Optics: Laser Light Show
Student Advanced Version

In this lab, you will explore the behavior of light. You will observe reflection and refraction of a laser beam in jello, and use a diffraction pattern to measure the width of a hair.

Key Concepts:
- Light always travels in a straight line except when it interacts with an object through **reflection, refraction,** or **diffraction**
- **Reflection:** when a light wave hits an obstacle (eg: a mirror), it can reflect (bounce back).
- **Refraction:** Some obstacles (eg: glass, water) allow light to pass through, but slow it down. In this case, the light ray bends as it crosses the object boundary. The angle of refraction depends on the speed of light in the object.
- **Diffraction:** Light waves can bend around a small obstacle or when passing through a narrow slit. Light waves generated by points around the obstacle overlap to create patterns of light and dark bands.

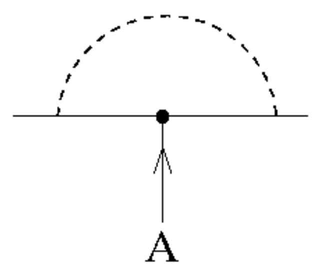
Part 1: Refraction - Measure the speed of light in Jello

You should have a sheet of paper labeled "Diagram 1" that shows your experimental setup. You will have a semi-circular block of jello sitting over the semicircle in the diagram. The labeled lines indicate the direction for shining your laser into the jello. The laser will be pointing into the center of the flat side of the jello.

The straight dashed line down the center of the diagram is called the **normal line**.

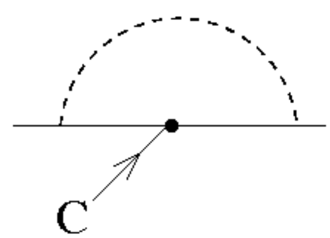
First, make some predictions:

QSA1. When you shine the laser along the normal line (line A), what direction will the laser beam have inside the jello? Draw the path in the diagram to the right:



QSA2. Do you think that light travels slower or faster in jello as compared to in air?

QSA3. When you shine the laser along line C, will the light beam bend away from the normal line or towards the normal line? Draw what you think the approximate path will look like on the diagram to the right:



QSA4. If you shine the laser along lines B, C, or D (in diagram 1), which will result in the beam within the jello being closest to the normal line?

Now test what actually happens:

1. Take the semi-circular block of jello and slide it onto the experimental setup diagram over the shape labeled “jello”. Do NOT take the off its wax paper. Your jello might be a different size from the diagram but you must have the curved side of the jello facing away from you and the **center of the flat side should match the black dot.**
2. Line up the laser along line A and shine it towards the central dot. Your partner should use a pencil to mark the point where the light beam comes out the curved side of the jello. Make sure you make the mark on the actual diagram, not the wax paper.
3. Shine the laser along lines B, C, and D and mark where the beam comes out on the curved side in each case. You may want to label your marks A, B, C, D so you don't forget which is which.
4. Using a ruler, draw lines connecting each of the marks you made to the central dot. Make the lines extend past the points that you marked (further towards the outside of the diagram).
5. Use a protractor to measure the **angle from the normal** for the incoming laser beam and for the path the beam takes in the jello. *Fill in the first 2 columns in the table below:*
6. Use a calculator to find the sine of each angle that you measured. *Fill in columns 3 and 4 in the table. Finally, fill in the last column with the ratio of the sine of the angle in jello to that in air.*

	Angle from normal		sin(angle from normal)		
	Incoming beam (θ_{air})	Beam in jello (θ_{jello})	Incoming beam $\sin(\theta_{air})$	Beam in jello $\sin(\theta_{jello})$	Ratio of sines $\frac{\sin(\theta_{jello})}{\sin(\theta_{air})}$
A	0°		0		xxxxxxx
B	30°		0.5		
C					
D					

7. According to **Snell's law**, the ratio of the speeds of light in two substances is given by:

$$\frac{\sin(\theta_{jello})}{\sin(\theta_{air})} = \frac{\text{speed}_{\text{jello}}}{\text{speed}_{\text{air}}}$$

QSA5. Given your experimental data, the speed of light in jello is approximately how big compared to its speed in air?

QSA6. Was your original prediction correct (does light travel faster or slower in jello than in air)?

