Cambridge Peterhouse College Kelvin Science Essay Competition 2023

Q3: I don't know how far away the moon lies, but here is how I proved that light is a wave

Abstract

This work explores evidence for light's nature as a wave. By contextualising, performing and analysing the experiment used by English scientist Thomas Young, I demonstrate the validity of the wave model of light.

Introduction

What is light? For millennia, discovering the true nature of light has been the centre of study amongst scientists and philosophers. Being the very phenomenon which allows us to see and appreciate our world, this question has spurred the emergence of countless speculations. As scientific instruments and experimental methods evolved, human understanding of light has changed significantly throughout history. For example, theories that light consists of 'probes' which emanate from the eye were proposed in Ancient Greece. Aristotle, on the other hand, postulated that light was an incorporeal phenomenon in which objects became 'transparent' creating the illusion that it travelled. (Osiris, 1958) The Middle Eastern mathematician Alhazen suggested that light was composed of a stream of particles. (O'Connor & Robertson, 2002) Following the Scientific Revolution, scientists reviewed and corroborated past theories using new findings, epitomising the essence of the Renaissance as a period where classical concepts were revised and modified. This was the case with Descartes, who believed that light was a propagation of 'pressure waves', with Huygens in his transverse wave theory, and with Newton's 'corpuscular' theory. Thus far, presented evidence was unconvincing and often originated from misinterpreted observations, and so the nature of light continued to remain imbued with much uncertainty. That is, until 1801 when was Thomas Young impeccably demonstrated that light is a wave, whose experiment and reasoning is re-created in this essay. Although seemingly definitive, Young's work was later shown to be only one side of the coin, as Planck and Einstein proved light's existence as a particle, thus bringing us to where we are today: the particle-wave duality theory in which light is believed to behave as both waves and particles. (Einstein, et al., 1949)

Apparatus

Young's experiment is relatively straightforward and is reproducible, so has not required the use of complex materials, but equipment easily found at home or available to the general public.

Young's Equipment (1801):

- Window-shutter
- Thick paper
- Fine needle
- Pieces of card

My Equipment (2023):

- Boxes
- White paper
- Pieces of black card
- Thin string
- Monochromatic light source

Apparatus:

Vertical tunnel, enclosed and hollow.

Mechanism (open) which allows only my wanted ray of light to enter from above.

A thin string was used to create very narrow slits. Black card absorbs radiation so ensures that the light past the slits had been diffracted.

Method

Originally, Young made a small hole in his window-shutter and covered it with thick paper which he then perforated using the needle. This would have produced a clear, thin ray of natural sunlight which would have been of the suitable dimension to pass through the slits. He then observed the pattern that light made behind the slits on some movable screens. (Young, 1803)

Although still centred around the same fundamental principles, my method was slightly different in order to obtain clearer results:

1. Firstly, I created a Camera Obscura (pinhole camera) of my own by connecting empty cardboard boxes together, resulting in a long, hollow vertical tunnel in which no light from the outside was present, as the only light I want is that from my ray.
2. I further ensured that no external light entered the tunnel by covering holes and spaces between the boxes with the black card.
3. I covered the inside bottom of my tunnel with white paper so as to observe accurately any colour patterns produced with no background interference from uneven or coloured parts of the boxes (which were partially damaged).
4. Then, I created a double slit. This was the most difficult part of the experiment as it required numerous attempts to produce such small slits. I eventually realised that using a thin piece of string would ensure a very small distance between the two slits (this would be beneficial because the thin incident ray was now able to go through both slits).
5. At the top of the vertical, enclosed tunnel I devised a system such that light from a ray could enter the tunnel through an opening, whilst simultaneously keeping the interference of other unwanted light to an absolute minimum. I did this by creating a box with a small hole at the top which, when open allowed me to access the inside, and when closed stopped unwanted light.
6. I also cut a small hole near the bottom of the tunnel to allow me to see inside for myself and record observations through the use of a picture.

7. Having set up the apparatus, I darkened the room by turning any lights off and closing the curtains. I then used different light sources for the experiment:
    - Using a red laser light
    - Using a UV light emitter
    - Creating monochromatic light by harnessing the sun's light and passing it through a coloured filter (made by colouring a plastic bottle red)

These light sources are all monochromatic whereas Young used the sun's white light which is composed of light waves of many different frequencies. This means that the diffracted waves of white light, being incoherent with each other, are more likely to negatively interfere with each other resulting in a more unclear image. In principle, my method should yield more easily observable results than Young's whilst, in the case of my homemade filter, still being accessible to him at the time.

