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PHY300 – Waves and Optics

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Diffracting to a Wave Theory of Light

Light is a wave: A formulation that is the result of the findings of the most elite thinkers throughout time. One of the catalysts in confidently steering the discussion on the theory of light towards the direction of waves was the phenomenon of diffraction. Great thinkers have always thought of light as a stream of particles until diffraction was first observed. Through this unusual contradiction to the intuitive interpretations of light greats minds arose, such as Thomas Young, Christiaan Huygens, Augustin-Jean Fresnel and Joseph Fraunhofer to pioneer undisputable evidence that light is in fact made up of waves.

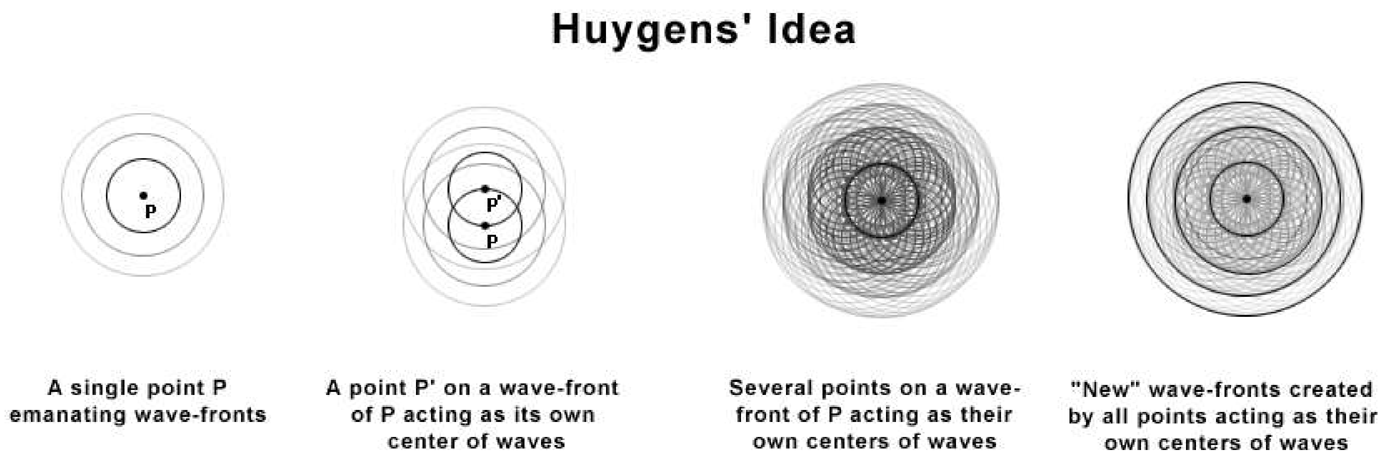
For a long time great minds have questioned the foundations of light, dating as far back as the time of Euclid (about 300 B.C.). However, many of the theories intuitively suggested light as a stream of particles, traveling in straight paths. Euclid, in his work entitled *Optica*, made conclusions that light travels in straight lines due to particular observations such as sunlight casting well-defined shadows (Hanson 372). Early thinkers like Euclid were convinced by this "observable fact" over a theory based on waves because when one considers water waves passing through obstructions, such as piers, the "shadows" produced behind these objects are not sharp and well-defined (372). Other early Greek philosophers made similar metaphors, such as Empedocles, who compared the casting of shadows to wind blowing sand against a book, producing a streak on the opposite side (373). However, it took until the seventeenth century to discover and expose an interesting contradiction to prior theories of well-defined shadows, and in turn on theories of light itself. Francesco Maria Grimaldi, an Italian physicist, had experimented in observing the shadows cast by hair. He noticed that the edges of the presumed shadow were actually fuzzy and that there were even additional "fringes" that were produced parallel to his supposed initial shadow; he coined the term "diffraction" (374). From latin origins, the term "diffraction" comes from the word diffringere, which translates into "breaking up into pieces" ("Diffraction" 1). There was no other way to explain this phenomenon without drawing to wave-like characteristics. Later in the seventeenth century came prominent Physicist and Mathematician, Sir Isaac Newton, who attempted to grapple with the origins of light. He wrote extensively about his findings in a compilation he dubbed *Opticks*. In an attempt to explain Grimaldi's findings, Newton remained in agreement with the early Greek thinkers on a particle theory. He described diffraction by attempting to reason that there existed wave-like disturbances deflecting the "pellets in an orderly, periodic manner" (Hanson 379). It was his prominence and prestige in the field of Physics that led to great popularity and support for the particle-based theory of light (Jones 1). Nevertheless Grimaldi's findings with the diffraction caused by hair continued to plague Newton's corpuscular hypothesis on light.

