

## Thomas Young and the Wave Nature of Light

### Historical Background

Isaac Newton was famous not only for formulating the laws of motion but also for pioneering in the study of optics. He used a prism to show that sunlight was a mixture of the colors that make up the rainbow. In his *Opticks* (1704), Newton argued that light was made up of tiny particles. Slightly earlier, the Dutch physicist Christiaan Huygens wrote a *Treatise on light*, in which he proposed that light was a wave. It was only in 1789 that Thomas Young proposed a simple experiment that appeared to resolve the controversy by showing that light indeed behaves as a wave (according to 20th-century quantum mechanics, however, even Young's wave description is incomplete). Young, a leading British natural philosopher, formulated an influential theory of color vision. He was also the first to decode the Egyptian hieroglyphics being brought to Europe by Napoleon's troops.

Although Newton and others had observed alternating patterns of bright and dark bands of light under certain circumstances, Young would be the first to explain these patterns, based on an analogy with water waves. Young used very simple equipment to produce patterns of light and dark bands: a candle and a card with a rectangular hole across which he stretched a single human hair. He used his observations to measure the wavelength of light. Notice that he was proposing that light is a wave and measuring its wavelength (something that cannot be directly observed!) to prove that it is indeed a wave. Young described the experiment as follows, in "An account of some cases of the production of colors not hitherto described" [1802], in Henry Crew, ed., *The wave theory of light* (New York, 1900), 63-64:

"I therefore made a rectangular hole in a card, and bent its ends so as to support a hair parallel to the sides of the hole; then, upon applying the eye near the hole, the hair, of course, appeared dilated by indistinct vision into a surface, of which the breadth was determined by the distance of the hair and the magnitude of the hole, independently of the temporary aperture of the pupil. When the hair approached so near to the direction of the margin of a candle that the inflected light was sufficiently copious to produce a sensible effect, the fringes [alternating bands] began to appear; and it was easy to estimate the proportion of their breadth to the apparent breadth of the hair across the image of which they extended. I found that six of the brightest red fringes, nearly at equal distance, occupied the whole of that image. The breadth of the aperture was  $66/1000$  [of an inch], and its distance from the hair  $8/10$  of an inch; the diameter of the hair was ...  $1/600$  [of an inch]. Hence, we have  $11/1000$  for the deviation of the first red fringe at the distance of  $8/10$ ; and as  $8/10 / 11/1000 = 1/600 / 11/480000$ , or  $1/43636$  [of an inch] for the difference of the routes of the red light where it was most intense."

Young has thus measured the wavelength of candle light to be  $1/43,636$  of an inch, or about 582 nm [**1 nanometer =  $10^{-9}$  m**; present measurements give yellow light a wavelength ranging from 550 to 600 nm]. Young provided no diagrams nor did he discuss the geometry upon which his computations rested, but he did provide a verbal explanation of the idea that underlies the calculation [ibid., 62]:

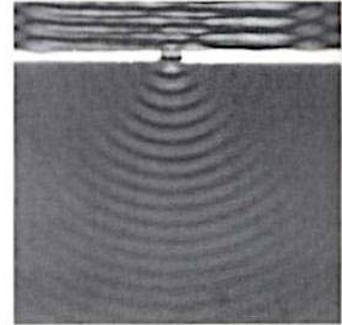
... wherever two portions of the same light arrive at the eye by different routes, either exactly or very nearly in the same direction, the light becomes more intense when the difference of the routes is any multiple of a certain length, and least intense in the intermediate state of the interfering portions; and this length is different for light of different colors.... [that is, different colored lights have different wavelengths]

The wave analogy is a powerful idea with many applications throughout science and society. All waves (including sound, light, radar and x-rays) and even some things that are usually thought of as particles (like electrons!) show behavior that can be explained using the wave analogy and the concept of interference.

## How waves interfere with each other

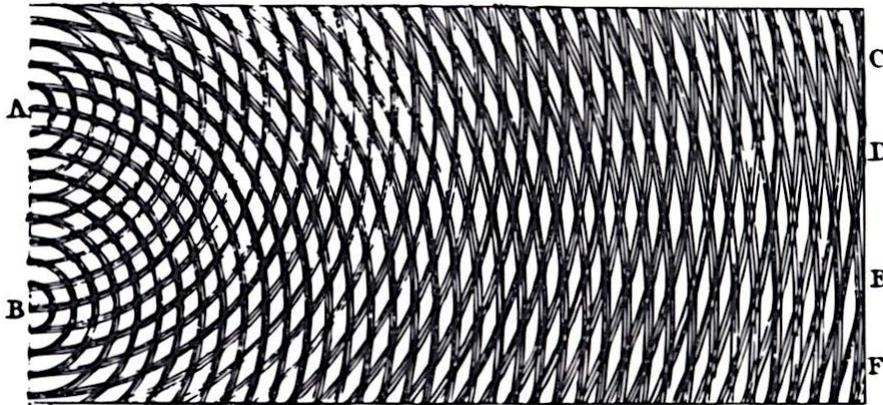
Young took the alternating light and dark band pattern he observed to be evidence of light behaving like a wave. In order to understand how Young concluded this, we need to examine how waves interact with each other and with barriers.