8. Make a prediction about how the laser beam will bend if you shine it into the jello along line E.

The angle from the normal of line E is:

The sine of this angle is:

The sine of the angle in the jello should be:
Hint: Solve Snell's Law for sine of the angle in jello. You already measured the ratio of speeds.

$$\sin(\theta_{jello}) = \sin(\theta_{air}) \times \frac{speed_{jello}}{speed_{air}}$$

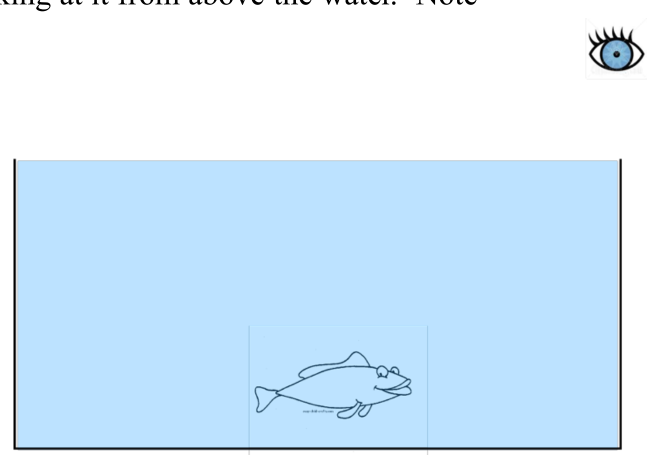
The angle of the beam in the jello should be: (use the $\sin^{-1}$ button on your calculator)

Draw a line going through the jello at this angle from the normal on your diagram.
Now test your prediction! Shine the laser along line E.

QSA7. Does the beam within the jello fall close to the line you drew?

Challenge question:

Imagine a fish at the bottom of a pool of water. You are looking at it from above the water. Note that light travels slower in water than in air.



(a) *Draw a ray of light from the fish to your eye in the picture.* Make sure the ray bends in the correct direction at the air-water interface due to refraction!
(b) When your brain processes information from your eyes, it always assumes that the light you saw traveled in a straight line. *Draw a (straight!) dashed line from your eye to where the fish* <u>*appears*</u> *to be.*

QSA8. Do objects under water appear to be shallower, deeper, or at the same depth as they really are?

Part 2: Total internal reflection and fiberoptics

1. Using Snell's Law, predict what you will see when you shine the light into the curved side of the jello, along the ray indicated on Diagram 2. At what angle will it exit the jello?

   Angle (from the normal) with which the ray will hit the flat side of the jello (θ_{jello}):

   Sine of this angle:

   Solve the Snell's law equation for $\sin(\theta_{air})$*:*

$$\sin(\theta_{air}) = \sin(\theta_{jello}) \div \frac{speed_{jello}}{speed_{air}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

   Expected angle of exit in air: θ_{air} =

   Draw a ray on your diagram indicating your prediction for where the light will go.

2. Transfer your jello, still on its wax paper, onto diagram 2. Shine the laser **into the curved side**, so that the beam goes through the jello and hits the center of the flat side at an angle. Have another student hold a curved sheet of paper vertically as indicated on the diagram.

3. You should see a spot appear on the vertical sheet of paper after the laser leaves the jello. Using a pencil, *make a mark on the diagram just below this dot.*

4. Draw a line connecting your mark to the black dot at the center of the flat side of the jello.

   QSA9. Does your outgoing ray approximately match your prediction?

   Note that the biggest value that $\sin(\theta_{air})$ can have is 1. So, according to Snell's law, $\sin(\theta_{jello})$ must always be less than the ratio (speed in jello)/(speed in air) in order for refraction to occur. The angle $\theta_{critical} = \sin^{-1}(speed_{jello}/speed_{air})$ is called the critical angle. Beyond this angle. The light ray will not be able to refract out of the jello into the air.

   QSA10. What is the predicted critical angle for your jello? $\theta_{critical}$ =

5. Measure the critical angle for your jello block. Move the laser to a larger and larger angle from the normal until the spot on the vertical sheet of paper disappears. Mark down the direction of the laser right at the point where the dot disappears. Measure this angle with your protractor.

   The measured critical angle is: $\theta_{measured}$ =

QSA11. What is the % error in your measurement? $(\theta_{measured} - \theta_{critical}) / \theta_{critical}$

QSA12. When you shone the light at a large angle from the normal, how many laser beams did you see in the jello? Explain where the extra beam(s) come(s) from.

