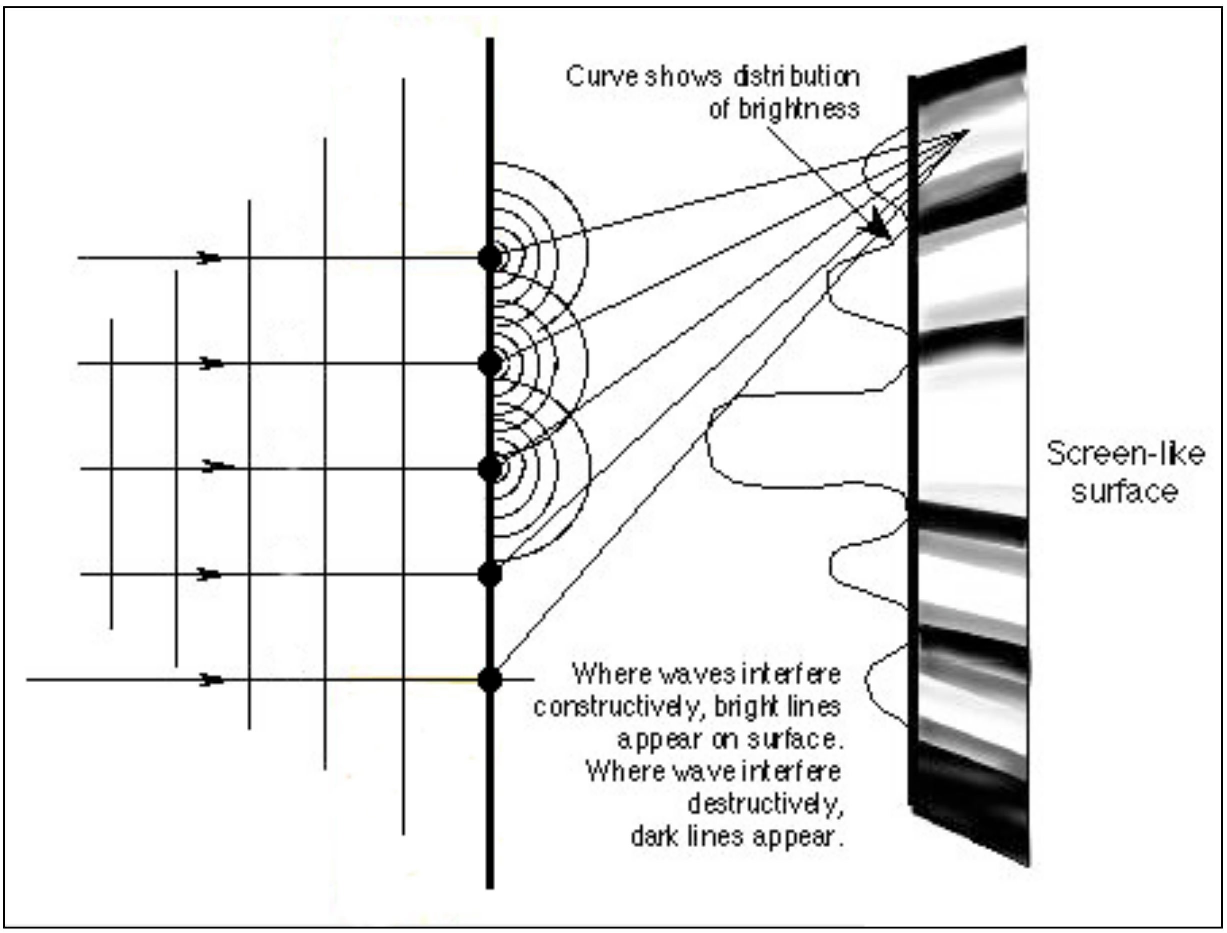
b. Qualitatively, how does the spot separation depend on mesh size?

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 and 1mm = 0.0394in)

