Module 7: The Nature of Light

Part 2: Light - Wave Model

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Contents

Syllabus content: The Nature of Light

Light: Wave Model

Inquiry question: What evidence supports the classical wave model of light and what predictions can be made using this model?

Students:

- conduct investigations to analyse qualitatively the diffraction of light
- conduct investigations to analyse quantitatively the interference of light using double slit apparatus and diffraction gratings $d \sin\theta = m\lambda$
- analyse the experimental evidence that supported the models of light that were proposed by Newton and Huygens
- conduct investigations quantitatively using the relationship of Malus' Law $I = I_{max} \cos^2\theta$ for plane polarisation of light, to evaluate the significance of polarisation in developing a model for light

Introduction

In our topic on geometric optics in year 11 we examined a a number of properties of light: reflection, refraction, dispersion and the inverse square law for intensity. Geometrical optics specifically does not apply to situations in which the wave nature of light is apparent.

In this module we will introduce three new properties of light that lie outside the limits of geometrical optics: diffraction, polarisation and interference [1].

[1] Note that interference and diffraction are both due to the same underlying physics of superposition - we will discuss this in detail later

In this module will examine how these new pieces of evidence influenced the development of our understanding of nature of light and (eventually) led physicists to conclude that light is a wave.

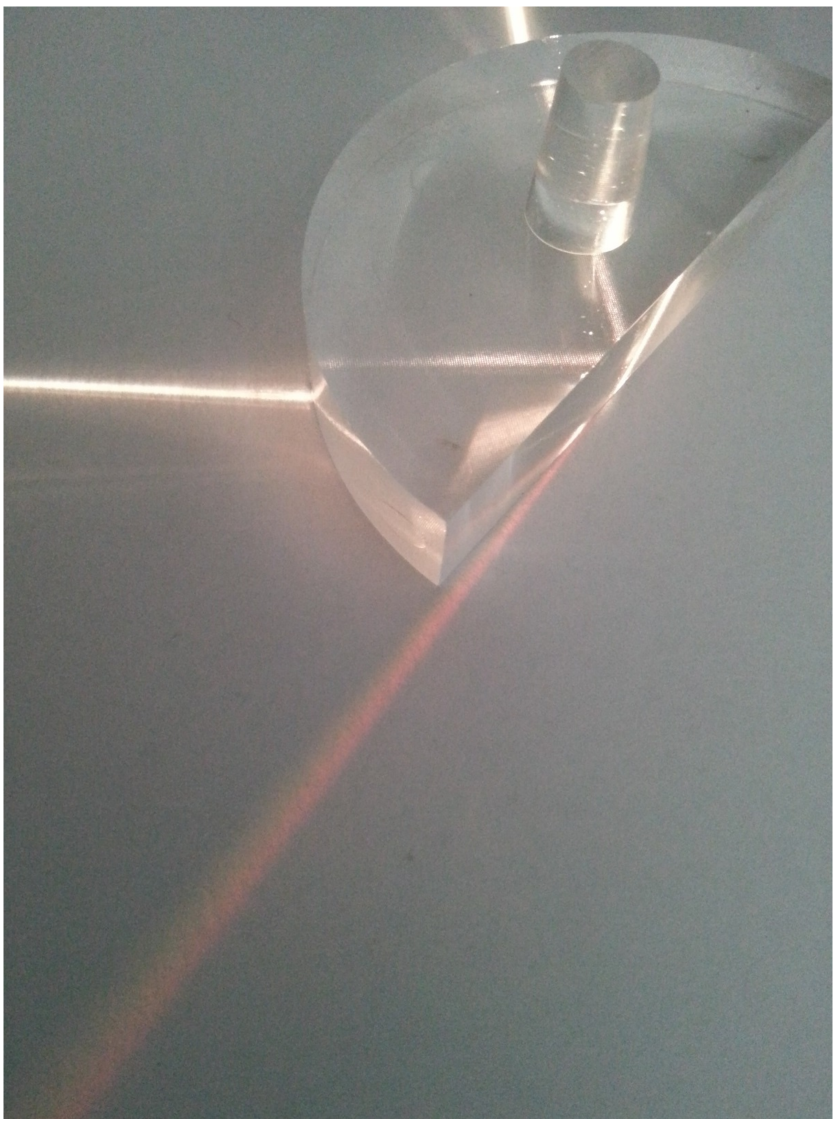


Figure 1: Demonstration of reflection, refraction and dispersion of light by a perspex prism. The incoming beam is at the top right. It enters the semi-circular prism at right angles so is not refracted at that interface. Reflection and refraction occur at the straight edge, with the refracted beam showing dispersion. Dispersion is the spreading of the refracted beam due to the dependence of refractive index on colour - the refractive index is highest for blue and lowest for red light.

Introduction - The particle versus the wave model of light

Our two protagonists of this section, Isaac Newton (1642-1726) and Christiaan Huygens (1629-1695) were contemporaries - each aware of the other's work, and of the properties of light known at that time: reflection, refraction, dispersion, polarisation, interference, and its finite speed (discovered by Rømer by timing the eclipse of Io of Jupiter). They proposed two different explanations for these properties - a particle and a wave model. Neither explanation was really complete - the resolution to the debate is to be found later in the work of Young, Fresnel and Foucault and Fizeau.

Newton's particle model of light

Newton's knowledge of the properties of light

Newton began thinking about the nature of light in his early 20s [2]. Using a glass prism he produced dispersion - the splitting of light into its constituent colours (due to the variation of refractive index of the glass with the colour of the light). He went on to conduct a large number of experiments in optics.

Newton published his theory of light in a 1703 work titled "Opticks"[3,4]. He begins by listing the known properties of light, including the following:

- Refraction (Newton calls this "refrangibility")
- Reflection (Newton calls this "reflexibility") and the amount of reflection depends upon the angle of incidence.
- For reflection, the angle of incidence equals the angle of reflection, and is in the same plane as the angle of incidence.
- Refraction from the 'rarer' material into the denser, is made towards the perpendicular.
- The sine of the angle of incidence is proportional to the sine of the angle of refraction, and this ratio is different for different colours of light.
- Light propagates at finite speed (taking about seven or eight minutes to pass from the sun to earth)

In his "axioms" Newton clearly outlines many practical implications of these properties of light. Some of these include reflection from a plane mirror (figure 3), focusing by a lens (figure 5), the image formation in the eye (figure 4) and how refraction in raindrops produces a rainbow (figure 6).

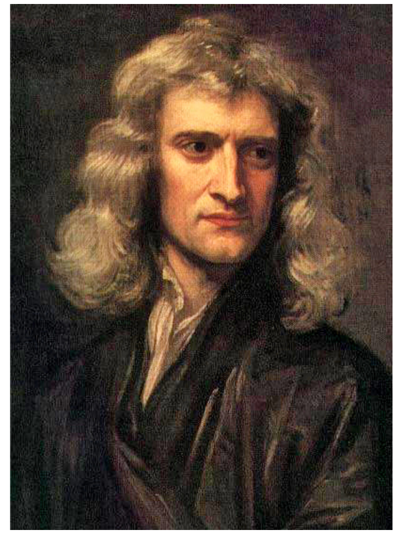


Figure 2: Isaac Newton. Painting by Godfrey Kneller (1689) [Public domain]

[2] Eugene Hecht. *Optics*. Addison-Wesley, 2nd ed. edition, 1987

[3] Isaac Newton. *Opticks or, a Treatise of the reflexions, refractions, inflexions and colours of light . Also two treatises of the species and magnitude of curvilinear figures*. 1704

[4] Fulltext at project Gutenberg.

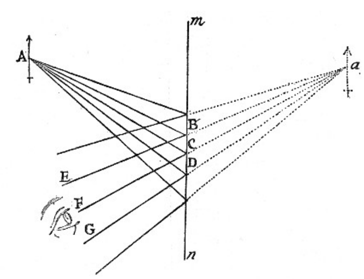


Figure 3: Reflection from a plane mirror, from Newton's "Opticks".

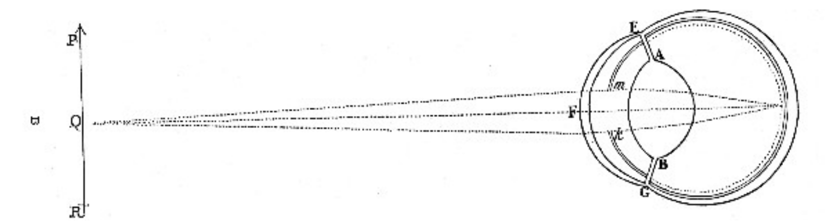


Figure 4: Focusing in the human eye, from Newton's "Opticks".

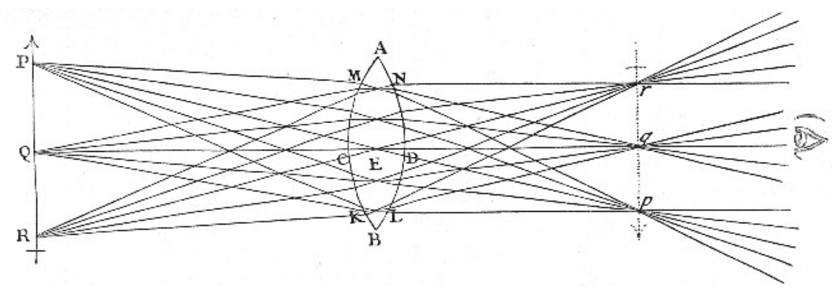


Figure 5: Image formation by a lens, from Newton's "Opticks".

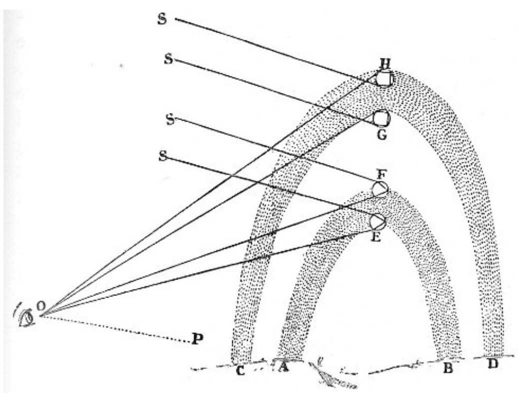


Figure 6: Formation of a (double) rainbow due to refraction and dispersion of light in raindrops, from Newton's "Opticks".

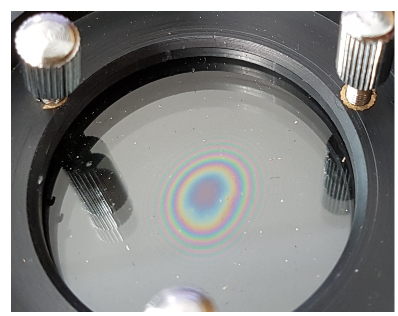


Figure 7: A photo of Newton's rings.

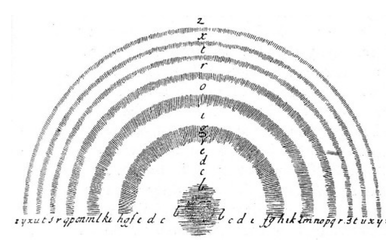


Figure 8: Newton's sketch of the coloured rings formed when a curved and flat glass plate are pressed together ("Newton's rings"), from Newton's "Opticks".

In his **second book of Opticks** Newton describes a number of experiments relating to colour, including experiments in which he produces coloured rings (now called "Newton's rings") by pressing a rounded glass plate down onto a flat glass plate, so that the plates are separated by a very small distance, that increases with distance from the point of contact. He drew (correct) comparisons between this and the colours that appear in bubbles of soap (see the front page of this booklet!) and in thin coatings of oil. These effects are now known as 'thin-film interference'.

