Optics: Laser Light Show
Teacher 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.

Pre-lab setup:
1. The night before, make jello – using the regular jello recipe, use the same amount of hot water recommended but with approximately half the amount of cold water. This will make the jello firmer and easier to work with.
2. Pour the liquid jello into pans about 1 inch deep. Try to make the top as smooth and flat as possible. Refrigerate overnight.
3. Once the jello has set, carefully cut semicircles with the non-serrated knife. It is important to keep the sides as smooth as possible. Each group will need one semicircle.
4. Cut strips about 2 cm wide and about 15 cm long out of the remaining jello, and carefully separate them out, trying to keep the edges and bottom as smooth as possible. Each group will need one strip.

Safety Notes: Talk to your students about laser safety; advise them to never look directly at a laser and never to shine it in anyone's face. If they intend to eat the jello afterwards, everyone should wash their hands and/or wear gloves.

Setup Note: This lab is best done in a dimly-lit room, to make it easier to see the laser beams.

Math Prerequisites:
Basic Lab: protractor use, basic calculator arithmetic

Advanced Lab: protractor use, basic calculator arithmetic, basic trigonometry (sin and $\sin^{-1}$ with a calculator)

California Science Content Standards:
4. Waves: Waves have characteristic properties that do not depend on the type of wave.
4f. Students know how to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization.

Materials:
- Red or yellow Jello mix (One 6 oz boxes per 8”x8” pan; two boxes per 9”x13” pan – each 8x8 pan provides materials for about 6 students/groups)
- Smooth (non-serrated!) knife

Every group of 2-3 students will need:
- 1 laser pointer
- 1 jello semicircle (about 2cm high, and 6cm diameter; exact dimensions do not matter)
- 1 jello strip (about 2 cm by 2cm by 15 cm; length does not matter)
- 1 protractor
- 1 ruler or straight-edge
- 1 meter stick

- Calculator (with a sine and inverse sine button, for advanced lab)
- Pencils, white paper, scissors
- Scotch tape
- OPTIONAL: a piece of horse-hair (eg: from a violin bow)

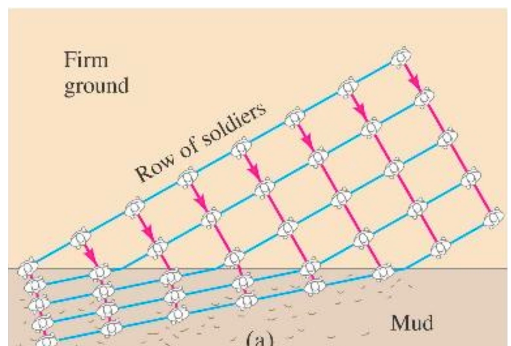
Key Concepts:

- Light always travels in a straight line except when it interacts with an object through **reflection, refraction,** or **diffraction**
- **Reflection** occurs when a light wave hits an obstacle (e.g. a mirror) and bounces back (reflects).
- Some obstacles (e.g. glass, water) allow light to pass through, but slow it down. In this case, the light ray bends as it crosses the object boundary. This is known as **refraction.** The angle of refraction depends on the speed of light in the object.
- 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. This process is known as **diffraction**.

Introductory Mini-lecture:

Ordinarily, light travels in a perfectly straight line. However this can change when the light hits an object. In this lab, we will explore three different behaviors that can cause light to bend: **reflection, refraction,** and **diffraction**.

When a light wave hits an obstacle, it can **reflect** (bounce back). This is exactly how mirrors work. If I shine a laser at a mirror, the laser beam will hit the mirror and then bounce off again. As a matter of fact, the only reason we can see anything at all is because of sunlight.



https://sites.google.com/site/bromfieldphysics/waves

Some obstacles (like glass or water) allow light to pass through but slow it down. In this case, the light ray bends as it passes into the object. This is why a pencil looks bent or broken if it is dipped into a clear cup of water. To understand why the light bends, imagine a light wave to be like a row of soldiers. Suppose the soldiers walk at an angle towards a muddy field. Anyone who passes the boundary into the mud starts walking more slowly. This will cause the entire line to change direction. (One can try this with a group of kids holding hands).