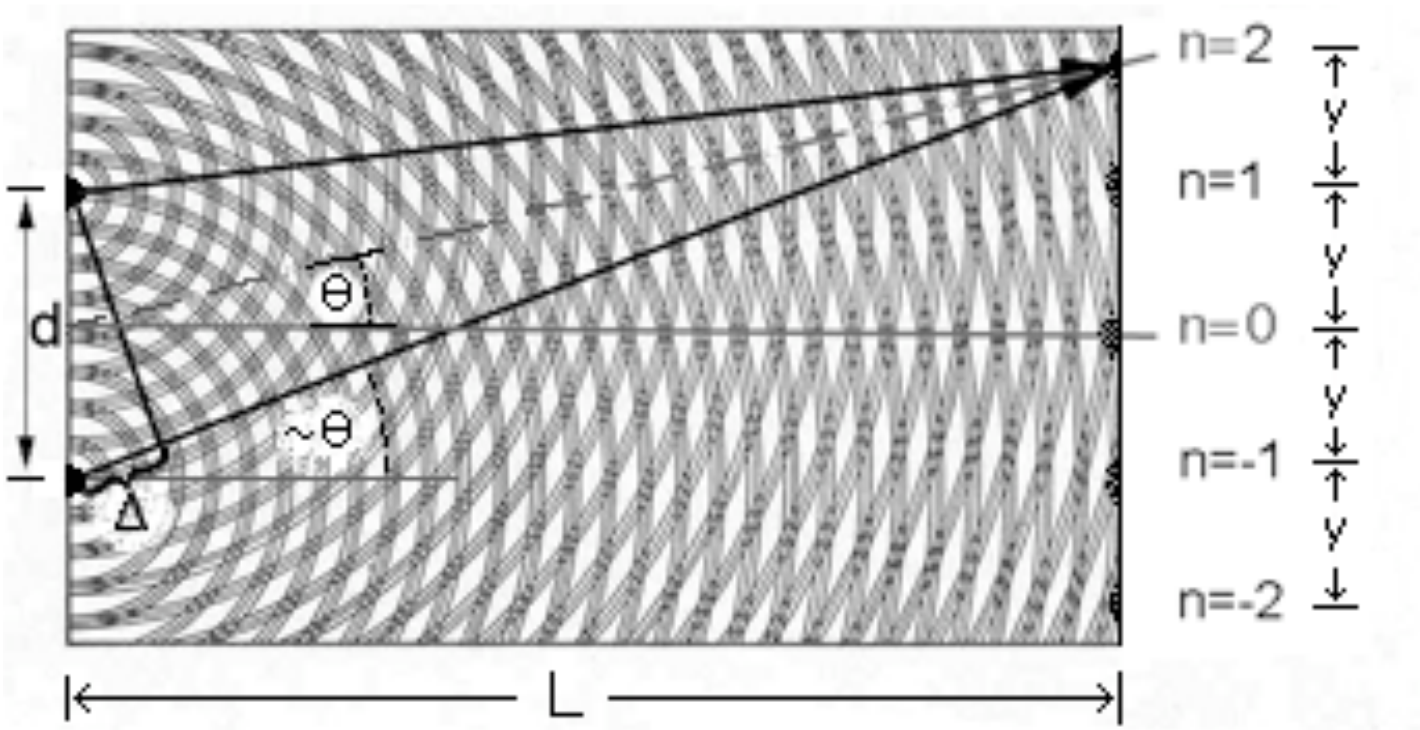
Porthole	Measured spacing "d" (millimeters)
110/in porthole	___________________
195/in porthole	___________________
305/in porthole	___________________
380/in porthole	___________________

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.

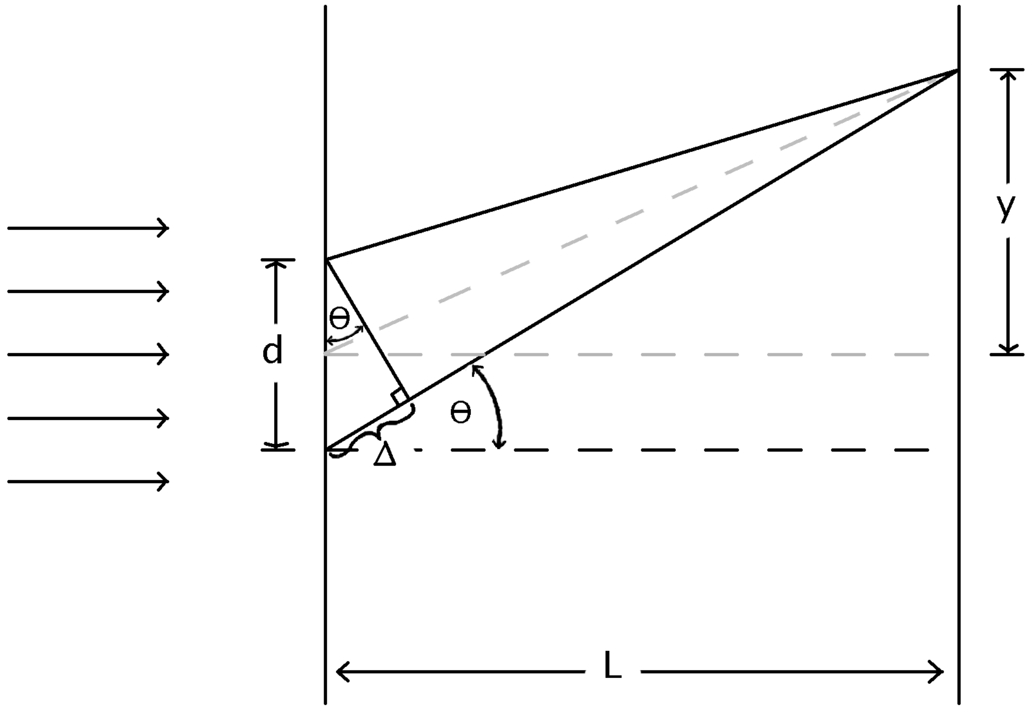
Knowing that the spots that we see through the portholes are caused by constructive interference, and knowing the size of the mesh that lets us see these spots, we can measure the length of the wave of the laser's light. Of course, waves that we're familiar with (like ripples on water, or waves in a 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 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.