While Newton's descriptions of light were promising, a less prominent, Dutch Physicist named Christiaan Huygens presented a completely different picture that was able to logically accommodate the observations published by Grimaldi. Huygens had proposed that light possessed the form of waves, emanating from a source in all directions (Fowles 2). Additionally in Huygens' principle there are three assumptions that must be made to describe the motion of light:

> (i) Each point of a wave front is the center of particular waves, (ii) the wave front is determined by the common tangent to the extremities of these wavelets and,

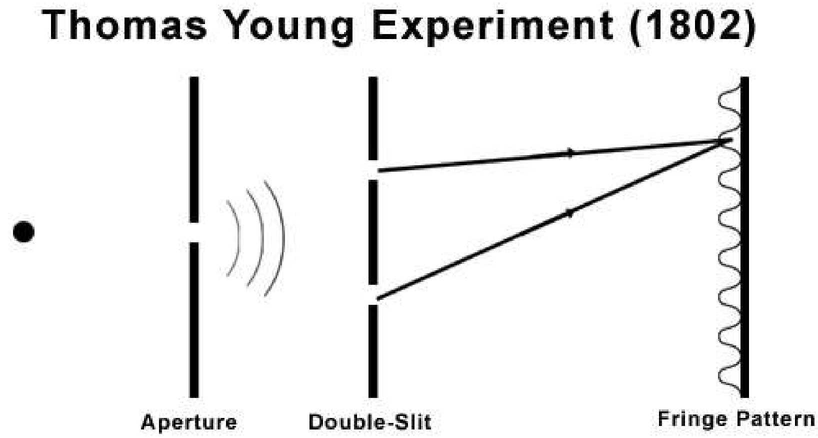
> (iii) the particular waves are perceptible only at their common tangent. (Shapiro 232)

What does this mean to the average Joe? All-in-all Huygens' principle is better understood by the use of a diagram to illustrate his idea of light.

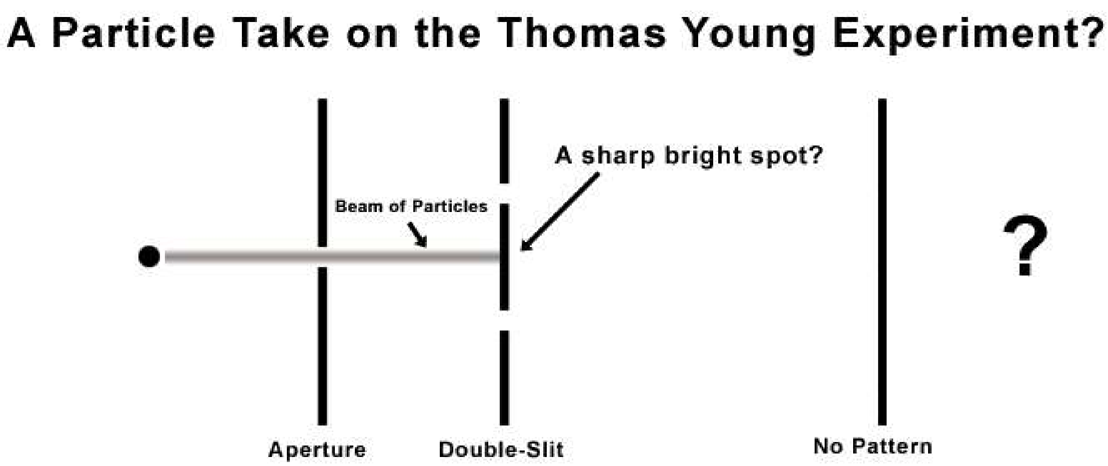


Although Huygens' principle required the existence of a universal medium called "aether" for his theoretical waves to travel through, his picture on a wave theory of light can still be applied to logically illustrate various phenomena, in our case: diffraction.