This phenomenon is called **"total internal reflection".** At a big enough angle from the normal, all of the laser light will be reflected and none will pass out into the air. Fiber-optic cables use total internal reflection to transmit light and other signals over long distances. You can make a model for a fiber-optic cable out of jello.

6. Obtain a long strip of jello from your teacher. Shine the laser into one end of it at an angle, making the laser reflect off the sides of the strip.

QSA13. How many times can you make the laser beam bounce off the walls before leaving the jello?

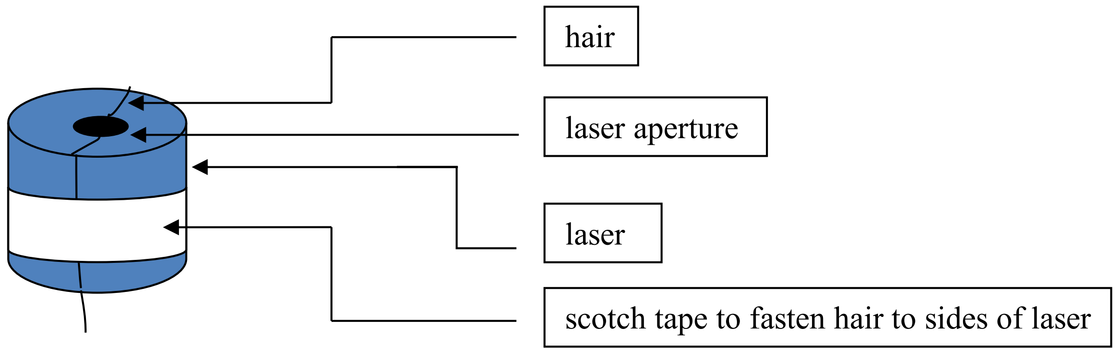
QSA14. Draw a diagram of its path in the strip.

Although light normally travels in a straight line, with a fiber-optic cable, we can make it curve around a corner!

QSA15. Try curving the jello strip. Can you still make laser light come out of the opposite end of the jello from where you shine the laser?

Part 3: Diffraction- Measure the thickness of your hair!

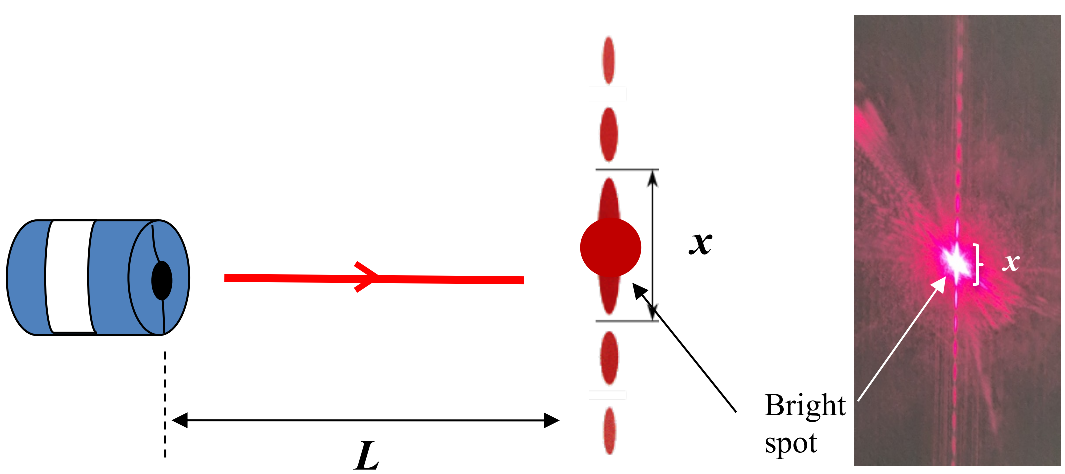
1. One student should volunteer a piece of hair from their head. The hair should be placed tightly across the center of the laser aperture and a piece tape attached around the laser to hold the hair in place (please see diagram below).



2. Measure (in cm) the distance from the edge of a table to a blank wall.

   Distance from table to wall is L = ________________ *cm*

3. Rest the laser on the edge of the table to keep it steady. Shine the laser towards the wall. A diffraction pattern of bright and dark bands should be visible. A bright spot will also appear across the central bright band.



4. Measure (in cm) the width of the central bright spot. That is, measure the distance between the **centers of the dark bands** on either side of the center.

