Dumpster Optics

BENDING LIGHT – DIFFRACTION

WHAT HAPPENS WHEN LASER LIGHT PASSES AROUND AN OBJECT? IF THE OBJECT IS A HAIR, CAN YOU USE THE PATTERN OF DARK AND BRIGHT SPOTS TO MEASURE ITS DIAMETER?

The calculations in this lesson require that students understand and can manipulate numbers in scientific notation. The qualitative activities #1–3 (looking at diffraction fringes) can be enjoyed by students of all ages.

MATERIALS

Activity 1 – What Do You Expect to See? (Diffraction by a Pinhead)

- Laser pointer
- Sewing pin with a "ball" head
- Spring-type clothespins as needed to hold everything in place

Activity 2 – Shadow of a Thin Slit

- Laser pointer
- Narrow "slit" made with a craft knife or single-edge razor in a black (opaque) painted glass slide or aluminum foil
- Spring-type clothespins as needed to hold everything in place

Activity 3 – Do I Need a Laser?

- Two pencils

Activity 4 – Measure the Width of a Hair

- Laser pointer
- Tape
- A hair at least 3 cm long
- Spring-type clothespins to hole everything in place
- Ruler
- Calculator (unless you just want to look at the fringe pattern)

Where to find materials:
Laser pointers are available for a few dollars sold as "cat teasers" in pet stores. They're also available at very low cost from amazon.com and on EBay.

VOCABULARY:

- Wavelength
- Obstacle (obstruct,obstruction)
- Diffraction
- Fringe
- Monochromatic
- Wave Interference
- Aperture

TEACHER NOTES:
All these activities except Activity 3 are done in a darkened room to make the laser patterns more visible. When setting up optical experiments it's important that everything be mounted so that it does not move around and make measurement difficult. For laser pointers, spring-type clothespins work well. Use as many as you need. You can keep the laser turned on by clipping one clothespin over the power switch. You can change the height of a component (lens, laser, pin, etc.) as needed by propping with more clothespins or stacking books or even building toys.

Be sure to talk about laser safety before experimenting with laser pointers (keep lasers on the table when turned on, no waving beams around the room, etc.)

WHAT IS DIFFRACTION? The photo on Slide 3 shows water spilling through a small opening in a wall and spreading out on the other side. When light or sound waves pass around obstacles or through small openings they also spread out into the geometric shadow. You can easily hear this effect with sound when you walk down a hallway and can hear voices of people in rooms ahead of and behind you. The sound waves bend around the door openings and into and up and down the hall.

When light bends around an obstacle, "fringes", or dark and bright stripes, appear in the shadow. The effects are usually most noticeable when the object or opening is comparable in size to the wavelength of light. Although a laser isn't necessary to see fringes (Activity 3) the monochromatic light of a laser makes them easier to see in a number of situations.

ACTIVITY 1 – SHADOW OF A BALL
PREDICTION: You would expect to see a shadow of the object, that is, a more-or-less uniformly dark circle like the shadow of a ball on the sidewalk in bright sun.

TRY IT Place the lens or magnifying glass in front of the laser to spread the beam out a bit on a nearby wall. You want the beam to be wider than the diameter of the pinhead, Use clothespins or whatever supports are handy to make this arrangement steady on a table. Examine the laser spot on the wall. It should be 3-4 cm across. If it isn't, try changing the position of the lens, or move the laser and lens farther from the wall. You will probably notice dark spots, some ringed by dark circles, in the red spot of laser light. These are also due to diffraction, probably around dust or dirt particles on the lens or laser optics. The spot probably won't be round for a laser pointer.

Once you have fairly large (several cm across) laser spot on the wall, place the pinhead into the beam. The pin can be put into a clothespin to hold it upright so the round head of the pin is centered in the beam. Be sure the laser light “spills” around the ball head on all sides. If you don’t have ball-head pins you can try a small ball bearing super-glued to a glass microscope slide. Use just a tiny bit of glue because it alters the pattern if it’s spread over the glass around the ball.

The “shadow” will not look very much like the round head of the pin. It should be surrounded by dark circles, “fringes” that occur because of diffraction. If the room is dark enough you should see a small bright spot in the center of the round shadow. If you don’t see this, try moving the pin head a little closer to the lens. The spot is easier to see with a small obstruction. I could not see it at all with a 6 mm paper circle glued to a microscope slide but it was clear with the 3 mm round head of a pin. This spot is called “Poisson’s spot” after the scientist who doubted its existence or the "Arago spot" after the scientist who first observed it. The interesting history of Poisson’s spot can be found here https://en.wikipedia.org/wiki/Arago_spot - History

Visit https://www.youtube.com/watch?v=KTDh1Bj-hIg to see this experiment performed in a "home lab".

ACTIVITY 2 – LIGHT THROUGH A SLIT

PREDICTION: You would expect a single long bright stripe on the wall surrounded by dark shadow. However, since Activity 1 showed the fringes produced by a laser source, students may expect something similar here.

The laser beam does not need to be expanded for this activity but the slit should be much, much narrower than the beam. The first time I did this experiment (in high school in the 1960s) we coated the microscope slide with soot from a candle and scratched a line across the soot with a single edged razor. It was very messy.

The fringes in the photo were taken with a microscope slide coated with flat black spray paint and scratched a craft knife. It is possible to just scratch a line into a piece of aluminum foil, but the foil is apt to pucker rather than cut smoothly. Use clothespins or other supports to hold the slit in front of the laser.