Newton's observations of diffraction

The **third book of Opticks** contains Newton's experimental observations of diffraction. He notes that the effect was first described by Grimaldi [5] and describes his experimental setup and observations as follows [6]:

> Grimaldo has inform'd us, that if a beam of the Sun's Light be let into a dark Room through a very small hole, the Shadows of things in this Light will be larger than they ought to be if the Rays went on by the Bodies in straight Lines, and that these Shadows have three parallel Fringes, Bands or Ranks of colour'd Light adjacent to them. But if the Hole be enlarged the Fringes grow broad and run into one another, so that they cannot be distinguish'd. These broad Shadows and Fringes have been reckon'd by some to proceed from the ordinary refraction of the Air, but without due examination of the Matter. For the circumstances of the Phenomenon, so far as I have observed them, are as follows.
> Obs. 1. I made in a piece of Lead a small Hole with a Pin, whose breadth was the 42d part of an Inch. For 21 of those Pins laid together took up the breadth of half an Inch. Through this Hole I let into my darken'd Chamber a beam of the Sun's Light, and found that the Shadows of Hairs, Thred, Pins, Straws, and such like slender Substances placed in this beam of Light, were considerably broader than they ought to be, if the Rays of Light passed on by these Bodies in right Lines.
> Obs. 2. The Shadows of all Bodies (Metals, Stones, Glass, Wood, Horn, Ice, c.) in this Light were border'd with three Parallel Fringes or Bands of colour'd Light, whereof that which was contiguous to the Shadow was broadest and most luminous, and that which was remotest from it was narrowest, and so faint, as not easily to be visible. It was difficult to distinguish the Colours, unless when the Light fell very obliquely upon a smooth Paper, or some other smooth white Body, so as to make them appear much broader than they would otherwise do.

[5] https://en.wikipedia.org/wiki/Francesco_Maria_Grimaldi

[6] Isaac Newton. *Opticks or, a Treatise of the reflexions, refractions, inflexions and colours of light . Also two treatises of the species and magnitude of curvilinear figures*. 1704

Newton's belief was that the edges of the hair and the knife *bend* light as it passes near it, the more so the closer the light passes (see figure 9.

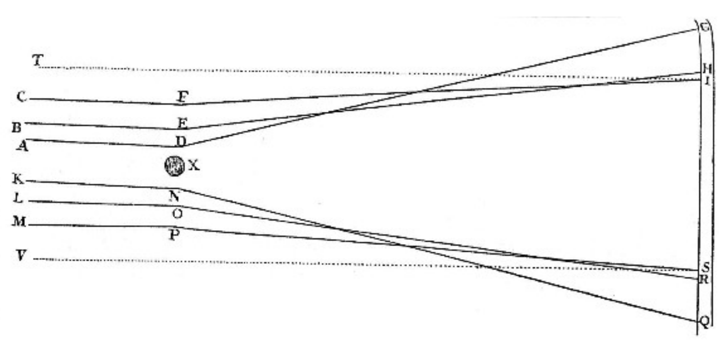


Figure 9: Newton's conception of how particles of light are bent when it passes by a hair to make a broad shadow and produce a diffraction pattern.

Diffraction demonstrations (qualitative)

Diffraction with a laser and a knife edge and hair

We will set up a laser with a beam spreader (for example, a lens with a $\approx$ 1cm focal length). This is not essential, but makes the pattern easier for a larger group of people to see [7]) and then place an object with a sharp edge in the beam and observe the diffraction pattern produced. We will use a knife and a hair (or a pin, or thread...) for our investigation, as these objects are what Newton reports using in his experiments.

Space to draw a diagram of our setup and observations.

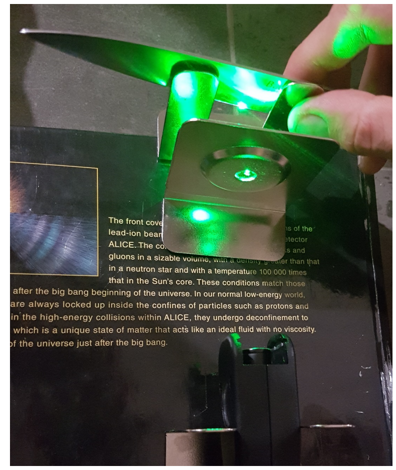


Figure 10: The setup we will use to observe diffraction for a knife edge and hair.

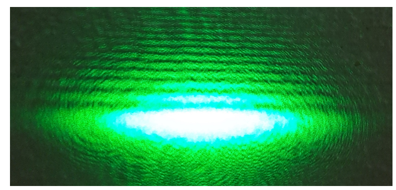


Figure 11: Diffraction pattern produced by a knife edge.

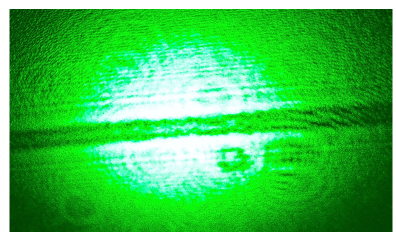


Figure 12: Diffraction pattern produced by a human hair.

[7] I used one from the Michelson Interferometer kit from Industrial Fibre Optics: `http://www.i-fiberoptics.com/replacement-parts-summary.php?cat=Michelson%20Interferometer%20Kit%20(45-94X)`

Newton's corpuscular (particle) theory of light

In the last part of "Optiks" Newton expounds his particle theory of light in a number of "Queries":

> When I made the foregoing Observations, I design'd to repeat most of them with more care and exactness, and to make some new ones for determining the manner how the Rays of Light are bent in their passage by Bodies, for making the Fringes of Colours with the dark lines between them. But I was then interrupted, and cannot now think of taking these things into farther Consideration. And since I have not finish'd this part of my Design, I shall conclude with proposing only some Queries, in order to a farther search to be made by others.

His queries relating to his observations of **diffraction** are the following:

> Query 1. Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action (ceteris paribus) strongest at the least distance?
>
> Qu. 2. Do not the Rays which differ in Refrangibility differ also in Flexibity; and are they not by their different Inflexions separated from one another, so as after separation to make the Colours in the three Fringes above described? And after what manner are they inflected to make those Fringes?
>
> Qu. 3. Are not the Rays of Light in passing by the edges and sides of Bodies, bent several times backwards and forwards, with a motion like that of an Eel? And do not the three Fringes of colour'd Light above-mention'd arise from three such bendings?
>
> Qu. 20. Doth not this Aethereal Medium in passing out of Water, Glass, Crystal, and other compact and dense Bodies into empty Spaces, grow denser and denser by degrees, and by that means refract the Rays of Light not in a point, but by bending them gradually in curve Lines? And doth not the gradual condensation of this Medium extend to some distance from the Bodies, and thereby cause the Inflexions of the Rays of Light, which pass by the edges of dense Bodies, at some distance from the Bodies?

Summary of Newton's explanation for diffraction: Newton proposes (Qu. 18) that the aether is "rarified" in dense bodies, and grows denser over some distance away from them (Qu. 20), and that this difference in density of the aether near material bodies can bend the path of the particles of light to produce diffraction patterns (Qu. 3). Different colours are bent by different amounts (Qu. 2).

Newton's proposal is not as "crazy" as it sounds. Gradients in the refractive index of material do cause light to bend (for example, variation in the refractive index of air above hot ground can cause light from the sky to bend upwards, causing mirages). We now know that Newton's explanation is incorrect, as there is no aether, so no way for its density to changes at the surface of solid objects.

Newton's queries relating to **refraction and reflection**:

Qu. 4. Do not the Rays of Light which fall upon Bodies, and are reflected or refracted, begin to bend before they arrive at the Bodies; and are they not reflected, refracted, and inflected, by one and the same Principle, acting variously in various Circumstances?

Qu. 5. Do not Bodies and Light act mutually upon one another; that is to say, Bodies upon Light in emitting, reflecting, refracting and inflecting it, and Light upon Bodies for heating them, and putting their parts into a vibrating motion wherein heat consists?

Qu. 17. If a stone be thrown into stagnating Water, the Waves excited thereby continue some time to arise in the place where the Stone fell into the Water, and are propagated from thence in concentrick Circles upon the Surface of the Water to great distances. And the Vibrations or Tremors excited in the Air by percussion, continue a little time to move from the place of percussion in concentrick Spheres to great distances. And in like manner, when a Ray of Light falls upon the Surface of any pellucid Body, and is there refracted or reflected, may not Waves of Vibrations, or Tremors, be thereby excited in the refracting or reflecting Medium at the point of Incidence, and continue to arise there, and to be propagated from thence as long as they continue to arise and be propagated, when they are excited in the bottom of the Eye by the Pressure or Motion of the Finger, or by the Light which comes from the Coal of Fire in the Experiments above-mention'd? and are not these Vibrations propagated from the point of Incidence to great distances? And do they not overtake the Rays of Light, and by overtaking them successively, do they not put them into the Fits of easy Reflexion and easy Transmission described above? For if the Rays endeavour to recede from the densest part of the Vibration, they may be alternately accelerated and retarded by the Vibrations overtaking them.

Qu. 19. Doth not the Refraction of Light proceed from the different density of this Aethereal Medium in different places, the Light receding always from the denser parts of the Medium? And is not the density thereof greater in free and open Spaces void of Air and other grosser Bodies, than within the Pores of Water, Glass, Crystal, Gems, and other compact Bodies? For when Light passes through Glass or Crystal, and falling very obliquely upon the farther Surface thereof is totally reflected, the total Reflexion ought to proceed rather from the density and vigour of the Medium without and beyond the Glass, than from the rarity and weakness thereof.

To understand what Newton is proposing in these queries, we also need to look at **first book of Opticks** in Proposition VI. Theorem V., where Newton discusses how Snells's law can be obtained by supposing

> That Bodies refract Light by acting upon its Rays in Lines perpendicular to their Surfaces. But in order to this Demonstration, I must distinguish the Motion of every Ray into two Motions, the one perpendicular to the refracting Surface, the other parallel to it.

Newton then argues using geometry that only the component of motion of the light particle *perpendicular* to the refracting surface is affected (picture an elastic collision between a ball and a wall - the velocity of the ball parallel to the surface of the wall is not affected by the collision). In figure 13 consider the vector v_{air} representing the velocity of the light particle in air as it approaches the refracting surface (water), and the velocity of the light particle inside the refracting medium (water) v_{water}. Newton proposes that the component parallel to the surface remains constant ($v_{air_\parallel} = v_{water_\parallel}$), but that the component perpendicular to the surface increases ($v_{air_\perp} < v_{water_\perp}$). In this way

$$\sin\theta_i = \frac{v_{air_\parallel}}{v_{air}}$$

and

$$\sin\theta_r = \frac{v_{water_\parallel}}{v_{water}}$$

so that

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{v_{water}}{v_{air}} > 1$$

Newton goes on to say:

> And this Demonstration being general, without determining what Light is, or by what kind of Force it is refracted, or assuming any thing farther than that the refracting Body acts upon the Rays in Lines perpendicular to its Surface; I take it to be a very convincing Argument of the full truth of this Proposition.