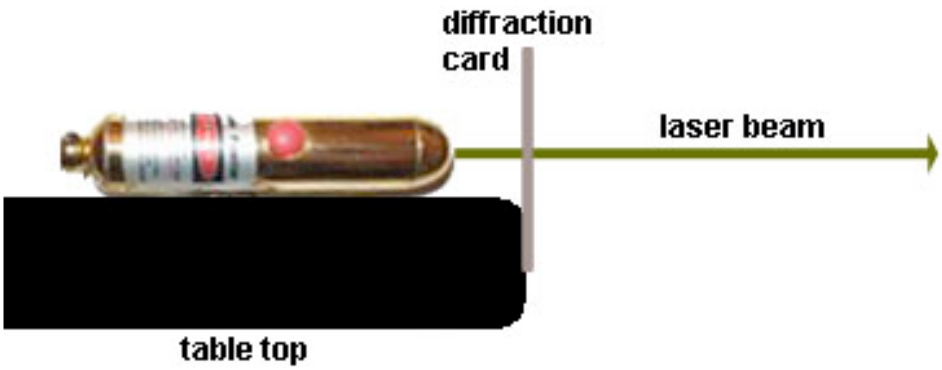
a. In the diagram, looking at the places where the waves from the holes overlap and interfere constructively, how many spots are labeled across the screen at right?

b. Which do you think is the bright spot?



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.)

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.

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

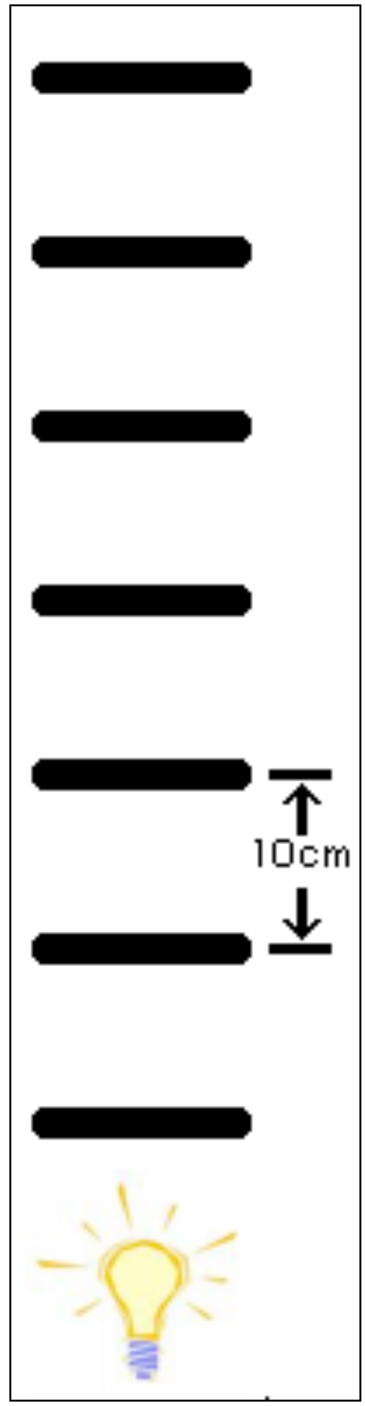
c. Try this experiment with the CD, in which the laser beam is held nearly perpendicular to the surface of the CD. It may be helpful to reflect the laser beam off of the CD instead of trying to shine it through (CDs can show diffraction either way). Using the wavelength of laser light that you discovered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

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?

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.

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)

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.

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 red light yellow light blue light	0.0020			
380/in				
305/in				
195/in				
110/in				

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?
In micron?

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

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

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)

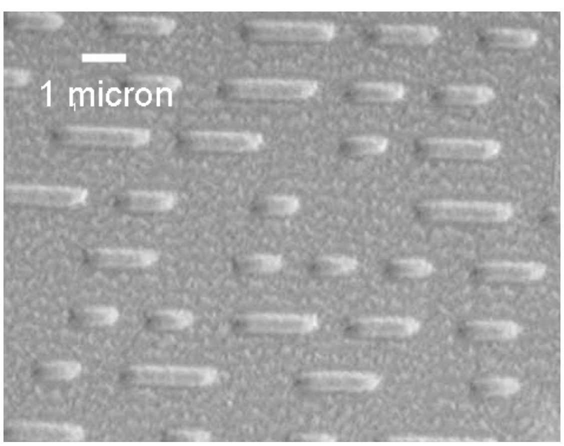
J. Using Diffraction to Explore Compact Disks

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?

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

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?

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.

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?

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.

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?