Safety

In terms of safety, this experiment does not pose much risk. One possible risk was that of injury from mishandling the cutter when building the vertical tunnel, so care was taken in ensuring this was avoided. During the experiment, I was attentive to not shine laser light into my eyes and to avoid looking at the sun directly as this would have resulted in severe damage to the eye. These risks likely resemble those faced by Young in his own experiment as he too would have needed to build tools of his own and was also dealing with light of high intensity.

Results and Conclusions

Looking through the opening, I observed interference patterns, alternating fringes or regions of light with high and no intensity. The presence of these fringes highlights a key phenomenon: diffraction, which is a property which pertains to waves only, not particles. For if light were only composed of particles, then it would not diffract and only 2 fringes would be seen in the shape of the slits. The formation of these fringes extending beyond the middle two indicates regions where the light waves from each slit superimpose constructively as a result of their being in phase with each other. Therefore, they create a resultant wave with a larger amplitude and, as $Intensity = |Amplitude|^2$, these regions have a high intensity, and are easily visible. Regions of darkness are a consequence of waves interfering destructively with each other as they are out of phase, thus cancelling each other out and forming a resultant wave with little or no amplitude and thus little or no intensity.

The distance between the fringes was occasionally constant and at other times varied. This is most likely due to the experiment's fine margins and sensibility to slight movements of the ray of light resulting in inevitably different patterns. In the case of the UV light, I believe the curvature of the ray emitter was responsible for the curved shape of the fringes, especially given that fringes from flat light sources were straight.

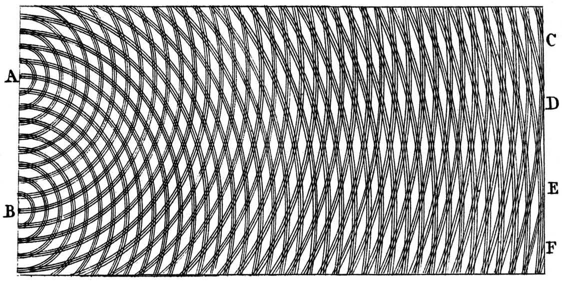
The interference pattern was observed for almost all colours of light. The ones shown here are the purely the best images, based on how easily fringes can be seen. This does not suggest that only some frequencies (colours) of light act as a wave, but is simply due to the fact that the length of my tunnel was better suited for the particular wavelengths of specific colours of light. In fact, Young did not have a fixed screen on which he observed the interference pattern: he had moveable screens made of card in order to 'adapt' to the wavelengths of the different colours.

Overall, my results, as interpreted by Young, testify to the wave-like nature of light.

A few of the observed interference patterns:

Blue light *Green light* *White light* *Red light*

(not monochromatic)

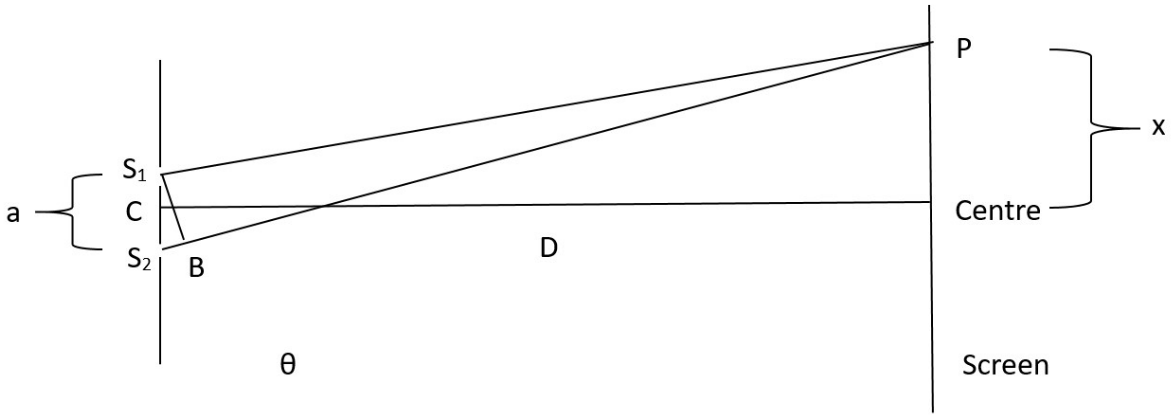


Young's sketch of an interference pattern. A and B are sources of coherent waves. Points C, D, E and F are maxima points on the wave.