Note that if we draw a line perpendicular to the edge of the mud, the direction in which the soldiers are moving bends towards this **normal line** as they enter the sand. If they were going backwards, from sand onto easy ground, their direction would bend away from the normal instead. In this lab, we will observe the **refraction** of light in jello, and measure how much jello slows down the light (advanced lab only). **Diffraction** occurs when light hits a very narrow slit or obstacle. We will discuss it further in part 3.

****TEACHER NOTE****
An instructional video for teachers can be found at
https://www.youtube.com/watch?v=a6g6kOF8Vjc

Part 1: Refraction
Measure the speed of light in Jello

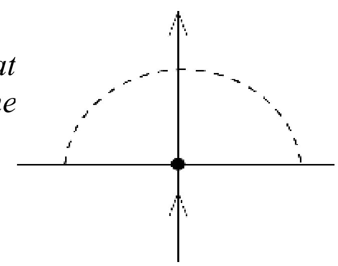
Teacher Note: *This part of the lab requires knowing how to use a protractor. For students who are not comfortable measuring angles, it might be good to have a demonstration beforehand of what they will do (marking the point where the laser comes out of the jello, drawing a line to connect it to the center, and measuring the angle from the normal)*

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:

QS1, 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:

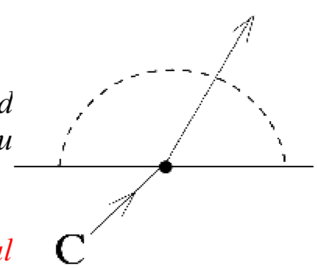


The beam should go straight along the normal.

QS2, QSA2 Do you think that light travels slower or faster in jello as compared to in air?

Jello is denser and we would expect light to travel more slowly in it.

QS3, 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:



If light travels more slowly in jello, it should bend towards the normal (think back to the soldier analogy).

---Advanced Lab Only --

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?

Light shining along B starts out closest to the normal and thus will come out closest to the normal on the other side.

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:*

---Advanced Lab Only --

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.*

(answers filled in below are approximate and will vary depending on the type and preparation of jello, except for columns 1 and 3 which are exact)

	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°*	0	*0*	xxxxxxxxxx
B	30°	*20°*	0.5	*0.4*	*0.7*
C	*45°*	*30°*	*0.71*	*0.5*	*0.7*
D	*60°*	*37°*	0.87	*0.6*	*0.7*

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?

Students should get a value of approximately 0.7, although this will depend on the type of jello and how it is made.

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--Basic Lab Only --

	Angle from normal	
	Incoming beam (θ_{air})	Beam in jello (θ_{jello})
A	0°	*0°*
B	30°	*20°*
C	*45°*	*30°*
D	*60°*	*37°*

QS4. Did the laser beam bend towards or away from the normal line when entering the jello? The beam bends towards the normal

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QS5, QSA6. Was your original prediction correct (does light travel faster or slower in jello than in air)? Light travels more slowly in jello than in air. See the introductory lecture for the marching soldiers analogy to explain why this would cause the laser beam to bend towards the normal line.

Teacher note: *This is a good time for the students to go back to their original predictions and see whether they got them right (did the beam stay along the normal line when coming in at A? Did it bend closer to the normal when going into the jello?)*

--Advanced Lab Only --

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: 50°
The sine of this angle is: 0.77

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.

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

0.54 (this is approximate, depends on your jello)

The angle of the beam in the jello should be: (use the $\sin^{-1}$ button on your calculator)
32° (again, approximately)

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 questions:

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.