There are many different textbook definitions existing for the term "diffraction," all of which may be correct. But to truly understand diffraction one must consider and observe specific experiments that explicitly exhibit the phenomenon and its elegance. Responsible for the design of the most fundamental, and popular setup used to observe light interference and diffraction is Thomas Young. In his 1802 experiment Young started with a light source, placed an obstruction in front of it with a small hole (aperture) to pass the light through another obstruction containing two small slits, finally to be viewed on screen to see what kinds of "shadows" are produced.



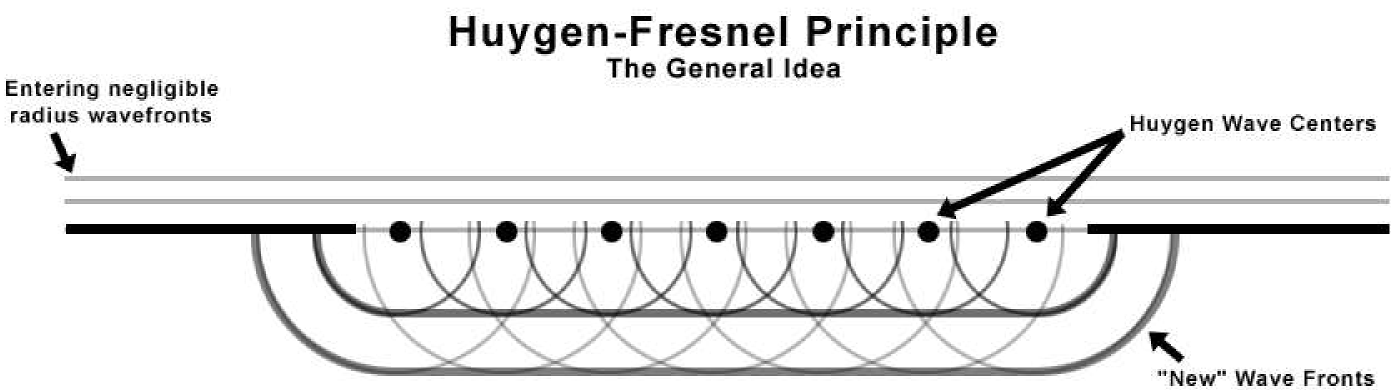
The results of his experiment showed fringes in opposition to earlier theories based on particles traveling in straight lines. If we go by earlier ideas on light based on particles traveling in straight paths one could only imagine what may be seen experimentally.



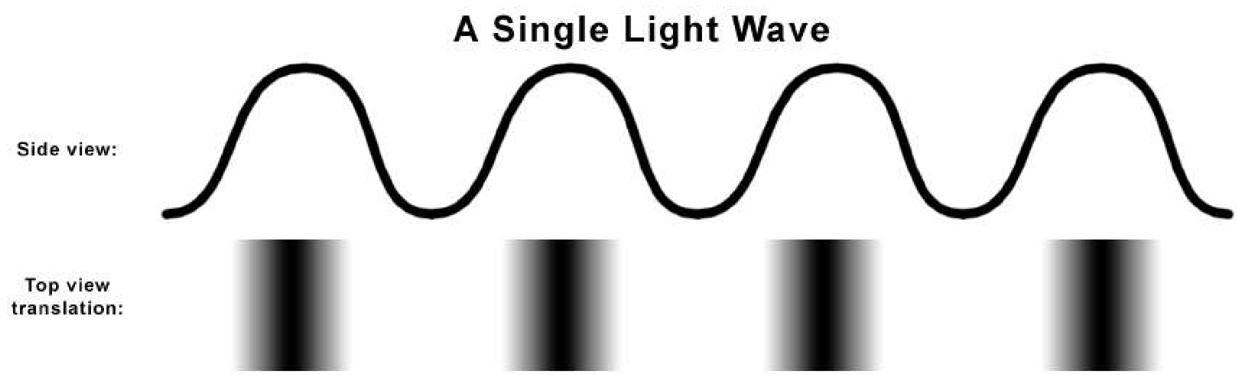
It will be admitted that this picture is an unfair judgment because it's rather vague. For one, the size of the slits and spacing between slits aren't well defined, they may be eighty centimeters (or relative to the width of a human) or eighty micrometers (or relative to the width of a single hair), this is the difference that can determine whether we observe fringes or not. In Young's experiment he used a relatively small aperture, often described as a "pinhole" (Fowles 61).

