Fall, 2020

Optics Magic at Home with Judy & Nancy

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

MATERIALS

Activity 1
- Laser pointer
- Sewing pin with a "ball" head
- Spring-type clothespins as needed to hold everything in place

Activity 2
- Two pencils

Activity 3
- 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 get supplies: 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.

PARENT AND TEACHER NOTES:

All these activities except Activity 2 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. 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. These are rules we find useful with children:
- Keep lasers flat on the table or mounting blocks when used
- Only turn laser on for the duration of the measurement
- Be aware of other people in the area and don't shine the beam on them

- Make sure your beam doesn't go beyond the edge of your work space
- No high sticking with the laser beam.

WHAT IS DIFFRACTION: When waves like light or sound 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 where redirected waves interfere with each other.. 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

Place the lens or magnifying glass in front of the laser to spread the beam out a bit and shine it on a wall 2-3 meters away. You want the beam to be 3-4 cm across. Use clothespins or whatever supports are handy to make this arrangement steady on a table. Examine the laser spot on the wall. If it isn't large enough, 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, but sort of rectangular.

Once you have fairly large laser spot on the wall, place the pinhead into the beam near the lens but where the laser spot is larger than the head of the pin. 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. 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 is in the references at the end of this document.

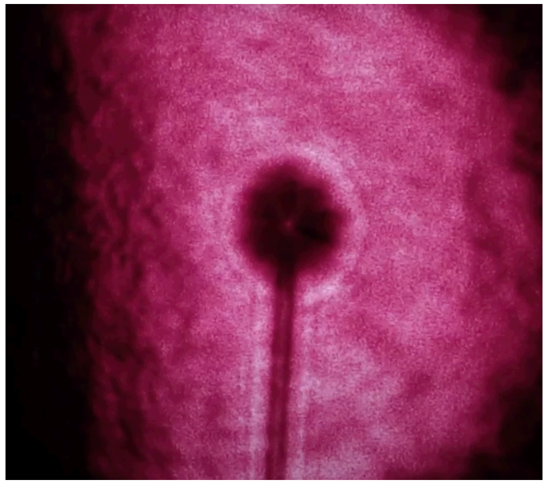

Figure 1 – Diffraction pattern of a pin with a ball head

ACTIVITY 2 – DO I NEED A LASER TO SEE DIFFRACTION?

This activity wasn't done in the webinar but it's interesting and easy to do. Place two pencils side by side, leaving just a very small gap between them. If the pencils have eraser ends, the metal bands at the top will hold them. Look into the gap, toward a source of light.

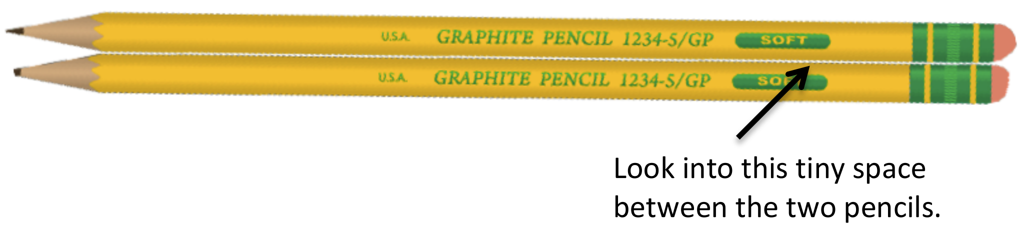

Figure 2 – How to hold the pencils

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 parallel to your fingers. 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. The waves of each color of the spectrum diffract (bend) a different amount leading to a rainbow effect.

ACTIVITY 3 – USING DIFFRACTION TO MEASURE THE WIDTH (DIAMETER) OF A HAIR

This activity is based on the diffraction by a narrow slit activity. 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 in the diffraction pattern is well known (below).

Be sure the hair is stretched over the laser aperture so it goes through the center of the beam. (Don't look into the beam to check, though. You can look at the end of the laser from the side to see if the hair is illuminated.) The easiest way to position the hair is to put one end of the hair on the tape and place the tape around the laser near the aperture. Then stretch the hair over the aperture and use the remainder of the tape to hold it in place. A video showing this procedure is listed in the references. A second video is also listed, showing students making typical math errors. 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. Best results are when the laser (hair) and screen (wall) are more then 1 meter apart.