Distance between dark bands is x = ________________*cm*

5. Your laser should have written on it the wavelength (λ) for the light that it produces.

Wavelength of laser beam is λ *=* ________________ *nm*

6. According to the laws of diffraction, the width, ***w***, of the hair (obstacle) will equal to:

$$w = \lambda \times L \div x \div 1000 = \underline{\qquad\qquad\qquad} \mu m$$

7. The average width of human hair is 100µm. The thickness can range anywhere from 10 µm to 200 µm.

QSA16. Is the thickness of your hair within the common range?

QSA17. Do you have thin, thick or about average hair?

8. Compare your results with other students.

QSA18. Does hair color or ethnicity tend to correspond to particularly thin or thick hairs?

QSA19. If, instead of human hair, you taped a hair from a horse's tail across the laser pointer, would you expect the peaks to be closer together or further apart?

Optional:
Test your prediction with a piece of horse-hair provided by your teacher.

QSA20. How many times thicker is the horse hair compared to your hair?

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Diagram 1

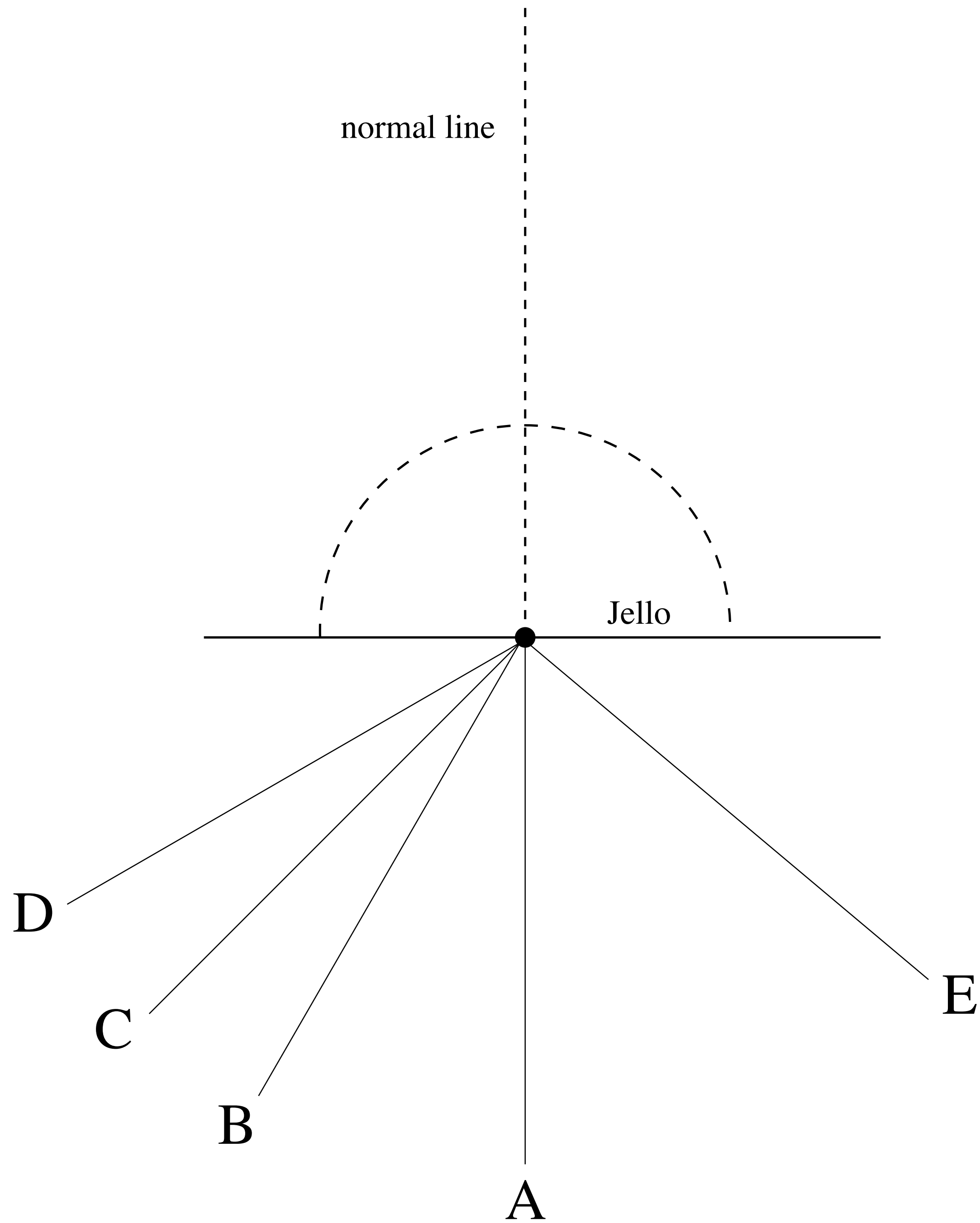
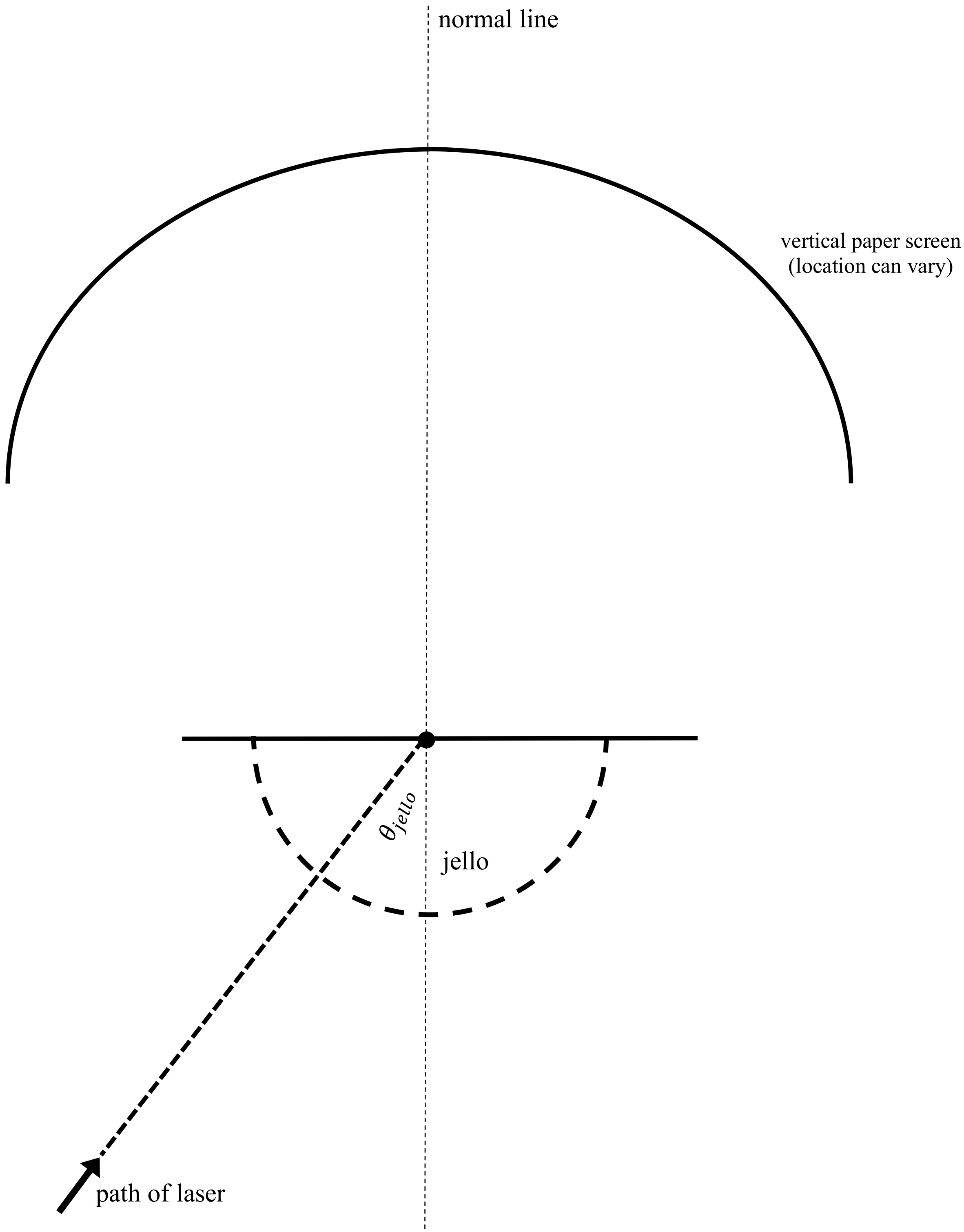


Diagram 2


normal line
vertical paper screen
(location can vary)
θ_{jello}
jello
path of laser