Suppose you are lying on the beach and you observe an ocean wave passing through a small break in a jetty. On the ocean side of the jetty, the crests form lines parallel to the shore. On the inland side of the jetty, the crests form semicircles (see photo at right).

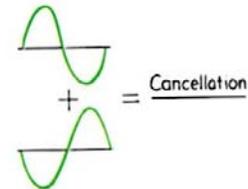
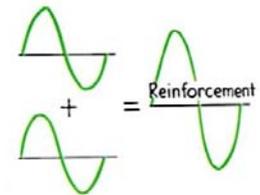


Plane waves pass through a small opening in a barrier, resulting in circular waves. (Hewitt p.292)

If there are two such openings near each other, two circular waves are created and the two waves interact with each other. A diagram from Thomas Young's work is shown below. The two openings, labeled A and B, are on the left side of the diagram. The circles represent the crests of the waves.



How does this information about waves connect to light and dark fringes? The reason lies in how waves add together. When two the crest of one wave meets the crest of another, the heights add (this is called constructive interference). When crest meets trough, the two waves cancel (destructive interference). The concept is illustrated at the right. Apply this idea to Young's diagram. Along the midline of Young's diagram (connecting the midpoint of A and B with the midpoint of D and E), the crests of waves starting from point A meet crests of waves starting from point B. All along this line, there is constructive interference. If A and B represent two slits through which light passes and the right end of the diagram represents a screen onto which the light is projected, one might expect a bright fringe at the midpoint between D and E.



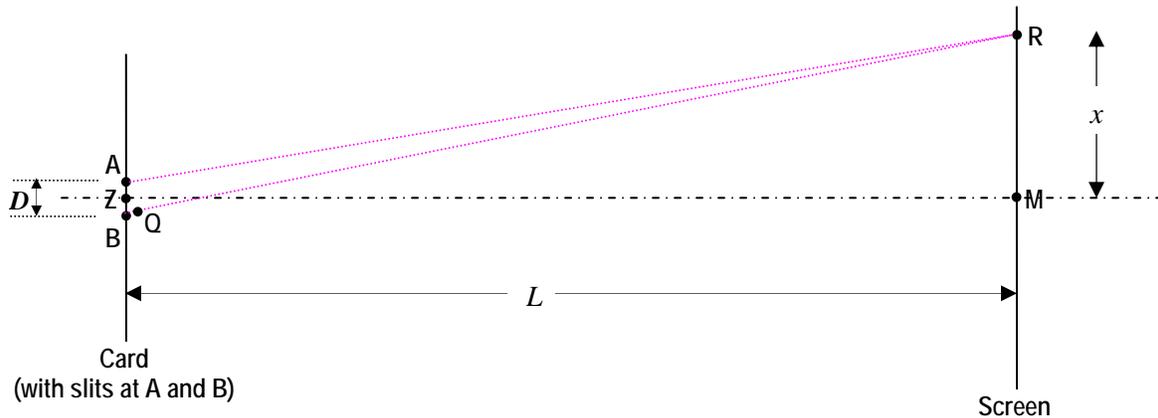
Try interpreting the diagram for yourself.

- Where do you think you might find other bright fringes? Where do you think dark fringes might be produced?
- How will the spacing between the fringes change if ...
  - you move the screen closer to the two openings?
  - points A and B were closer together?
- Locate any bright fringe on the screen on Young's diagram. Compare the distance from that fringe to opening A to the distance from that fringe to opening B. What do you notice? (Hint: You can measure distance by counting the number of rings). Can you expand this observation into a general rule?

If you understand the ideas above, it seems plausible that you can figure out the distance from the middle of the screen to any bright fringe by knowing the distance between the openings, the distance to the screen and the distance between one circular wave crest and the next. The distance between wave crests is called wavelength. Wavelength is usually represented by the Greek letter  $\lambda$ .

## Using Young's diagram to get an equation

What makes Young's diagram powerful is that it allows us to connect things we can measure directly (the distance between two slits and the locations of bright fringes on a screen) with something that cannot be measured directly (the wavelength of light). The next few paragraphs show how to combine Young's diagram with some geometry and algebra to calculate the wavelength of light.