Summary for reflection and refraction: Newton proposes a mechanism to explain refraction as due to the difference in density of the aether inside and external to a body (Qu. 4 Qu. 19). Falling *away* from the region of high aether density and *toward* region of low density, the light ray changes its direction of motion and speed in the direction perpendicular to the surface (like a projectile as it falls towards earth), accounting for how a ray bends towards the normal on entering a medium. The ray's velocity perpendicular to the surface decreases on leaving a medium, so bends away from the normal (like a projectile moving away from earth). In each case the horizontal

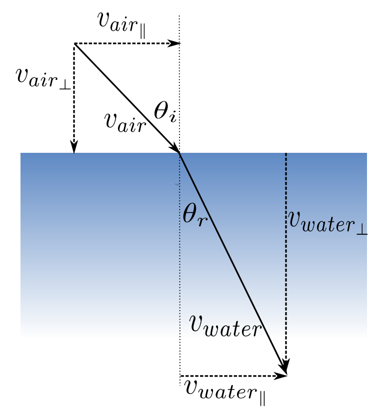


Figure 13: Diagram of Newton's concept of refraction, in which the particle gains velocity perpendicular to the interface as it moves from air to water, but where its velocity parallel to the surface remains constant. To help make sense of why Newton's explanation is incorrect, note here that the arrows are representing velocities, not simply a ray. We now know that the velocity decreases, so the correct velocity vector would have the same angle, but be shorter.

Figure adapted from Baierlein. R., *Newton to Einstein :the trail of light : an excursion to the wave-particle duality and the special theory of relativity.* Cambridge University Press (1992) pg. 38.

speed is unchanged, and this accounts for Snell's law (within Newton's theory).

The much harder problem for Newton's theory is the need to account for part of the ray being reflected and part refracted. In Query 17, Newton proposes that the light particle hitting the medium is analogous to a stone hitting the surface of water, and exciting waves. He suggests that light particles produce

> Waves of Vibrations, or Tremors, be thereby excited in the refracting or reflecting Medium at the point of Incidence, and continue to arise there, and to be propagated from thence as long as they continue to arise and be propagated... ...And do they not overtake the Rays of Light, and by overtaking them successively, do they not put them into the Fits of easy Reflexion and easy Transmission described above? For if the Rays endeavour to recede from the densest part of the Vibration, they may be alternately accelerated and retarded by the Vibrations overtaking them.

Newton is suggesting that the vibrations in particles of the medium produced by the light particles hitting the surface (perhaps with some interaction with the aether as well?) can alternately *assist* the particles to enter the surface or *prevent* them entering the surface, producing both a reflected and a refracted beam.

Queries relating **colour and dispersion**:

> Query 29 ...Nothing more is requisite for producing all the variety of Colours, and degrees of Refrangibility, than that the Rays of Light be Bodies of different Sizes, the least of which may take violet the weakest and darkest of the Colours, and be more easily diverted by refracting Surfaces from the right Course; and the rest as they are bigger and bigger, may make the stronger and more lucid Colours, blue, green, yellow, and red, and be more and more difficultly diverted. Nothing more is requisite for putting the Rays of Light into Fits of easy Reflexion and easy Transmission, than that they be small Bodies which by their attractive Powers, or some other Force, stir up Vibrations in what they act upon, which Vibrations being swifter than the Rays, overtake them successively, and agitate them so as by turns to increase and decrease their Velocities, and thereby put them into those Fits.

Summary for colour and dispersion:

Newton explains colour in terms of particles of different sizes. Blue is the smallest, and most easily bent during refraction.

Finally, Newton's queries relating to double refraction (**polarisation of light**) by calcite crystals:

> Qu. 25. Are there not other original Properties of the Rays of Light, besides those already described? An instance of another original Property we have in the Refraction of Island Crystal, described first by Erasmus Bartholine [8], and afterwards more exactly by Hugenius, in his Book De la Lumiere... ...If a piece of this crystalline Stone be laid upon a Book, every Letter of the Book seen through it will appear double, by means of a double Refraction. And if any beam of Light falls either perpendicularly, or in any oblique Angle upon any Surface of this Crystal, it becomes divided into two beams by means of the same double Refraction. And if two pieces of Island Crystal be placed one after another, in such manner that all the Surfaces of the latter be parallel to all the corresponding Surfaces of the former: The Rays which are refracted after the usual manner in the first Surface of the first Crystal, shall be refracted after the usual manner in all the following Surfaces; and the Rays which are refracted after the unusual manner in the first Surface, shall be refracted after the unusual manner in all the following Surfaces.

> Qu. 26. Have not the Rays of Light several sides, endued with several original Properties? For if the Planes of perpendicular Refraction of the second Crystal be at right Angles with the Planes of perpendicular Refraction of the first Crystal, the Rays which are refracted after the usual manner in passing through the first Crystal, will be all of them refracted after the unusual manner in passing through the second Crystal; and the Rays which are refracted after the unusual manner in passing through the first Crystal, will be all of them refracted after the usual manner in passing through the second Crystal... ...Every Ray of Light has therefore two opposite Sides, originally endued with a Property on which the unusual Refraction depends, and the other two opposite Sides not endued with that Property.

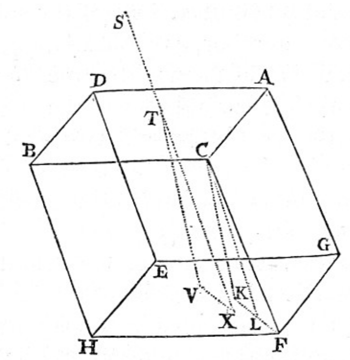


Figure 14: Newton's diagram of double refraction in calcite ("Iceland Spar").

[8] `https://en.wikipedia.org/wiki/Rasmus_Bartholin`

Summary **Polarisation** of light: Newton points out that once the light is separated into two parts through double refraction, it is not separated into two beams again on passing into other calcite crystals - whatever causes the first separation is "an original property" of the light particle that remains with it. Newton attributes polarisation to light having two "sides", with the direction of refraction through calcite depending upon the orientation of the "sides" of the light particles with respect to the orientation of the sides of the calcite crystal (we would now speak of light having two different directions in which its electric field oscillates).

*Queries arguing **for** a particle and **against** a wave model of light*

Finally, in Query 28, Newton argues that the evidence, taken together, points to **light being a particle**.

Firstly, Newton argues that light cannot be a wave, or it would diffract "into the shadow" like water or sound waves, and Newton's limited/incomplete observations have led him to believe this doesn't happen:

> Qu. 28. Are not all Hypotheses erroneous, in which Light is supposed to consist in Pression or Motion, propagated through a fluid Medium?... ...if it consisted in Pression or Motion, propagated either in an instant or in time, it would bend into the Shadow. For Pression or Motion cannot be propagated in a Fluid in right Lines, beyond an Obstacle which stops part of the Motion, but will bend and spread every way into the quiescent Medium which lies beyond the Obstacle... ...The Waves on the Surface of stagnating Water, passing by the sides of a broad Obstacle which stops part of them, bend afterwards and dilate themselves gradually into the quiet Water behind the Obstacle. The Waves, Pulses or Vibrations of the Air, wherein Sounds consist, bend manifestly, though not so much as the Waves of Water. For a Bell or a Cannon may be heard beyond a Hill which intercepts the sight of the sounding Body, and Sounds are propagated as readily through crooked Pipes as through straight ones. But Light is never known to follow crooked Passages nor to bend into the Shadow... ...The Rays which pass very near to the edges of any Body, are bent a little by the action of the Body, as we shew'd above; but this bending is not towards but from the Shadow, and is perform'd only in the passage of the Ray by the Body, and at a very small distance from it. So soon as the Ray is past the Body, it goes right on.

Secondly, Newton argues that double refraction by calcite (we now know this is due to polarisation) cannot be explained by Huygen's longitudinal wave model.

> To explain the unusual Refraction of Island Crystal by Pression or Motion propagated, has not hitherto been attempted (to my knowledge) except by Huygens, who for that end supposed two several vibrating Mediums within that Crystal. But when he tried the Refractions in two successive pieces of that Crystal, and found them such as is mention'd above; he confessed himself at a loss for explaining them [9]. For Pressions or Motions, propagated from a shining Body through an uniform Medium, must be on all sides alike; whereas by those Experiments it appears, that the Rays of Light have different Properties in their different Sides. He suspected that the Pulses of Aether in passing through the first Crystal might receive certain new Modifications, which might determine them to be propagated in this or that Medium within the second Crystal, according to the Position of that Crystal. But what Modifications those might be he could not say, nor think of any thing satisfactory in that Point.

[9] Mais pour dire comment cela se fait, je n'ay rien trove jusqu' ici qui me satisfasse. C. H. de la lumiere, c. 5, p. 91.

Summary of Newton's particle theory of light

Newton proposes that:

- light consists of small solid particles with intrinsic properties which include size and 'sides'.
- Matter and light particles can interact, matter bending the path of light particles and light particles causing vibrations in matter.

With a particle theory of light, Newton believes he can explain:

- Snell's law of refraction: the particle's velocity perpendicular to the surface increases as it enters a denser medium due to a change in the density of the aether) experiences an *increase* in velocity in the perpendicular direction when it enters a denser medium due to the lower density of aether in the medium and a corresponding *decrease* in perpendicular velocity as it leaves.
- Reflection: particles excite vibrations in the medium which produce "fits of easy transmission and reflection" which alternatively promote reflection then refraction, so both producing both rays.
- Double refraction/polarisation: as the light particle has "sides", particles with different "sides" will be refracted by calcite differently, depending on the orientation of the sides of the light particles with respect to the sides of the calcite crystal.
- Colour: light particles come in different "sizes", red being the largest and violet the smallest.
- Dispersion: different size particles experience different changes in perpendicular velocity during refraction, red experiencing the least change as it is the largest particle and violet being bent the most as it is the smallest.
- Diffraction: which Newton explains as the bending of the path of light particles due to a variation in the density of the aether near the edge of a medium. The path of particles closest to matter is bent most, and bent *away* from the shadow.

Newton's arguments against the wave model of light rest on:

- the fact that Newton doesn't see light "bend into the shadow" during diffraction, if light were a wave it should bend easily around obstacles as sound and water waves do.
- that light must be a particle to possess the "original properties" of "sides" and "size" required to explain polarisation and colour.

Huygens' wave model of light

Cristiaan Huygens' published his own theory of light a decade or so before Newton, in his "Treatise of Light" [10,11].

Huygens begins his treatise by setting out his beliefs that light must consist in vibrations (i.e. as a wave passing through the aether) rather than the transport of particles:

> It is inconceivable to doubt that light consists in the motion of some sort of matter. For whether one considers its production, one sees that here upon the Earth it is chiefly engendered by fire and flame which contain without doubt bodies that are in rapid motion, since they dissolve and melt many other bodies, even the most solid; or whether one considers its effects, one sees that when light is collected, as by concave mirrors, it has the property of burning as a fire does, that is to say it disunites the particles of bodies. This is assuredly the mark of motion, at least in the true Philosophy, in which one conceives the causes of all natural effects in terms of mechanical motions...
>
> Further, when one considers the extreme speed with which light spreads on every side, and how, when it comes from different regions, even from those directly opposite, the rays traverse one another without hindrance, one may well understand that when we see a luminous object, it cannot be by any transport of matter coming to us from this object, in the way in which a shot or an arrow traverses the air; for assuredly that would too greatly impugn these two properties of light, especially the second of them. It is then in some other way that light spreads; and that which can lead us to comprehend it is the knowledge which we have of the spreading of Sound in the air.
>
> We know that by means of the air, which is an invisible and impalpable body, Sound spreads around the spot where it has been produced, by a movement which is passed on successively from one part of the air to another; and that the spreading of this movement, taking place equally rapidly on all sides, ought to form spherical surfaces ever enlarging and which strike our ears. Now there is no doubt at all that light also comes from the luminous body to our eyes by some movement impressed on the matter which is between the two; since, as we have already seen, it cannot be by the transport of a body which passes from one to the other. If, in addition, light takes time for its passage - which we are now going to examine - it will follow that this movement, impressed on the intervening matter, is successive; and consequently it spreads, as Sound does, by spherical surfaces and waves: for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it, and which present a successive spreading as circles, though these arise from another cause, and are only in a flat surface.