While Thomas Young showed that fringes are observed by shining light through a series of tiny pinholes an accurate picture of what actually may be occurring wasn't drawn until

Augustin-Jean Fresnel chimed in. Fresnel was able to unify the theories of Christiaan Huygens with the experiments conducted by Thomas Young to show precisely how the fringes are being produced. Fresnel, using a model similar to Young's, except with a single slit rather than a double slit, was still able to observe a fringe pattern, and with this used ideas initiated by Huygen to explain what was happening. Dubbed the Huygens-Fresnel Principle it states: "a spherical wavelet originates from every point of a wavefront, and that the wavefront at any later moment can be considered as the envelope of these wavelets" (Bergmann 334). Again, for the average Joe these are merely words on paper, so it's better to visualize, in general, what the principle implies.

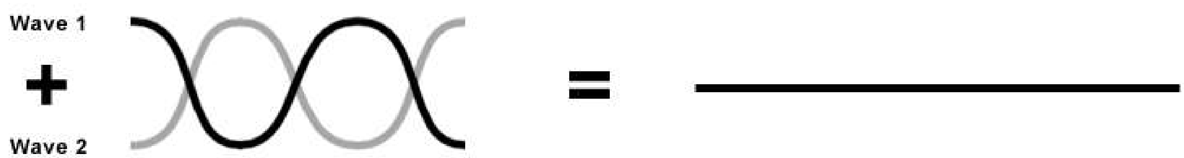


There are many different ways to view this intricate concept, but this is the general idea of what is being laid forth by Fresnel. German Physicist, Joseph Fraunhofer, was also influential in simplifying the image by inserting a "collimating lens" just before the slit to make the incoming wave fronts of negligible radius (almost planar) (Bergmann 334). Take the picture as being viewed from above; a side view of an isolated wave would translate to the following diagram:

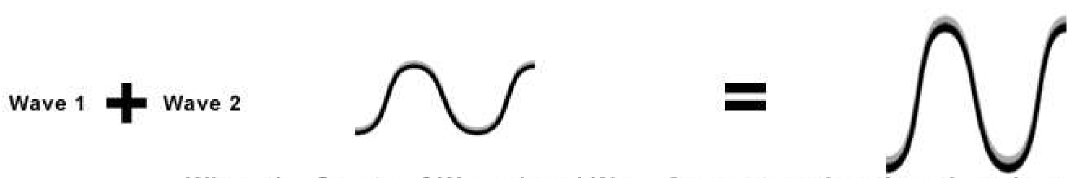


In general, the crests of the wave are represented by wave front lines from above.

So how is does this pattern come about under a theory of waves? It mainly has to do with the superposition of the waves with constructive and deconstructive interference. In general when crests meet with crests light is intensified while when crests meet with troughs the waves effectively cancel and no light is produced.