The diagram above extracts the vital features from Young's diagram. The openings are at points A and B and a bright fringe is located at point R. The points Z and M note the location of the midline between the slits and the screen. Point Q is marked so that the distance  $d_{BQ}$  equals the extra distance that light must travel to get to point R from point B, compared to the distance to R from A. Stated mathematically,  $d_{RA} - d_{RB} = d_{BQ}$ .

The starting point for getting the equation is this: Since R is the location of a bright fringe, the difference in distance from R to A and the distance from R to B must be equal integer number of wavelengths (Can you see why this is from Young's diagram on the previous page?):

$$d_{BQ} = n\lambda \quad [1]$$

where  $\lambda$  represents the wavelength and  $n$  is a whole number that identifies which fringe is at R. If point R is the location of the third (or fourth or fifth) bright fringe from the middle, then  $n = 3$  (or 4 or 5).

Equation [1] isn't very useful, since it's impossible to measure  $d_{BQ}$  directly (why?). Some geometry (and an approximation to make the math easier) is needed to connect the wavelength with quantities that are easily measurable. If  $D$  is very small compared to  $L$ , the lines AR and BR are nearly parallel and the line AQ is nearly perpendicular to both AR and BR. That means the triangles ABQ and ZMR are approximately similar. (Similar triangles share the same shape, but not necessarily the same size). Since the triangles are similar, the ratios of corresponding sides are equal:

$$\frac{d_{BQ}}{D} = \frac{x}{L}, \text{ or } d_{BQ} = \frac{xD}{L} \quad [2]$$

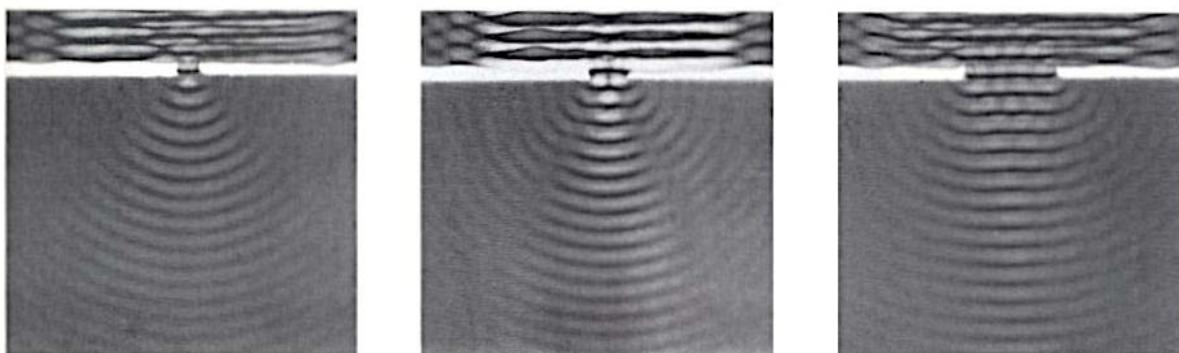
We can use equation [2] to replace the tiny distance we don't know ( $d_{BQ}$ ) with ones that are easy to measure ( $x$ ,  $L$  and  $D$ ) in equation [1]. The result is

$$\frac{xD}{L} = n\lambda \quad [3]$$

If Young's idea is right, equation [3] should correctly predict the relationship between the wavelength of light, locations of bright fringes, distance between the slits and distance between slits and screen. In this lab, you will use Equation [3] to measure the wavelength of the light used in the experiment, using the logic of Young (and 20<sup>th</sup> century equipment).

### Another phenomenon you might notice

Interference patterns can be also produced when waves encounter a single slit (this phenomenon is called diffraction). The photos below show water waves passing through apertures of various sizes.



The photos show two main features. First, the apertures bend the waves, with smaller apertures having a larger effect. Second, there are interference patterns. Notice the 'V' shaped patterns in the lower half of all three pictures. In between the lines of the vees, the wave crests are pronounced (corresponding to bright fringes) and in the vees the wave crests are not visible. The math is messier, but the principle that underlies two slit interference can be used to explain the one slit patterns by thinking of each larger aperture as (infinitely) many small apertures, set side by side. The interference patterns that you will observe from real world double slits will mostly resemble the double slit interference pattern predicted by Young, but will also contain evidence of single slit diffraction.

**Lab Instructions: Observing fringes (using things Young might have had)**

*The room should be lit for this part of the experiment.*

1. Obtain a card with two slits cut in it. One slit should be narrow (about the width of a razor blade). The other should be reasonably wide (a few millimeters). Look through each one and record what you see. Try looking through each slit at a variety of distances, from very close to your eye to a long distance away. Record your observations here:

Newton thought of light as a stream of particles traveling in straight lines. Which of the observations might Newton be able to explain by thinking of light as particles? Explain.

Which of your observations might Newton have a hard time explaining using a particle model for light?