[10] Christiaan Huygens. *Treatise on Light*. 1690

[11] Fulltext available at Project Gutenberg

Figure 15: Christiaan Huygens. Painting by Caspar Netscher [Public domain].

Figure 16: Huygens' concept that each point on a luminous body acts as a source of spherical waves. From Huygens' Treatise on Light

Huygens proposes light is not a vibration in air, but aether

> Now if one examines what this matter may be in which the movement coming from the luminous body is propagated, which I call Ethereal

> matter, one will see that it is not the same that serves for the propagation of Sound. For one finds that the latter is really that which we feel and which we breathe, and which being removed from any place still leaves there the other kind of matter that serves to convey Light. This may be proved by shutting up a sounding body in a glass vessel from which the air is withdrawn by the machine which Mr. Boyle has given us, and with which he has performed so many beautiful experiments.
>
> One sees here not only that our air, which does not penetrate through glass, is the matter by which Sound spreads; but also that it is not the same air but another kind of matter in which Light spreads; since if the air is removed from the vessel the Light does not cease to traverse it as before.

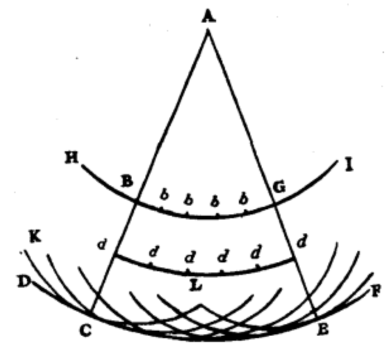


Figure 17: Huygens' principle - each point on the wavefront acts as a new source of spherical waves, with the new wavefront being the tangent to the wavefronts of all the individual wavelets. From Huygens' Treatise on Light

Huygen's principle

Huygen's most enduring insight is what is now called "Huygen's principle" [12], which proposes that **each point on a wavefront acts as a new spherical source of wavelets** (see figure 17). **The wavefront at a later time is then the tangent to all these secondary wavelets**.

Huygens argues for this principle as follows:

> There is the further consideration in the emanation of these waves, that each particle of matter in which a wave spreads, ought not to communicate its motion only to the next particle which is in the straight line drawn from the luminous point, but that it also imparts some of it necessarily to all the others which touch it and which oppose themselves to its movement. So it arises that around each particle there is made a wave of which that particle is the centre.

Huygens explains how the wave theory eliminates the problem of particles 'hitting' each other when travelling in opposite directions

> Another property of waves of light, and one of the most marvellous, is that when some of them come from different or even from opposing sides, they produce their effect across one another without any hindrance. Whence also it comes about that a number of spectators may view different objects at the same time through the same opening, and that two persons can at the same time see one another's eyes. Now according to the explanation which has been given of the action of light, how the waves do not destroy nor interrupt one another when they cross one another, these effects which I have just mentioned are easily conceived.

[12] See, for example: `http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/huygen.html`

Huygen's explains the law of reflection

> Having explained the effects of waves of light which spread in a homogeneous matter, we will examine next that which happens to them on encountering other bodies. We will first make evident how the Reflexion of light is explained by these same waves, and why it preserves equality of angles.

Looking at figure 18 it can be seen that as the parallel rays approach the surface, they reach point A first. This point acts as a source of spherical wavefronts which begin to move outwards. The ray then reaches successive points marked K which each act as a source of spherical waves. By the time the last part of the ray meets the surface at B, the tangent to the wavefront made by all the spherical waves together is the straight line NB.

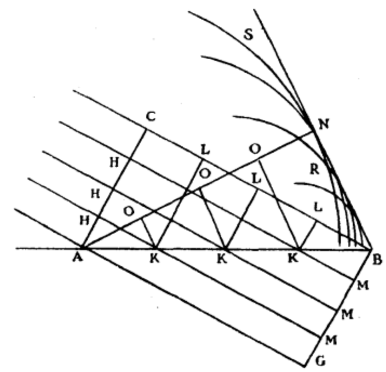


Figure 18: Huygens' principle applied to reflection. From Huygens' Treastise on Light.

Huygen's proposes matter contains aether

Huygens proposes that aether particles occupy the spaces between matter particles:

> he waves of light are carried on in the ethereal matter, which continuously occupies the interstices or pores of transparent bodies. For since it passes through them continuously and freely, it follows that they are always full of it. And one may even show that these interstices occupy much more space than the coherent particles which constitute the bodies.

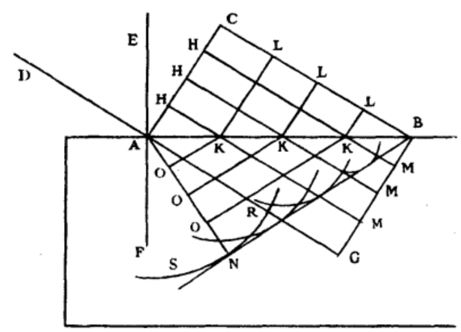


Figure 19: Huygens' principle applied to refraction. From Huygens' Treastise on Light.

Huygen's explains the law of refraction

Having argued that matter contains aether, so light can propagate through it, Huygens can use his principle to explain refraction. Significantly, Huygens proposes that the speed of light is *reduced* (not, as Newton suggested, *increased*) as it passes through matter:

> Let us pass now to the explanation of the effects of Refraction, assuming, as we have done, the passage of waves of light through transparent bodies, and the diminution of velocity which these same waves suffer in them.

In figure 19 a ray, DA, approaches a surface. As the velocity of the wave is reduced as it enters the medium, the spherical wavefronts produced by particles inside the medium do not travel as far during each time period, resulting in the wavefront bending toward the normal as it enters the material, and away from the normal as it leaves the material.

Snell's law can be derived from Huygen's principle (as we did in year 11).

Huygen's observes double refraction (polarisation) in calcite

Huygens goes on to explain a number of phenomena such as refraction by the atmosphere using his principle. Of most interest to us is his description of the phenomenon of double reflection by "Iceland Crystal" (calcite). Huygens describes with great care the two refracted rays which are produced by calcite. He then reports an important discovery (see figure 20):

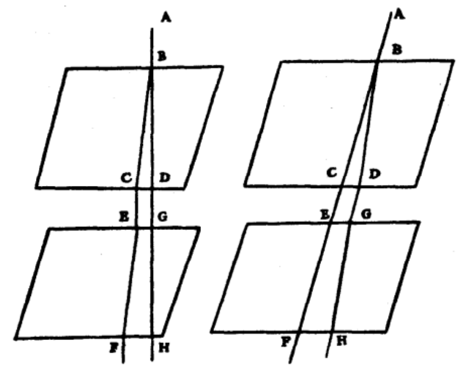


Figure 20: Huygens' demonstration that rays of light are only split once by Calcite. From Huygens' Treatise on Light.

> Before finishing the treatise on this Crystal, I will add one more marvellous phenomenon which I discovered after having written all the foregoing. For though I have not been able till now to find its cause, I do not for that reason wish to desist from describing it, in order to give opportunity to others to investigate it.
>
> The phenomenon is, that by taking two pieces of this crystal and applying them one over the other, or rather holding them with a space between the two, if all the sides of one are parallel to those of the other, then a ray of light, such as AB, is divided into two in the first piece, namely into BD and BC, following the two refractions, [Pg 93]regular and irregular. On penetrating thence into the other piece each ray will pass there without further dividing itself in two; but that one which underwent the regular refraction, as here DG, will undergo again only a regular refraction at GH; and the other, CE, an irregular refraction at EF... ...When one considers here how, while the rays CE, DG, remain the same, it depends on the position that one gives to the lower piece, whether it divides them both in two, or whether it does not divide them, and yet how the ray AB above is always divided... ...to tell how this occurs, I have hitherto found nothing which satisfies me.

Huygens' observation that, once split by one calcite crystal, light is not split again by another crystal orientated in the same way, is significant. Huygens was not able to explain this with his longitudinal wave model of light, as there is no inherent asymmetry in such a model that could cause there to be two 'types' of waves that are split by calcite. Newton attempted an explanation by proposing that particles of light had "sides", whose orientation determined which path they took through calcite.

Summary of Huygens wave model of light

Huygens' model of light proposed that:

- light consisted of vibrations (waves) that move very rapidly through the aether
- the aether consists of tiny, hard (elastic) particles which pervade the vacuum as well as matter
- light propagates in such a way that each point on a wavefront acts as a new source of spherical waves - the new wavefront consists of the tangent to the wavefronts produced by all the individual sources

Huygens' model successfully explains:

- why light rays can "pass through" each other (waves exhibit the property of superposition)
- diffraction of light
- the law of reflection
- Snell's law for refraction

Huygens' longitudinal wave model has the limitations that:

- it cannot explain double refraction (polarisation) of light by calcite
- it does not provide an explanation for colour

Experiments by Thomas Young 150 years later would show that these last two problems could be solved by assuming that light was a *transverse* wave, where the wavelength was related to the colour of the light.

Experimental evidence for the wave versus particle model of light

Newton's model of light, published a decade after Huygens, was accepted by most scientists (at least all English scientists!) for a century. A number of new observations then gradually shifted the opinion of most scientists from a particle to a wave model of light. These were:

- Young's demonstration of interference with the 'double slit' experiment
- The observation of the Poisson/Arago spot due to diffraction, predicted by Fresnel
- Foucault's experiment demonstrating that light travels slower (as predicted by Huygens wave theory) in water, not faster (as predicted by Newton's particle theory)

Young proposes that light waves obey superposition and colour is related to wavelength

Thomas Young (1773 - 1829) contributed to science in a great many fields, from optics to elasticity (Young's modulus) to hieroglyphics (he contributed to translating the Rosetta stone)[13]. One of his most enduring contributions is his identification that light undergoes interference due to superposition, which was accepted as substantial evidence that light is a wave (not so substantial as to overturn Newton's weight of opinion in an instant, however).

In work presented to the Royal Society in 1802[14], he proposed a general law which accounted for different colours of light as due to different wavelengths of light:

> The law is, that "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 most 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 colours"

Young points out that he can account for all the phenomena described in the second and third book of Newton's "Optics" with this law.

Figure 21: Thomas Young. Frontispiece from The Life of Thomas Young, M.D., F.R.S., tc. (1855) by George Peacock [Public domain]

[13] Emilio. Segre. *From falling bodies to radio waves : classical physicists and their discoveries*. W.H. Freeman, 1984

[14] Thomas Young. An account of some cases of the production of colours, not hitherto described. *Philosophical Transactions of the Royal Society of London*, 92:387–397, 1 1802

Young's demonstration of interference

In 1804 Young presented the results of his now famous experiment on interference in his Bakerian Lecture [15].