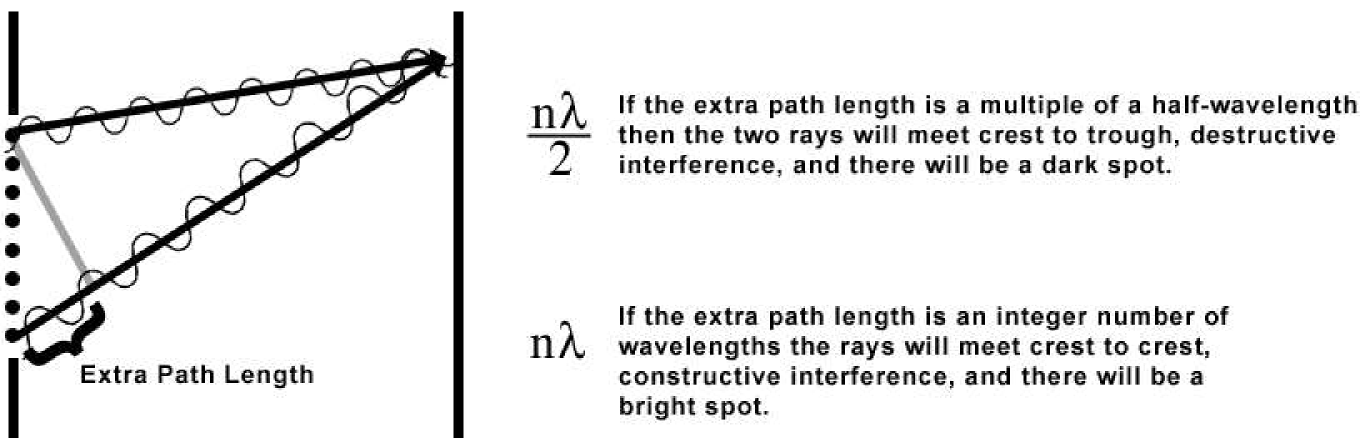


When the Crest of Wave 1 meets with the trough of Wave 2 there is deconstructive interference and no light appears because they effectively cancel each other out.

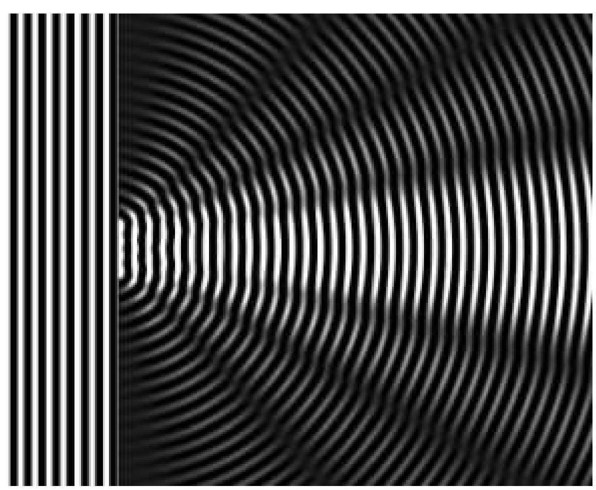


When the Crests of Wave 1 and Wave 2 meet together then there is constructive interference and the light is intensified.

When we consider the picture created by Fresnel and Fraunhofer, it is usually drawn using Huygens point sources but with light rays drawn rather than wave fronts. These light rays only represent the direction in which the wave fronts move; they do not depict the propagation of light particles! In our model for diffraction we use light rays to show the paths individual light waves take to get to the viewing screen. It is drawn this way to show that each point source of light within the slit actually travels a different distance to particular points on the screen. Since each wave comes from the same exact light source the only difference is the path that each wave took to reach a particular point on the screen. If we consider our theoretical wave picture of light we see there is a direct correlation with the wavelength of light being used with the path length taken to reach either a bright spot or a dark spot in the fringes produced on the screen.



With this picture in mind, if we zoom out of the proposed single slit experiment and consider many more wave front lines and Huygens points we can see the beginnings of how a diffraction pattern is produced by a theory based on waves:



(Source: http://en.wikipedia.org/wiki/Image:Wave_Diffraction_4Lambda_Slit.png)

Fresnel managed to bring together two speculative ideas to produce undeniable evidence that light is certainly a wave through the observation of diffraction. The single slit experiment has been even further expanded with the implementation of two slits, three slits to many slits, which then become known as diffraction gratings. Additionally, circular and rectangular apertures can be used to view other kinds of diffraction phenomena. Overall, the methodology in determining the existence of fringes in each model follows along the same lines as the basic single slit model. One may then ask: why don't we see fringes when out bodies obstruct the light from the sun? The answer is that the diffraction phenomenon only occurs when the obstruction is along the same order of the wavelength of light that's being used. The reason we observe "sharp-looking" shadows in the sunlight is because the size of our bodies are much larger than the wavelength of light, which is around the order of 10^3 nanometers; therefore the diffraction effects are very small.

The careful design created by Fresnel and Fraunhofer helps us to easily and logically explain what Grimaldi observed when he looked at the shadow produced by a piece of hair. The only significant difference is that the piece of hair is a "negative" slit. Nonetheless it is seen how a simple observation can go a long way in discovering experimental truth behind some of the most fundamental aspects of life.

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