Discuss your findings and analysis with an instructor before continuing.

## Lab Instructions: Observing fringes (using LASERS)

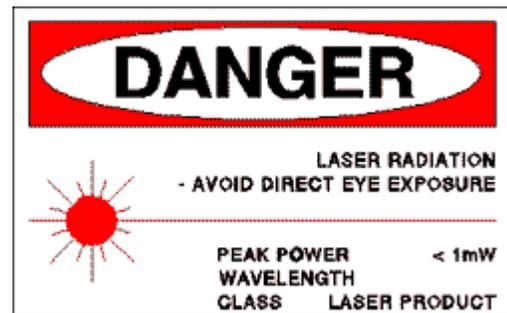
### Equipment

- Low power HeNe laser
- PASCO Slit wheels
- Ruler
- Clipboard and paper
- Ruler and/or meterstick

The room should be **dark** for this part of the experiment. Each station should have a small desk lamp for reading and writing. Please shut off the desk lamp when you are not using it.

### LASER SAFETY

- **Do not look into the beam!** Even these relatively safe lasers can damage your vision.
- **Be aware of stray reflections!** Not all the light goes in the direction you intend. Glass and even plastic surfaces can create unwanted reflections. You can detect stray reflections by walking around you lab table and seeing if the laser illuminates you. (Note: This technique is not safe for high power lasers!) Block off any stray reflections that other groups might accidentally view.



### PROTECT OUR EQUIPMENT

- **Don't touch optical surfaces!** Scratches caused by dust can ruin expensive equipment. Always handle optical elements (like slit plates, slit wheels, lenses) by their edges.

### Instructions

1. Produce an interference pattern using the provided equipment. Select a setting on the slit wheel that sends the laser light through a pair of slits. (There are labels on the slit wheel). Project the interference pattern on the "screen" (clipboard with paper). Use a pencil or pen to record the position of the fringes.
2. Make some predictions based on Young's diagram on page 2 or equation [3]. Record the prediction as well as your reasoning for each prediction below. What do you think will happen to the interference pattern if...
  - you increase/decrease the distance between the screen and the slits (without changing anything else)?
  - you increase/decrease the distance between the laser and slits (without changing anything else)?
  - you increase/decrease the distance between slits (without changing anything else)?

Discuss your predictions and the reasoning behind them with your group. *If your prediction changes as a result of talking with your group, record the group's predictions and new reasoning here.*

3. Check your predictions. Record your procedures, observations and any measurements below.

	Discuss your results with an instructor before continuing.
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4. In this part, you will use the information written on the slit wheel (and any other measurements you might need) to calculate the wavelength of the light from the laser.
- Plan your experiment. Some questions to consider:
    - What quantities will you measure?
    - What precautions will you take to get high quality measurements?
    - How will you calculate the wavelength from the things you measure?

	Discuss your plan with an instructor before continuing.
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- Record your procedure, observations/data, measurements and calculations here. (A diagram may be helpful).
- Calculate the value and compare it to the value given by the manufacturer of the laser and to the value calculated by a nearby lab group.



Have an instructor check your calculations.

### Optional: Observing interference patterns from a single slit using the LASER

Replace the slit wheel with a slit wheel that has a variety of single slit. Some things to try:

- Observe what happens to the pattern as the width of the slit changes.
- Compare the interference pattern from a single slit to that from a double slit. (You may need to record the patterns to notice the main difference).
- Check out the cool patterns made by some of the non-slit shaped apertures (hex, square, circle).

### Optional: Reproducing Young's measurement

Measure the wavelength of candlelight with Young's technique. Use a human hair, attached tautly to a card across a rectangular hole, and a candle to reproduce Young's original apparatus and measurement. Hold the card close to your eye with the hair running vertically, place the lighted candle about 4-5 inches from your eye, and look toward a distant, dark background about 10-20° left or right of the candle. The exact distances between your eye, card and candle for best seeing the interference bands will depend on the optical system of your eye (whether you are near- or far-sighted). You may need to remove your glasses or contact lenses. Count the number of bands you see with fuzzy, out-of-focus vision across the surface of the hair, and have a friend estimate the distance between the surface of your eye and the card. Calculate the wavelength of the candlelight. Use the same value for the diameter of human hair (1/600 of an inch) that Young did.

Additional (challenging) puzzle: Young's description of his experiment on the first page of this handout strongly suggests that he had measured the thickness of human hair using the apparatus described in the paragraph. How might he have done this? (Ironically, the method relies on a particle model of light!)

### Post-lab Assignment

Write an abstract (200 to 400 words) that synthesizes the experiment: what was done, how the data were collected and analyzed. Explain how your observations support Young's view of light as a wave. You may include graphs or other diagrams. (A picture may be worth a thousand words, but it does not affect the word count).