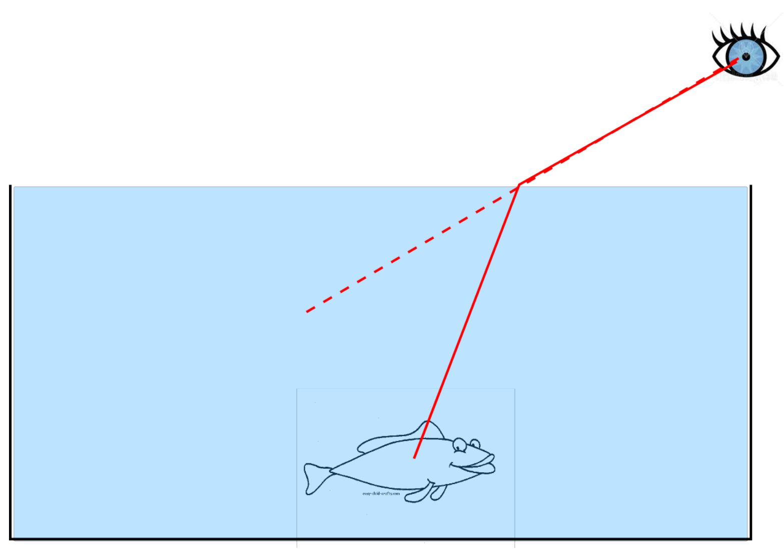
(a) *Draw a ray of light from the penny to your eye in the picture.* Make sure the ray bends in the correct direction at the air-water interface due to refraction!

The solid red line in the picture indicates approximately how a ray of light would travel from the fish to the eye. The important feature is that the ray bends away from the normal when going from water to air (or, equivalently, towards the normal when going from air to water). This happens because light travels slower in water than in air.

(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 appears to be.*

The dashed red line in the picture indicates where the eye perceives the fish to be, since our brain always assumes that light travels in a straight line. Notice that the apparent position of the fish at the end of the dashed ray is shallower than it really is.

QS6, 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 fiber optics

--Advanced Lab Only --

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}): 38°
   Sine of this angle: 0.62
   Solve the Snell's law equation for $\sin(\theta_{air})$:

   $$\sin(\theta_{air}) = \sin(\theta_{jello}) \div \frac{speed_{jello}}{speed_{air}} = 0.62/0.7 = 0.89$$ *(approximate, depends on the jello)*

   Expected angle of exit in air: θ_{air} = 62° (approximate)
   Draw a ray on your diagram indicating your prediction for where the light will go.

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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.**

---Basic Lab Only --

Mark down the line along which the laser goes into the jello.

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

---Basic Lab Only --

QS7. Did the laser beam bend away from the normal or towards the normal when it left the jello and entered the air?

The ray bends away from the normal when leaving the jello.

5. Now change the angle of your incoming beam so that the laser passes through and hits the flat side of the jello at a greater and greater angle.

QS8. When you shine the light at a large angle from the normal, how many laser beams do you see in the jello? Explain where the extra beam(s) come(s) from.

If the light hits the flat side of the jello at a sufficiently large angle, there will be an extra beam going back towards you caused by reflection of the laser from the flat side.

QS9. Can you make the dot on the paper made by the laser leaving the jello disappear?

If the light hits the flat side at a large enough angle, all of the light will be reflected and none will pass out on the other side, so the dot will disappear.

--**Advanced Lab Only** --

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? $\theta_{critical}$ = ***44°*** *(approximate)*

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? $(\theta_{measured} - \theta_{critical}) / \theta_{critical}$

errors in the 10-20% range are likely.

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.

If the light hits the flat side of the jello at a sufficiently large angle, there will be an extra beam going back towards you caused by reflection of the laser from the flat side.

Teacher Note: *This next part of the lab is much more impressive in a dark or very dimly lit room*

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.

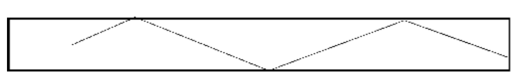
6. Obtain a long strip of jello from your teacher. Shine the laser into one end of it at an angle, making the laser reflect off the sides of the strip.

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

If the sides of the strip are nice and smooth and the strip itself is not too wide, students should be able to see 2-3 bounces of the light within the jello "cable"

QS11, QSA14, Draw a diagram of its path in the strip.