You need to measure

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

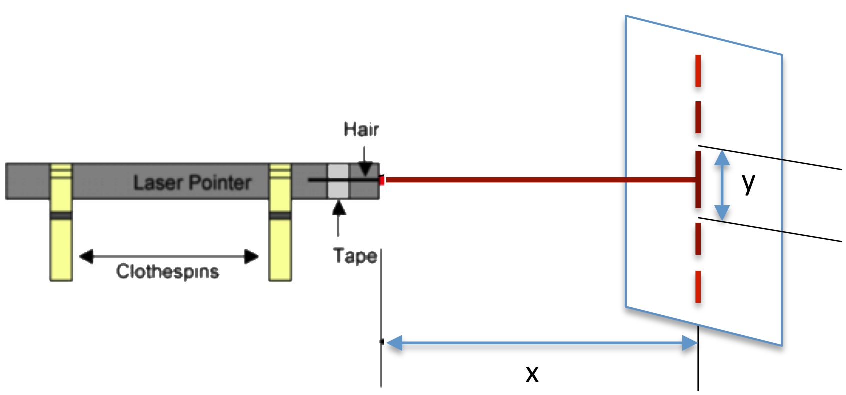

Diagram is not to scale. Laser is much farther from the wall than shown. Also you may see one or more bright fringes on either side, depending on how dark the room is and how bright the laser.

Figure 3 – What gets measured in this experiment

The diameter of the hair is given by the equation

$$\mathbf{D = 2\lambda x/y} \quad (\lambda \text{ is the wavelength of the laser light})$$

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 Physics or PreCalculus students

Why doesn't the equation above look like the one in my physics book? 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:

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

- m is the "order" of the dark fringes: counting out from the center the first is m=1, then m=2, m=3 etc. (Technically, the numbering on the other side should be -1, -2, -3…)
- 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 as shown below for m=3
- *x* is the distance to the screen
- *y* is the distance from the *center of the pattern* to the dark fringe

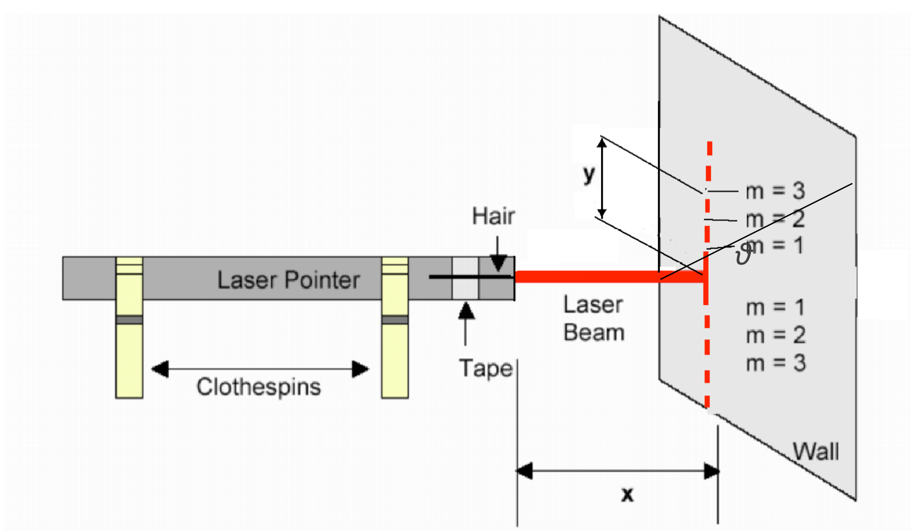

Figure 4 – The usual textbook set-up for this experiment

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

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

(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.)

With the small angle approximation, equation [1] becomes

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

We measured the distance *between* the first two dark spots (2y), so m=1. We can set m=1 and divide y by 2 to correct for measuring twice the distance.

$$(1)\lambda \approx D\,(y/2x) \qquad [3]$$

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

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

That is, 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 between the two dark spots on either side of the center bright spot.

REFERENCES

Diffraction of water waves in a shallow wave tank. If you look closely you can see the places where waves interfere to form lines of peaks and valleys.

https://www.youtube.com/watch?v=7pyQaifB7Fw
https://www.youtube.com/watch?v=sfcMnVpsYlo

The story of "Poisson's Spot" also called "Arago's Spot"

https://en.wikipedia.org/wiki/Arago_spot - History

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

Diameter of a hair exploration video

http://bit.ly/1oXNmCy – in this video the formula is simplified for non science children
http://bit.ly/1KE7tj4 – this video uses the complete formula, and the children make some math mistakes trying to solve it