The diffraction pattern for a single slit is a series of bright and dark fringes stretching in a direction perpendicular to the direction of the slit. The slit for the photo was held vertical in front of the laser so the fringes are in the horizontal direction. The center (brightest) fringe is twice the size of the dimmer fringes on either side. If needed, you can make the pattern appear larger by moving the slit away from the screen (wall).

It can be shown that the narrower the slit, the more spread out the fringes. If the slit is too wide, the fringes will be so small and close together they are hard to see. If you scan the laser beam up and down along the slit you may see the size and spacing of the fringes change because the width of the slit is not the same from end to end.

ACTIVITY 3 – DO I NEED A LASER?

You should see dark (gray) and light fringes in the crack between the pencils. The space must be quite small to see them. You can also see these fringes if you look into the narrow space between two fingers held together. They look like fine threads. Hold your first and second fingers lightly together (gap between them about 1 mm) in front of a light source. They are sharpest for me when my hand is about 10 cm in front of my eye.

You can also see diffraction effects if you look through sheer curtains at a street light or the light on a neighbor's house. You don't need to be close to the curtains. You should see a multicolor pattern of light around the lamp.

ACTIVITY 4 – USING DIFFRACTION TO MEASURE THE WIDTH (DIAMETER) OF A HAIR

This activity is based on the diffraction by a narrow slit activity (Activity 2). The pattern formed by a very narrow solid rectangle (like the cross section along a hair) is the same as that formed by a slit except near the center of the pattern. The equation for the position of the dark fringes is well known (below).

Be sure the hair is stretched over the laser aperture so it goes through the center of the beam. The easiest way to do this is to put one end of the hair on the tape, place the tape around the laser near the aperture, stretch the hair over the aperture and use the remainder of the tape to hold it in place. A video showing this procedure is at http://bit.ly/1oXNmCy. A second video, showing students making typical math errors can be found here: http://bit.ly/1KE7tj4. When they get an unbelievable answer, the students realize they didn't properly take into account the powers of 10.

The laser can be mounted with clothespins or just placed on a table so it doesn't move. A spring-type clothespin will hold the laser on. If the fringes are too close together and not clear, try moving the laser farther away from the wall.

Students need to measure

- the distance from the end of the laser (the hair) to the screen (x)
- the distance from the first dark fringe on one side of center to the first dark fringe on the other side (twice y in the diagram below)

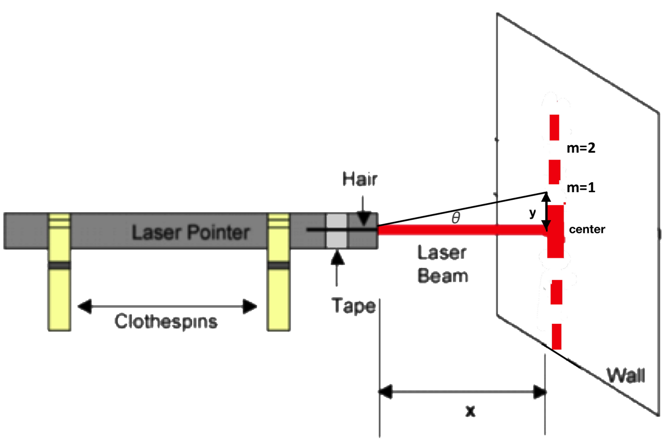

Diagram is not to scale. Laser is much farther from the wall than shown.

The diameter of the hair is given by the equation (**λ** is the wavelength of the laser light)

$$D = 2\lambda x/y$$

The wavelength of most red lasers is usually 650 nm. Check the caution label to be sure. The measurement is made from one dark spot to another because it's difficult to find the exact center of the pattern, which is very bright and may be blurry.

The hair diameter is usually between 50 and 100 micrometers. Note that care must be taken with the units: wavelength is in nanometers (10^{-9} m), x and y are probably measured in centimeters (10^{-2} m) and D will be in micrometers (10^{-6} m).

This method can be used to measure the sizes of thin narrow objects without touching them, like optical fibers when they are being manufactured.

Some math, suitable for high school Algebra II or PreCalculus students

For the diffraction pattern made by a long narrow slit (or rectangle) the spacing of the dark fringes is given by the well-known equation:

$$m\lambda = D \sin\theta \qquad [1]$$

- m is the "order" of the dark fringes: counting out from the center the first on either side is m=1, then m=2, m=3 etc.
- λ is the wavelength of the laser light
- *D* is the width of the hair (for a slit, it's the width of the slit)
- θ is the angular distance from the slit to the fringe (see diagram above)

Because the angle is very small we can use the small angle approximation:

$$\sin\theta \approx \tan\theta = y/x$$

(The "small angle approximation" is not difficult to show using the definitions of radian, sine and tangent and noticing what happens when the angle is very small.)

Equation [1] can be written:

$$m\lambda \approx D\,(y/x) \qquad [2]$$

- y is the distance from the *center of the pattern to the dark spot*
- x is the distance from the hair to the screen

Solving Equation [2} for "*D*" gives

$$D = m\lambda x/y \qquad [3]$$

This says that to calculate the width (diameter) of the hair you only need to know the laser wavelength and measure how far the hair is from the screen and the distance from the center of the pattern to one of the dark fringes.

Since you measured twice the distance from the center to the dark spot (2y), you need to divide by 2. Putting m=1 and y/2 to correct for your doubling of the y measurement gives

$$D = 2\lambda x/y \qquad [4]$$