Students may see something like:



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

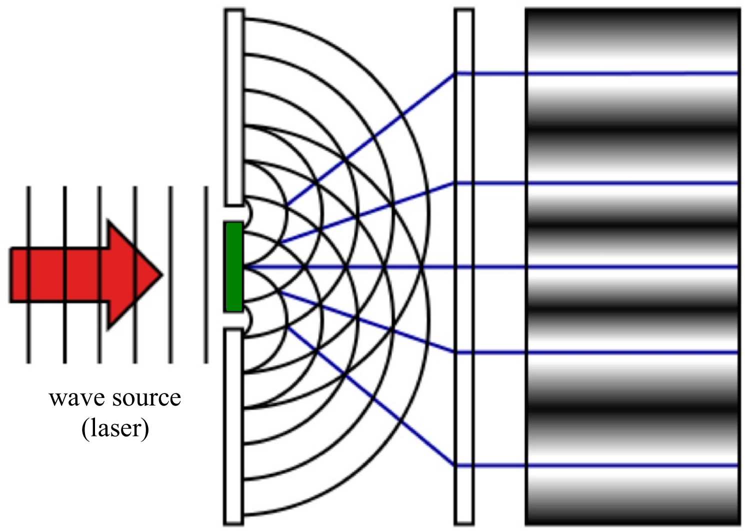
QS12, QSA15. Try curving the jello strip. Can you still make laser light come out of the opposite end of the jello from where you shine the laser?

This can be done if you make the laser bounce off the sides of the strip just right, but it can be a bit tricky if the jello is wiggly. Students can see whether the laser light makes it all the way to the other side of the strip by placing their finger at the end to check whether it is lit with a red spot.

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

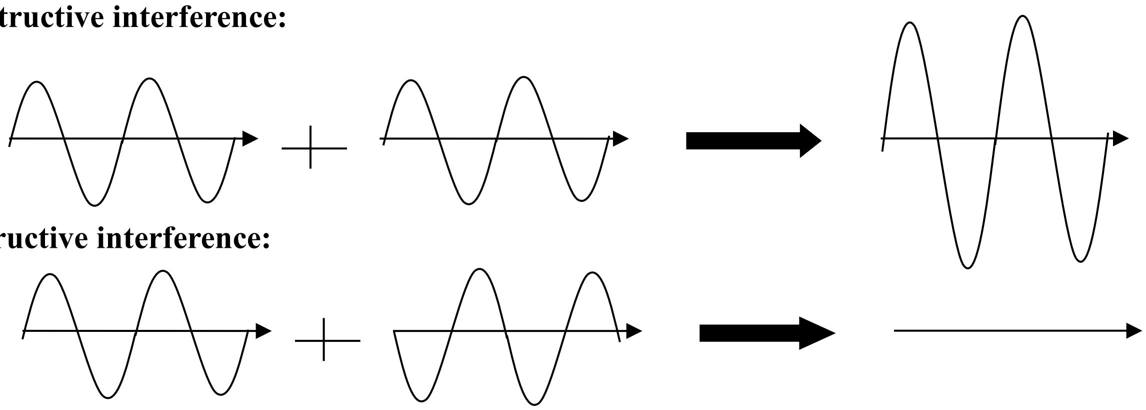
Introductory Mini-Lecture:

When light encounters a narrow slit or a thin obstacle, it bends around the edges of the slit and spreads out, forming multiple circular waves that overlap with each other. At points where the waves with the same pattern overlap, they add together and a bright band is formed (**constructive interference**). At points where waves with opposite patterns overlap, the waves cancel each other out to form a dark band (**destructive interference**). A typical diffraction pattern is shown in the diagram on the right.