> I made a small hole in a window-shutter, and covered it with a piece of thick paper, which I perforated with a fine needle... I brought into the sunbeam a slip of card, about one-thirtieth of an inch in breadth, and observed its shadow, either on the wall, or on other cards held at different distances. Besides the fringes of colours on each side of the shadow, the shadow itself was divided by similar parallel fringes, of smaller dimensions, differing in number, according to the distance at which the shadow was observed, but leaving the middle of the shadow always white. Now these fringes were the joint effects of the portions of light passing on each side of the slip of card, and inflected, or rather diffracted, into the shadow. For, a little screen being placed a few inches from the card, so as to receive either edge of the shadow on its margin, all the fringes which had before been observed in the shadow on the wall immediately disappeared...

[15] Thomas Young. I. The Bakerian Lecture. Experiments and calculations relative to physical optics. *Philosophical Transactions of the Royal Society of London*, 94:1–16, 1 1804

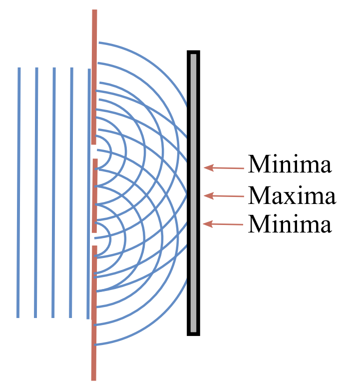


Figure 22: Plane wavefronts passing through a double slit (or mulitple slits) produce an interference pattern

Note the profound difference between Young's observation and Newton's - Young sees white area in the middle of the shadow due to constructive interference between rays that travel equal distances from either edge of the card. He notes that:

> The experiment of Grimaldi, on the crested fringes within the shadow, together with several others of his observations, equally important, has been left unnoticed by Newton.

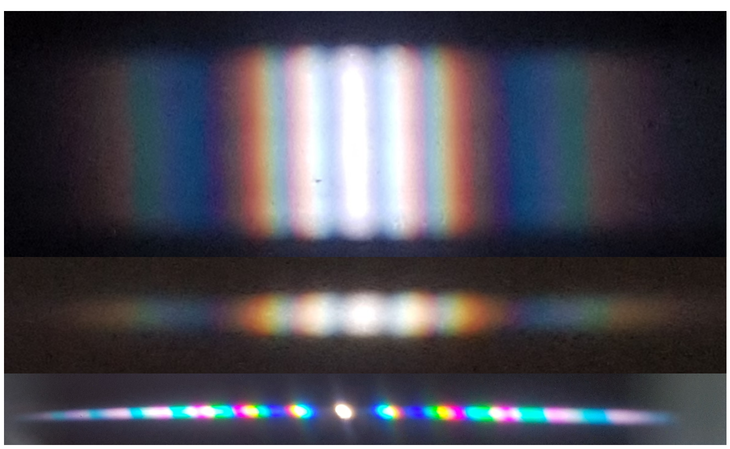


Figure 23: Images of the interference pattern produced by sunlight when passing through: (top image) a double slit (0.05mm apart, 0.025mm wide), (middle image) The same double slit, but with most of the slit covered (so images of the sun are produced, as in Derek's video. (Bottom image) Interference pattern produced by sunlight passing through a small hole in front of a diffraction grating (80 lines/mm). The camera obscura design used to take these images (similar to the way Derek does it in his video) is given the the Appendix.

We will watch the Veritasium youtube video on Young's double slit experiment (`https://www.youtube.com/watch?v=Iuv6hY6zsd0`), and the first part of the video on single photon interference (`https://www.youtube.com/watch?v=GzbKb59my3U`) and have a look at what they are looking at in the video using our own camera obscura boxes (see figure 43 in the appendix).

Young concludes by suggesting that the evidence points to light being a wave phenomena:

> From the agreement of the measures, and from the similarity of the phenomena, we may conclude, that these intervals are the same as are concerned in the production of the colours of thin plates ; but these are shown, by the experiments of Newton, to be the smaller, the denser the medium ; and, since it may be presumed that their number must necessarily remain unaltered in a given quantity of light, it follows of course, that light moves more slowly in a denser, than in a rarer medium: and this being granted, it must be allowed, that refraction is not the effect of an attractive force directed to a denser medium. The advocates for the projectile hypothesis of light, must consider which link in this chain of reasoning they may judge to be the most feeble; for, hitherto, I have advanced in this Paper no general hypothesis whatever. But, since we know that sound diverges in concentric superficies, and that musical sounds consist of opposite qualities, capable of neutralising each other, and succeeding at certain equal intervals, which are different according to the difference of the note, we are fully authorised to conclude, that there must be some strong resemblance between the nature of sound and that of light.

Augustin Fresnel and the Poisson/Arago/Fresnel 'spot'

Augustin Fresnel was a French civil engineer and contemporary of Thomas Young. Living in rural France and unaware that Young had already published his theory of interference of light, Fresnel independently derived many of his results[16]. Fresnel made very significant contributions to developing a quantitative wave theory of light. Siméon-Denis Poisson, a staunch believer in Newton's particle model of light[17], demonstrated that according to Fresnel's theory for diffraction by a circular disk there should be a bright spot at the centre of the shadow. François Arago performed the experiment, and when the spot was observed it was considered a significant victory for the wave theory of light. See the Veristasium video for a great discussion: `https://www.youtube.com/watch?v=y9c8oZ49pFc`

Figure 24: Augustin Fresnel. [Public domain]

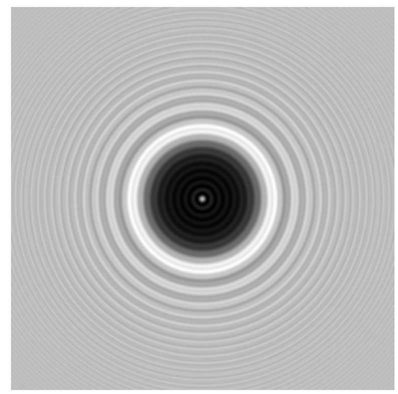


Figure 25: Simulated (i.e. calculated) image of a Poisson/Arago/Fresnel spot. By Treisinger at en.wikipedia, CC BY-SA 3.0, `https://commons.wikimedia.org/w/index.php?curid=22022394`

Foucault measures the speed of light in water

The final nail in the coffin of the particle theory of light came with the Foucault's demonstration that the speed of light in water was less than that in air, contrary to Newton's particle theory. Foucault observes the deflection of the beam returning from the distant mirror in the direction which demonstrated that the beam took longer to pass through water than through air. Foucault concludes[18]:

> Nous arrivons donc à cette conclusion définitive et à tout jamais inconciliable avec le système de l'émission : La lumière se meut plus vite dans l'air que dans l'eau.

Roughly translated: "So we arrive at this conclusion, which is irreconcilable with emission theory: Light moves faster in air than in water."

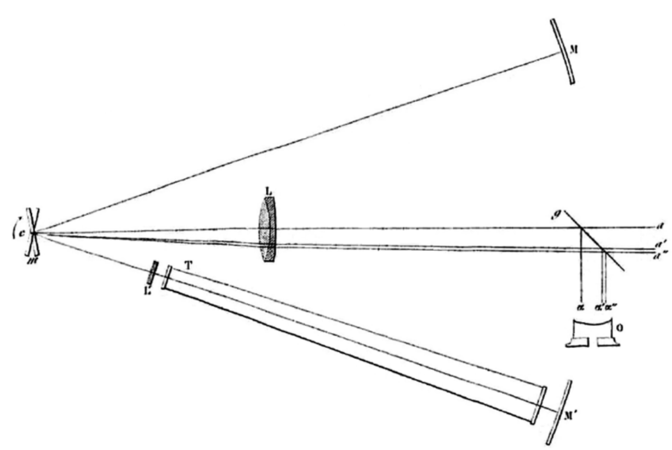


Figure 26: Foucault's experiment using a rotating mirror to compare the speed of light in water to the speed of light in air. The difference in speed means that the mirror rotates further during the time the beam travels to the distant mirror and back.

[16] Emilio. Segre. *From falling bodies to radio waves : classical physicists and their discoveries*. W.H. Freeman, 1984

[17] Ralph. Baierlein. *Newton to Einstein : the trail of light : an excursion to the wave-particle duality and the special theory of relativity*. Cambridge University Press, 1992

[18] Léon Foucault. *SUR LES VITESSES RELATIVES DE LA LUMIÈRE DANS L'AIR ET DANS L'EAU*. PhD thesis, 1853

Young's double slit experiment (Quantitative)

Theory

In this section we will derive an expression for the position of interference maxima and minima for a double slit interference pattern.

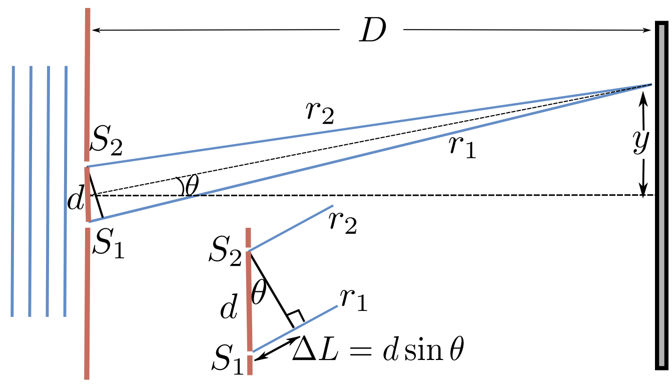


Figure 27: Rays passing through the slits at an angle θ travel different distances to a distant screen, producing an interference pattern. Note that in reality when this experiment is performed, the distance between the slits, d is much smaller than shown on this diagram, and the distance to the screen much larger. This means that the rays shown in the diagram emerge from the slits approximately parallel. This is indicated in the inset, which shows the difference in path length travelled by the says, ΔL.

This figure is modelled after Figure 35-10 in "Fundamentals of Physics" 10th Ed. by Jearl Walker.

We will consider two rays, one (r_1) that passes through the bottom slit S_1 and another (r_2) that passes through the top slit S_2. These rays are chosen (recall that light emerges in all directions from both slits, as shown in figure 22), so that they meet at a point P, a distance y from the point on the 'screen' directly in front of the slits. A line from y to the center of the slits makes an angle θ to the perpendicular.

When the distance from the slits to the screen is much larger than the separation of the slits ($D >> d$), then these two rays are very close to parallel, as shown in the inset to figure 27.

One ray (in this case r_1) has to travel a distance $\Delta L = d\sin\theta$ further to reach point P. If this additional distance is an integer number of wavelengths, m (where $m \geq 0$), then the rays arrive *in-phase* with each other, and a bright spot appears on the screen.

Maxima for double slit:

$$d\sin\theta = m\lambda \tag{1}$$

If the additional distance travelled by ray r_1 is equal to $m + \frac{1}{2}$ wavelengths ($m \geq 0$), then the waves arrive *out-of-phase*, so that destructive interference occurs and there is a dark spot on the screen.

Minima for double slit:

$$d\sin\theta = (m + \frac{1}{2})\lambda \tag{2}$$

These equations can be related to the distance y at which the maxima or minima appears on the screen by noting that

$$y = D\tan\theta \approx D\sin\theta$$

for small θ. This is an excellent approximation in this experiment as the distance between maxima and minima is much smaller than the distance from the slits to the screen.

In this case, our previous equations become (for $m \geq 0$):

Distance of maxima from center of interference pattern:

$$y_m = \frac{m\lambda D}{d} \tag{3}$$

Distance of minima from center of interference pattern:

$$y_{m+\frac{1}{2}} = \frac{(m+\frac{1}{2})\lambda D}{d} \tag{4}$$

As long as d is small compared to D (i.e. θ is small), then the distance between each successive maxima (or minima) remains constant, and equal to

$$\Delta y = y_{m+1} - y_m = \frac{\lambda D}{d}$$

A sample double slit experiment using lasers

This section contains a sample setup for a double slit experiment [19] performed with lasers of 3 different colours to allow comparison of the spacing of interference maxima for each colour. The theory we have derived assumes that the distance from the double slit to the screen on which the pattern is viewed is much much larger than the slit spacing. I have used a screen-slit spacing of 1m and a slit spacing of 0.1mm, as shown in figure 28.