Analysis

Having asserted light's behaviour as a wave, the relationship between its wavelength, distance between the slits and distance between the fringes can now be mathematically described.

Below is an illustration of experiment:



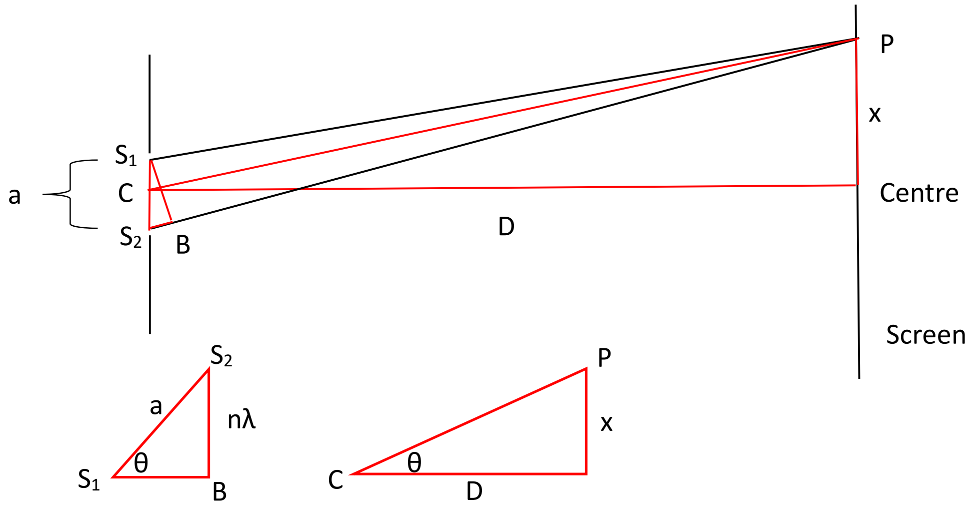
S_1 and S_2 are sources of coherent waves, which are split by a distance labelled a.

The perpendicular distance between the middle of the slits and the screen is D.

P is a point on the screen where the waves interfere constructively and so are in phase.

B is a point on the wave path from S_2 such that $S_1P = BP$. For the waves to be in phase at P, the extra distance travelled by the waves from S_2, S_2B, must be equal to an integer wavelength, i.e. $S_2B = n\lambda$.

Re-drawing and highlighting areas of the experiment:



As *D* is much greater than *a*, the triangles are both right-angled and having a very similar angle θ, we can establish that the two triangles are similar, so:

$$\sin\theta = \frac{n\lambda}{a} \qquad \tan\theta = \frac{x}{D}$$

And since at small angles $\theta = \sin\theta = \tan\theta$,

$$\boxed{\frac{n\lambda}{a} = \frac{x}{D}}$$

which describes the relationship between:

- n, the order of maxima from the centre
- λ, the wavelength of the light wave
- a, the distance between the two slits
- x, the separation between two adjacent fringes
- D, the distance between the slits and the screen

Evaluation

Overall, I would consider my investigation to have been a successful one, firstly for having achieved the aim of confirming the wave nature of light and secondly for having performed an experiment very similar to Young's, using nothing more complex than a string, save for a monochromatic light source which has made my observations possibly more easily conclusive than Young's. However, with hindsight, one improvement to my experiment is to have had a moveable screen so as to obtain better defined interference patterns by making the light waves' wavelengths suit the changeable distance from the source to the screen. An extension to my experiment would be to test the relationship between the size of the slits diffraction grating and the distance between the maxima orders of light and show whether the experiment validates the mathematical equation derived above. Lastly, it is important to note that my investigation, like Young's, although correct, does not yield a definitive model of light, as later physicists established its dual nature, which can be achieved from an extension of the Double Slit Experiment by firing single photons through the slits and observing the pattern they produce. As such, the beauty, reproducibility and inherent complexity of the experiment have led distinguished physicist Richard Feynman to describe it as a phenomenon "which has in it the heart of quantum mechanics…it contains the only mystery".

Bibliography

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