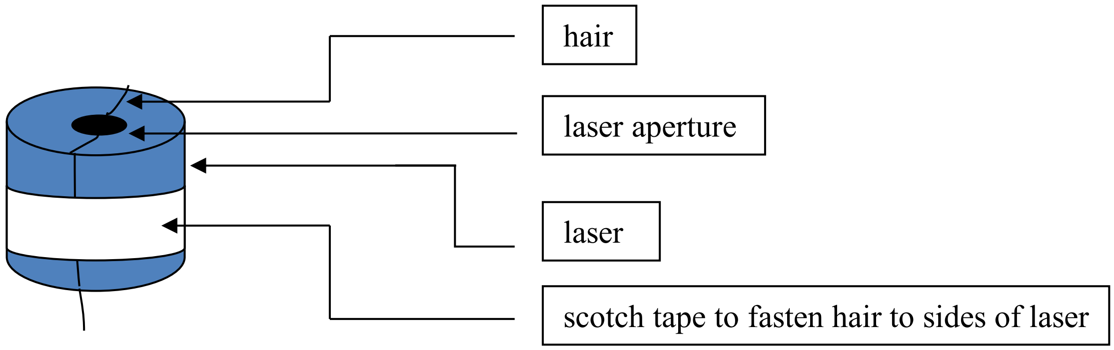


constructive interference:

destructive interference:



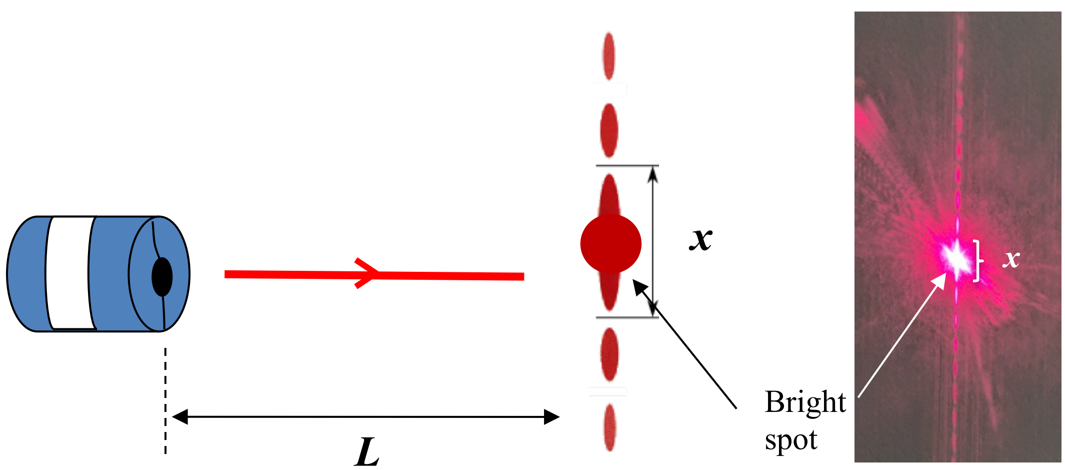
1. One student should volunteer a piece of hair from their head. The hair should be placed tightly across the center of the laser aperture and a piece tape attached around the laser to hold the hair in place (please see diagram below).



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 with a bright spot in the middle. The central band will appear through the center of this bright spot.
Teacher note: A distance of approximately 100 cm (1 m) from the wall is convenient for measuring the central bright band from a human hair. Too close to the wall will make the bands very narrow and the bright spot will obscure the central bright band. Too far will make it very difficult to keep the pattern steady and not shaking.



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 central bright spot.

Distance between dark bands is x = ________________*cm*

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

Teacher note: if the wavelength is not written on the laser pointer, use the common value of 650 nm

Wavelength of laser beam is λ = ________________ nm

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

$$w = \lambda \times L \div x \div 1000 = \_\_\_\_\_\_\_\_\_\_\_\_ \mu m$$

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

   QS13, QSA16. Is the thickness of your hair within the common range?

   QS14, QSA17. Do you have thin, thick or about average hair?

8. Compare your results with other students.

   QS15, QSA18. Does hair color or ethnicity tend to correspond to particularly thin or thick hairs?

   Generally, black hairs are the thickest and blonde or red hairs the thinnest. Ethnicity also tends to play a role. Younger children tend to have thinner hair.

   QS16, 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?

   Since horse-hair is thicker, the peaks should be closer together. In the equation above, you have to divide by a smaller separation x to get a larger width w.