[19] An equivalent experiment can also be performed with a diffraction grating instead of a double slit, and the pattern will be both brighter and more widely spaced. Diffraction gratings with rulings anywhere from 80/mm to 300/mm are all suitable.

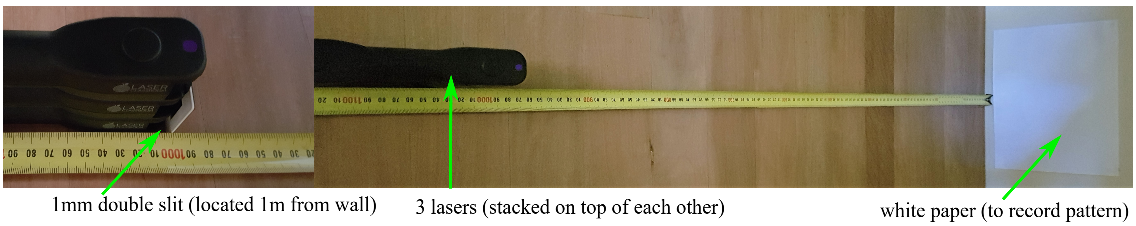


Figure 28: A sample setup for double slit experiment

One laser was switched on, the positions of its diffraction maxima were recorded on the white paper along with the position of its central (brightest) maxima (indicated with an arrow), and the pattern labelled with the colour of the laser.

This process was repeated for the other two lasers. Photos of the interference patterns obtained are shown in figure 29.

The data recorded on the white paper was photographed, with a ruler next to the patterns for scale, and is shown (at scale) in figure 30.

Figure 29: Interference pattern produced by a double slit 1mm apart for a red, green and violet laser (not to scale - actual spacing is shown in figure 30).

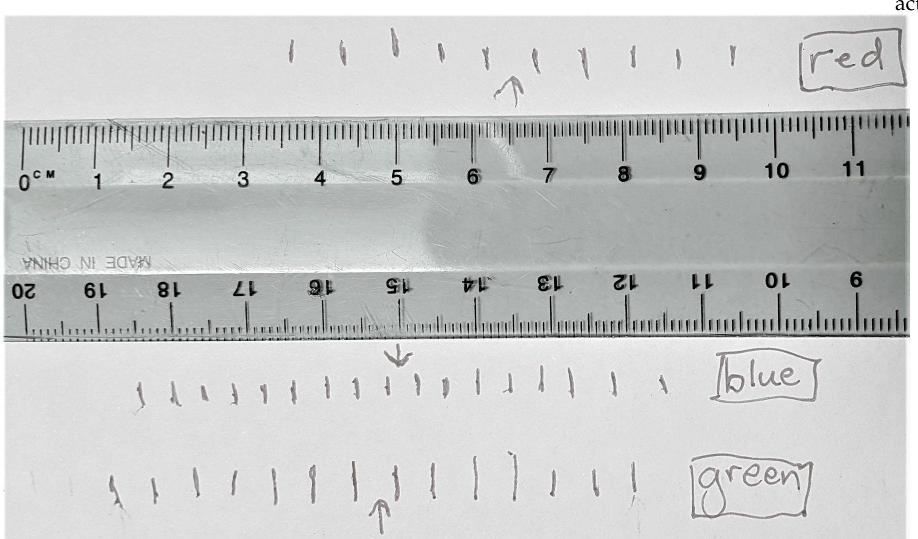


Figure 30: Raw data recorded for a double slit experiment. If you view or print this document at 100% then the data should be to scale. Lines are marked at minima in the interference pattern for each laser, and an arrow marks the central maxima.

Sample calculation using data from the red laser

Using the data shown in figure 30, we can calculate the distance between 8 successive maxima or 9 successive minima (this happened to be the number of bright fringes in the interference pattern before a *diffraction* minima occured). Using a ruler, I measure a distance of 5.8cm between the left-most and right-most minima. If this corresponds to 9 minima, then the distance between successive minima is

$$\Delta y = \frac{0.058}{9} = 6.44 \times 10^{-3}\text{m}$$

As $D = 1$m and the slit spacing $d = 1 \times 10^{-4}$m, the wavelength of the laser can be calculated to be

$$\lambda = \frac{\Delta y d}{D} = \frac{6.44 \times 10^{-3} \times 1 \times 10^{-4}}{1} = (640 \pm 10)\text{nm}$$

The value printed on the red laser I used was 635nm.

Question 1.

(a) Was 2 significant figures the correct uncertainty to quote for my measurement?

(b) Why did I measure the distance between 9 minima rather than the distance between two adjacent minima?

(c) Will the reliability of this experiment be affected by whether you choose to measure the distance between successive minima or the distance between successive maxima?

(d) Was my result accurate?

(e) How could I have designed my experiment differently to obtain a more reliable (i.e. precise) result for my determination of the wavelength?

Question 2. Use the data to calculate the wavelength of the green laser.

Question 3. If the actual wavelength of the blue laser that was used was 405nm and that of the green laser was 532nm, and that of the red laser was 635nm, use these values and the available data for the spacing of the minima for each laser to estimate the separation between the slits more precisely than the $d = 0.1$mm value given on slits.

Polarisation

Polarisation of EM waves

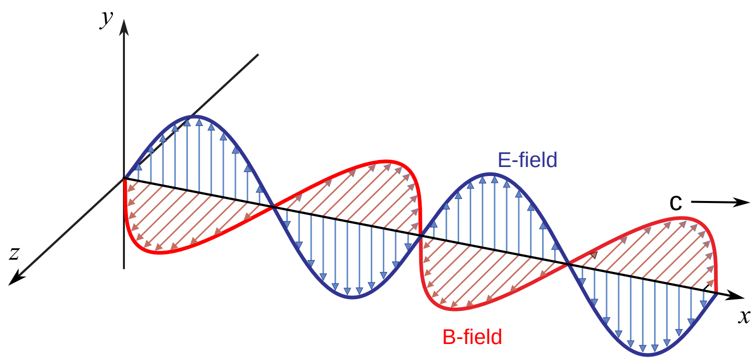


Figure 31: Vertically polarised electromagnetic wave.

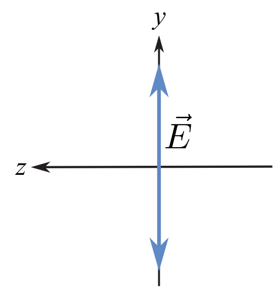


Figure 32: A 'front-on' view of the electric field only of the polarised EM wave shown in figure **??**

The orientation of the electric field in a light wave is called its direction of *polarisation*. For example, the EM wave shown in figure 31 is vertically polarised, as this is the direction in which its electric field is oscillating (see figure 32 for a view of the electric field of this wave, looking along the x-axis).

Unpolarised light consists of light with electric field vectors oscillating in all directions in the plane perpendicular to the direction of propagation, as shown in figure 33.

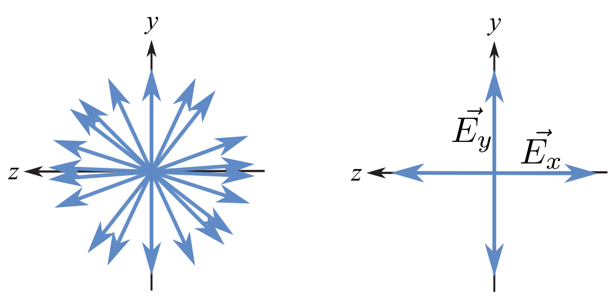


Figure 33: (Left) A 'front-on' view of an unpolarised EM wave, showing the electric field vectors point in all directions. (Right) To simplify the representation of an unpolarised wave, all the electric field vectors can be split into their components in the vertical and horizontal directions.

Polarising filters

A polarising filter usually consists of plastic containing long molecules which are all orientated in one direction. These molecules absorb the component of the electric field vector parallel to the alignment of the molecules, while the component perpendicular to the filter passes through [20].

Take your polarising filters and slowly rotate one relative to the other. Describe what you see:

Figure 34: Two polarising filters crossed at an angle to each other, in front of a polarised computer screen.

[20] We will examine this again after learning about light quanta. See the 3Blue1Brown Youtube video on this for more detailed information: `https://www.youtube.com/watch?v=MzRCDLre1b4`

Place a ruler or protractor between your two polarising filters. What do you see?

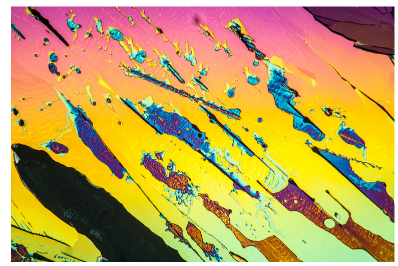


Figure 35: Urea crystals viewed through a polarising filter. Shutterstock.

Can you identify any other surfaces (e.g. reflections from windows?) from which light is polarised?

Polarisation by calcite

1. We will begin by having a look at an object (e.g. our fingers or a ruler...) through a piece of calcite[21].

2. Then look at the image again, this time through a polarising filter. Slowing rotate the filter and describe/sketch what you see in the space below. What is happening to light passing through the calcite crystal?

[21] Can be obtained through ebay from the US - I bought a 6cm × 6cm × 2cm 'gem clear' piece from "treasure mountain mining" MA.

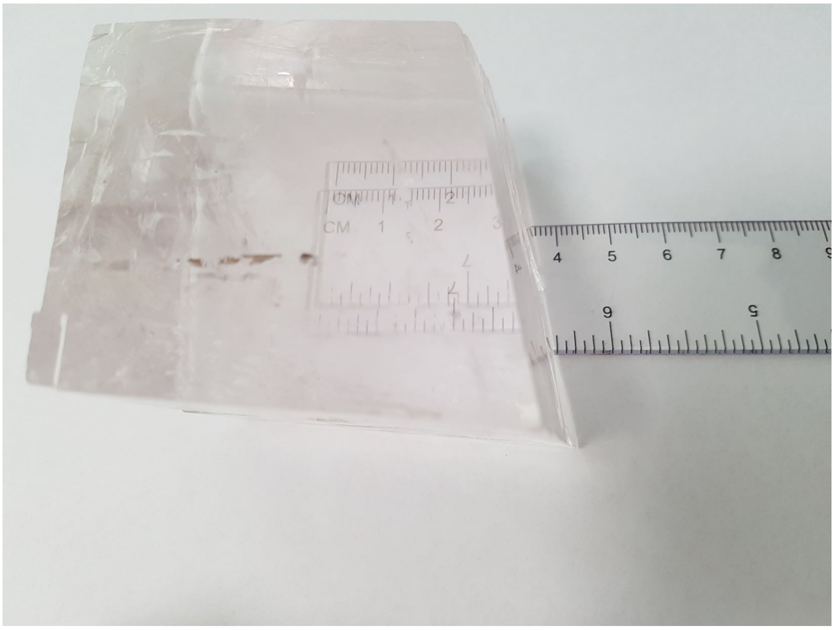


Figure 36: Double refraction of a ruler through calcite. Evidence that light has "sides" (see Newton's discussion of calcite).