Optional:
Test your prediction with a piece of horse-hair provided by your teacher.
Teacher note: The bands of the horse hair will be very narrow and might be difficult to see and measure at a distance of 1 m. It is helpful to stand farther away from the wall (~2 m) such that x *is larger and easier to measure.*
QS17, QSA20. How many times thicker is the horse hair compared to your hair?
Students can simply recalculate the width using the equation above or they can find (Width of horse hair) ÷ (width of human hair) = (x for human) ÷ (x for horse)

Diagram 1

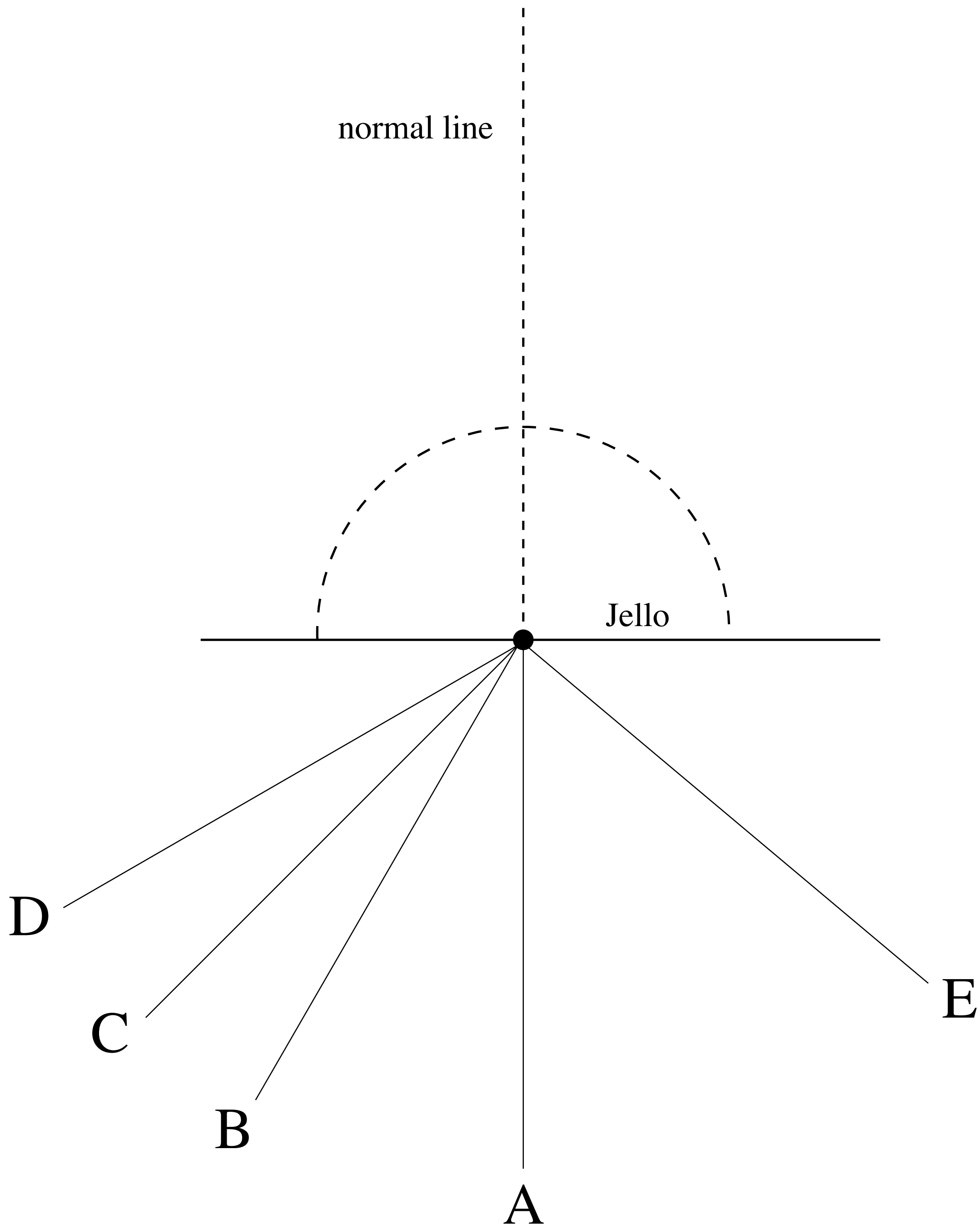
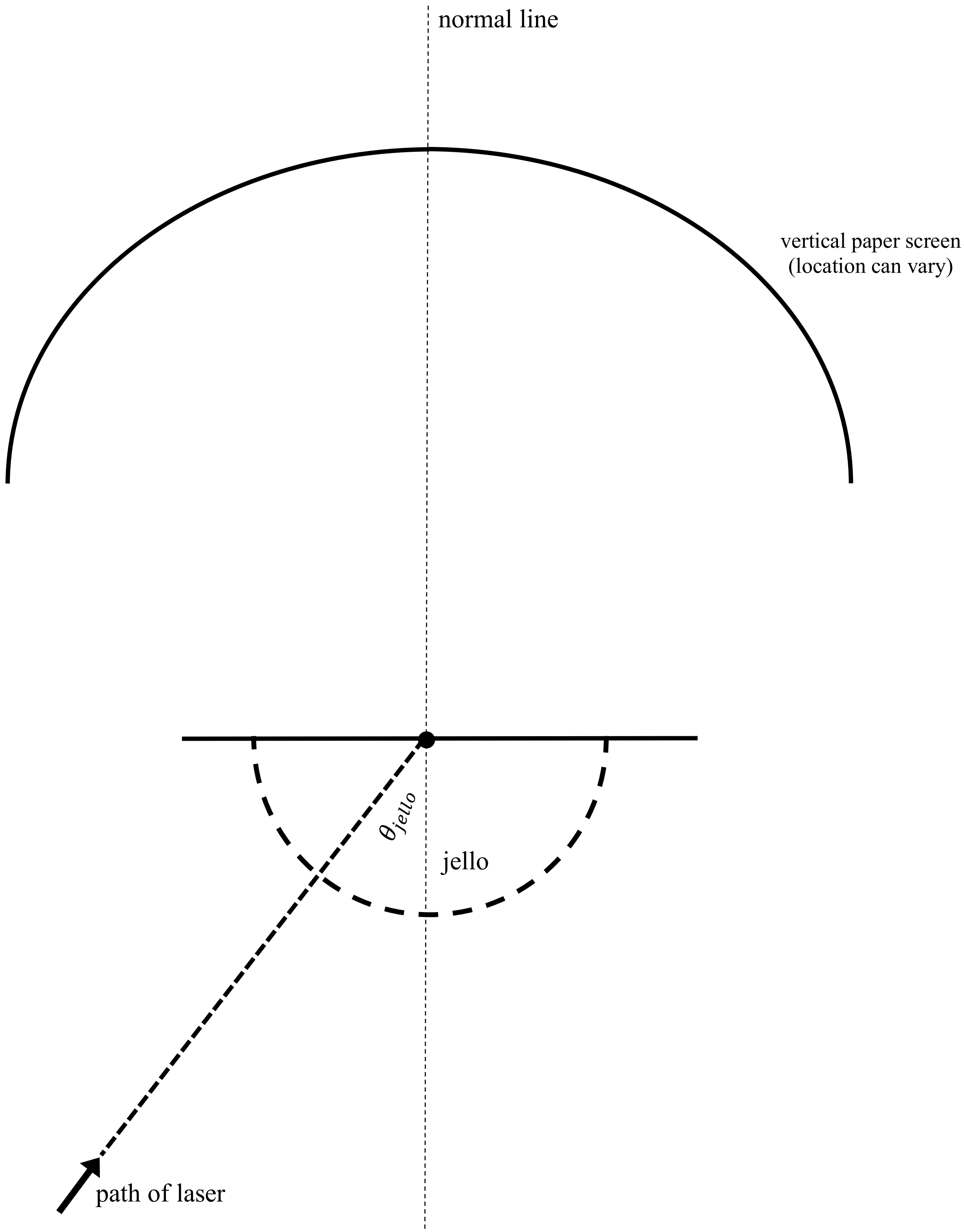


Diagram 2



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