The significance of polarisation in developing a model of light

We saw in an earlier part of this module that polarisation of light by calcite played a crucial role in providing support for Newton's particle model of light, due to his proposal that light particles had "sides" and could be refracted differently by calcite depending on the orientation of the "sides" of the light particle relative to the planes of the crystal lattice in calcite. Huygens was unable to provide an explanation of this effect using his longitudinal wave model of light.

During the early 1800's, the work of Thomas Young and then later the more mathematically complete work of Fresnel (as well as work by Arago and Brewster) established that a transverse wave model of light could account for all observed polarisation effects. [22].

In 1864 Maxwell mentions Faraday's experiments on the effects of magnetic fields on the polarisation of light [23] in his paper "A dynamical theory of the electromagnetic field" [24] as evidence underlying Faraday's suggestion that light is a transverse electromagnetic wave. The equations in Maxwell's paper establish mathematically that electromagnetic radiation is in fact a transverse wave and that polarisation relates to the orientation of the oscillation of the electric field.

We will see in the next section of the module that in the 1900s it was discovered that light also has the properties of a particle (quantum physics). Even though evidence from polarisation (*and* inter-

[22] . In addition see the extensive and well referenced Wikipedia page `https://en.wikipedia.org/https://www.overleaf.com/project/5c2c90b8d9d85710a193fab0wiki/Augustin-Jean_Fresnel#cite_note-172`

Eugene Hecht. *Optics*. Addison-Wesley, 2nd ed. edition, 1987

[23] now known as "The Faraday effect" `https://en.wikipedia.org/wiki/Faraday_effect`

[24] `https://upload.wikimedia.org/wikipedia/commons/1/19/A_Dynamical_Theory_of_the_Electromagnetic_Field.pdf`

ference) was critical in the development of the wave theory of light during the 1800s, it is still possible to explain these effects using a quantum model of light and probability. [25].

[25] See the 3Blue1Brown YouTube video on polarisation: `https://www.youtube.com/watch?v=MzRCDLre1b4` and the complementary video by Minute Physics: `https://www.youtube.com/watch?v=zcqZHYo7ONs&t=847s`

A note: This syllabus content was tested as a multiple choice question in question 10 of the 2019 HSC, with the official answer being that polarisation "supported a wave model of light".

My thought would be that this is actually a complex historical question - polarisation has been used to support both particle and wave models of light over the last 300 years, and is consistent with the modern understanding of light as both a wave and a particle.

Polarisation - quantitative

***Unpolarised** light through a polarising filter*

If **unpolarised** light is incident on a polarising filter then the intensity of the transmitted light is half the intensity of the incident light. This is often called the **one-half rule**, and is used *only* when the incident light is unpolarised.

$$I = \frac{1}{2} I_0 \tag{5}$$

*Malus' law - **polarised** light passing through a polarising filter*

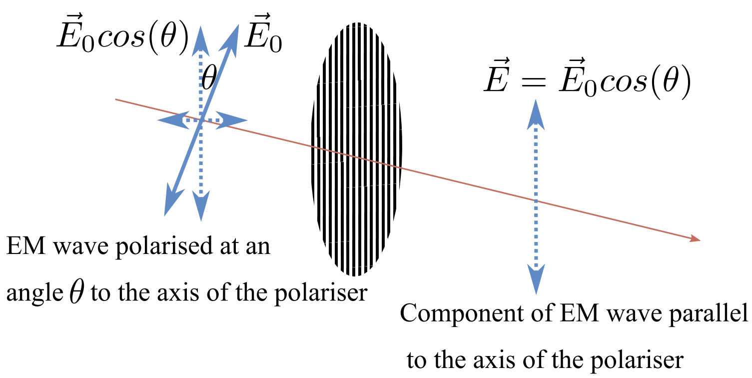


Figure 37: If a polarised EM wave with amplitude E passes through a polarising filter orientated at an angle θ to its direction of polarisation, then the amplitude of the waves that passes through the filter is the component in the direction of the polarisation of the filter, $E_0 \cos(\theta)$.

If polarised light is incident at an angle θ to the axis of the polariser, then only the component of the electric field that is parallel with the axis, $\vec{E}\cos(\theta)$ will be transmitted.

The intensity of light is proportional to the square of the electric field vector [26]

$$I_0 \propto E_0^2$$

As the transmitted electric field vector is given by $\vec{E} = \vec{E}_0 \cos\theta$, and the intensity of the transmitted EM wave is proportional to the transmitted electric field vector squared, $I \propto E^2 = (E_0 \cos\theta)^2$

[26] It follows (by pythagoras' theorem) that if the wave is split into two perpendicular components, the intensity of each of the two components simply adds to give the total intensity of the wave.

The intensity of **polarised** light passing through a polarising filter is given by **Malus' law**:

$$I = I_0 \cos^2\theta \tag{6}$$

Experimental determination of Malus' law

Option 1

This approach requires:

- smart phone with "Physics Toolbox Suite" installed
- lcd computer screen (which produces polarised light), set to maximum brightness and displaying a white screen
- 1 polarising filter, attached with sticky tape in front of the light sensor on the smart phone

We will use the "multi-record" option in the free app "Physics toolbox suite" to simultaneously measure the angle and intensity of light passing through a polarising sheet attached in front of the phone's light sensor as it rotates while facing a computer screen emitting polarised white light.

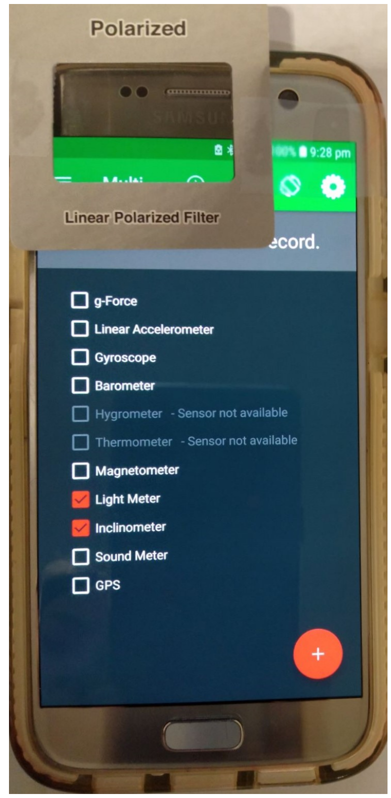


Figure 38: A smartphone with a polarising filter taped over the light sensor, for use in 'option 1'. The screen shows the options to select inside the 'multirecord' feature of the Physics Toolbox Suite app.

Procedure

- Attach the polarising filter to your phone and ensure it is covering the light sensor and is aligned square with your phone
- Press the record button to simultaneously record angle and illuminance then place your phone on the white screen.
- Rotate your phone through a full 360° and then remove your phone and stop recording.

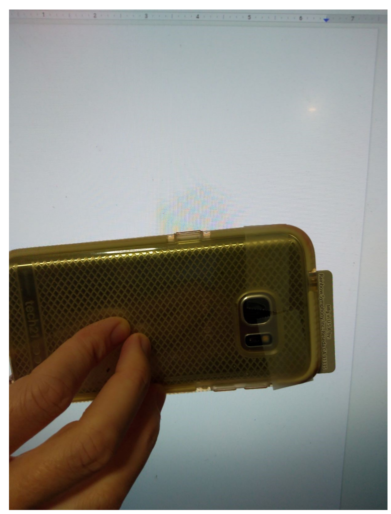


Figure 39: Smartphone with polarising filter being rotated in front of a white computer screen which emits polarised light. Data is being taken for both angle and illuminance by the multirecord feature on the Physics Toolbox suite app while the phone is rotated.

Instructions for data analysis in Excel

- On your device, access the folder on your phone called "Physics Toolbox Suite" and download the data file that you created. Open in Excel (or whatever spreadsheet or data analysis program you wish to use).
- There will be one column of time data, one column containing data on light intensity and three columns of data for angle. The 'pitch' column will be the one to use (if it works the same on your phone as it does on my phone...).
- You will need to delete data from when you pressed 'record' and when you actually had your phone on the screen and began rotating. You will also need to delete data from the time when you removed your phone from the screen and pressed 'stop'.

- Copy and paste your 'pitch' column to a new column to the right and do the same with your Illuminance column. Insert a scatter graph with the pitch on the horizontal axis and illuminance on the vertical axis.
- Identify the maximum illuminance using the command "=MAX(B2:B1803)" where you need to replace 'B2:B1803' with your column (and number of rows) that contains illuminance.
- Make two additional calculated columns. One containing the ratio of I/I_0 where I_0 is maximum illuminance, and a second column to calculate $cos^2\theta$ using the command $= (COS(RADIANS(pitchcolumn)))^2$, where you need to replace 'pitchcolumn' with your column that contains angle (pitch).
- Insert a scatter graph of $cos^2\theta$ on the horizontal axis and I/I_0

A place to stick your graphs:

Option 2

This approach requires:

- an IEC polaroid pair (`https://www.scientrific.com.au/PDFs/hl1883-060.pdf`) in a holder to measure the angle between two polarising sheets
- a light meter (or any app that can display light intensity (such as Physics toolbox suite, google science journal or a native app on the phone)

We will take data "by hand" by:

1. holding the IEC polaroid pair over the light meter or light sensor on your phone
2. noting the angle and the intensity
3. rotating the pair 5° or 10° and then repeating the measurement.

Be very sure that you are not shading the sensor with your hand when you take your reading. If you are doing this prac using sunlight, be careful to do it on a sunny day - if clouds pass across the sun while you are in the middle of your measurements you will get (close to) meaningless data.

Space for a table of data. You will need columns for measured values of "angle", "Illuminance", and calculated values of "$cos^2\theta$" and "I/I_0".

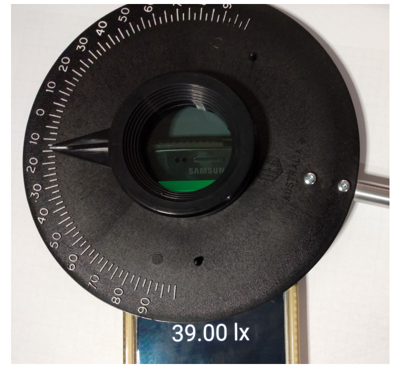
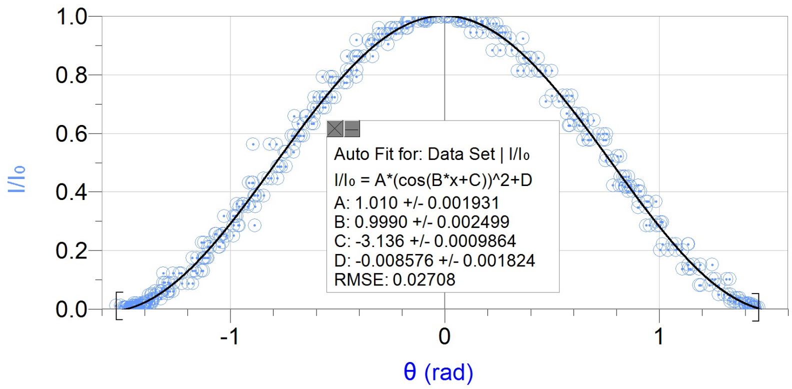


Figure 40: An IEC polaroid pair covering the light sensor of a smartphone with an app (here Physics Toolbox suite) open to measure illuminance as the angle between the pair of polaroid filters is changed.



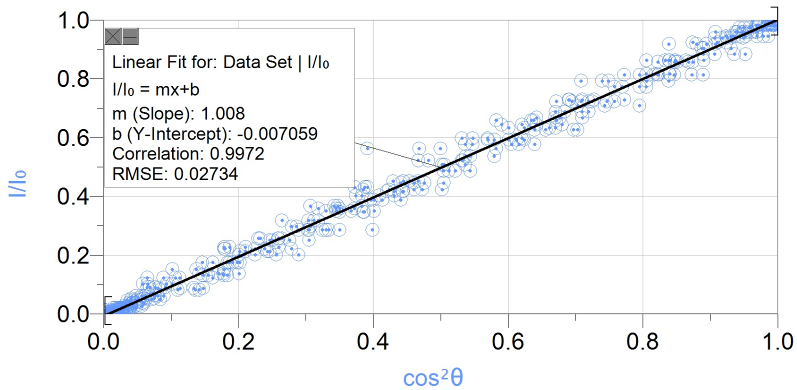


Figure 41: Sample data taken with the smartphone app "Physics toolbox suite". The vertical axis has been scaled by the maximum reading. Vernier LoggerPro has been used for graphing. Link to original data in .xlsx format: `https://drive.google.com/file/d/1OQ3cNBeWN-pkjNLC_s4ooGScPEgIbRwm/view?usp=sharing`

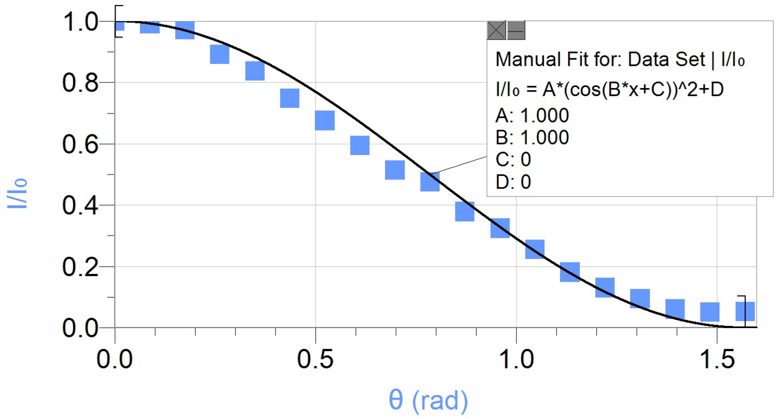
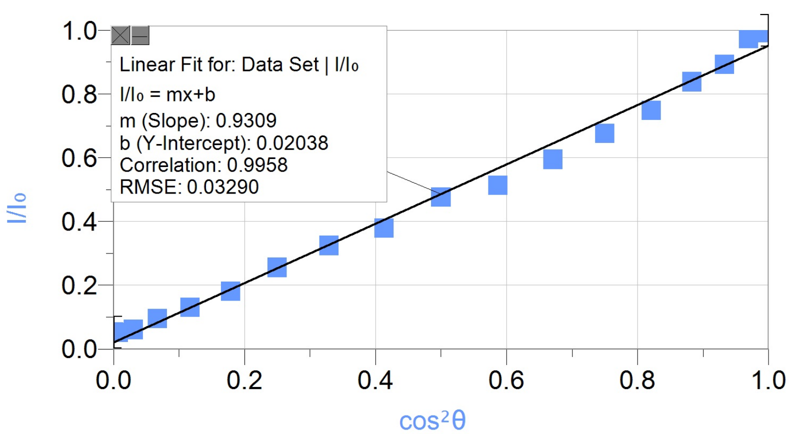


Figure 42: Sample data taken using the IEC polaroid pair and a light meter app (Physics toolbox suite) on a smartphone, outside on a sunny day. The vertical axis has been scaled by the maximum reading (3700 lux). Vernier LoggerPro has been used for graphing. Link to data in .xlsx format : `https://drive.google.com/file/d/1OcKhA1v4D1xSkboHe0kHxP3TDrlyprAB/view?usp=sharing`



Appendix: Camera obscura design

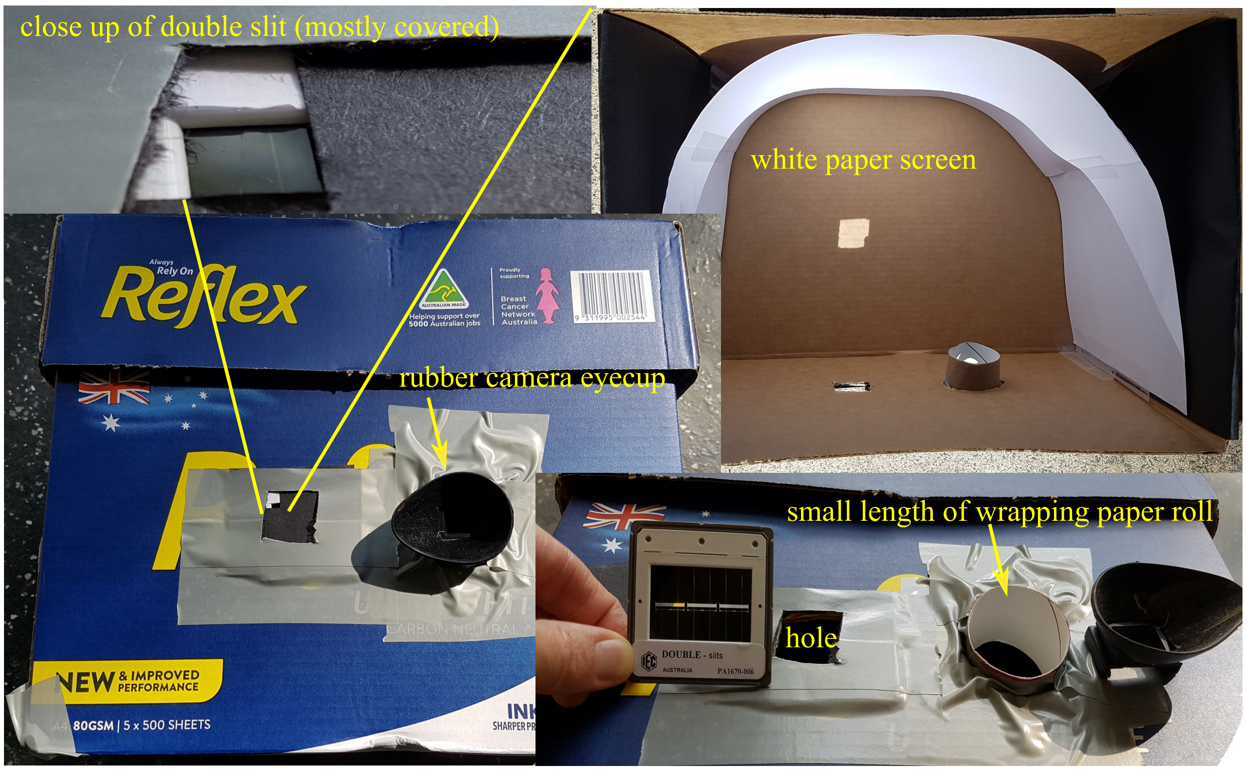


Figure 43: Design of the camera obscura used to take the images of the double slit interference pattern produced by the sun shown in figure 23 on page 23.

References

[1] Eugene Hecht. *Optics*. Addison-Wesley, 2nd ed. edition, 1987.

[2] Isaac Newton. *Opticks or, a Treatise of the reflexions, refractions, inflexions and colours of light . Also two treatises of the species and magnitude of curvilinear figures*. 1704.

[3] Christiaan Huygens. *Treatise on Light*. 1690.

[4] Emilio. Segre. *From falling bodies to radio waves : classical physicists and their discoveries*. W.H. Freeman, 1984.

[5] Thomas Young. An account of some cases of the production of colours, not hitherto described. *Philosophical Transactions of the Royal Society of London*, 92:387–397, 1 1802.

[6] Thomas Young. I. The Bakerian Lecture. Experiments and calculations relative to physical optics. *Philosophical Transactions of the Royal Society of London*, 94:1–16, 1 1804.

[7] Ralph. Baierlein. *Newton to Einstein : the trail of light : an excursion to the wave-particle duality and the special theory of relativity*. Cambridge University Press, 1992.

[8] Léon Foucault. *SUR LES VITESSES RELATIVES DE LA LUMIÈRE DANS L'AIR ET DANS L'EAU.* PhD thesis, 1853.

Answers

Answer 1.

(a) My measurement of the distance between 9 minima was precise to only $\pm$1mm or so, meaning that my uncertainty in this measurement was about 2%. When I divide this measurement by 9, this means the uncertainty in my measurement of the distance between *successive* minima is closer to 0.2% (which is why we should measure the distance between many minima as possible). My measurement of the distance to the screen is precise to around 2mm, which corresponds to an uncertainty of around 0.2% as well. The distance between the slits is the limiting factor - the label on the slide only quotes 0.1mm, so it is unclear how precise this value is, and we have no real way of knowing other than looking at how close the value we obtain for wavelength is to the true value - from the numbers we obtain it looks at though it might be $0.1 \pm 10\%$ or so. This is the limiting factor for the precision of our measurements, and in the absence of any other information (for example the actual value of the wavelength), I should really be more cautious and perhaps only give my result to 1 significant figure. Given the additional information that the wavelength of the laser is 635nm, it appears that the slit spacing quoted on the slide is reasonably precise, so in light of this giving my result to 2 s.f. is probably reasonable (but arguable!).

(b) As mentioned in part (a), the uncertainty in the measurement of distances on the screen is likely to be of the order of 1mm. That will stay same whether you are measuring the separation of 1 adjacent maxima/minima or 10, however the percentage uncertainty in the former measurement is 10 times larger than in the latter case.

(c) In the double slit experiment data shown here, the minima are narrow, with a well defined position, wheras the maxima are broad (i.e. the intensity stays high right across the maxima before dropping abruptly at the location of the minima. It's ceryainly possible to use the maxima, but it would be necessary to estimate the centre if each, which is likely to increase the uncertainty of the measurement.

(d) Yes, my result agreed with the theoretical value to within the precision (estimated uncertainty) of my measurement.

(e) Using a larger distance D, for example the length of the lab rather than 1m would decrease the percentage uncertainty in the measurement of the spacing between minima (as well as the percentage uncertainty in D). The mild disadvantage is that the maxima are dimmer, requiring a dark room to perform the measurement.

Answer 2.

When I look at the data for the blue laser I am suspicious about the rightmost two marks - the spaces between them look substantially larger than all the others. Perhaps these were starting to be in a diffraction minima (an additional larger pattern of light and dark due to the finite width of each slit that is superimposed on the double slit pattern) or were simply poorly marked. I am going to choose to not include these two minima in my calculation.

I measure the distance over which leftmost 13 minima occur to be 5.7cm, giving $\Delta y = 4.38 \times 10^{-3}$m.

Plugging in to the formula:

$$\lambda = \frac{\Delta y d}{D} = \frac{4.38 \times 10^{-3} \times 1 \times 10^{-4}}{1} = (438 \pm 10)\text{nm}$$

Answer 3.

I measure the distance between 13 minima for the green laser to be 6.9cm, giving a value for $\Delta y = \frac{0.069}{13} = 5.31 \times 10^{-3}$m.

We can find the estimated slit width for each of the three measurements and average (assuming we trust each measurement equally).

For the green laser:

$$d = \frac{D}{\Delta y} = \frac{532 \times 10^{-9} \times 1}{5.31 \times 10^{-3}} = 1.00 \times 10^{-4}\text{m}$$

For the red laser:

$$d = \frac{D}{\Delta y} = \frac{635 \times 10^{-9} \times 1}{6.44 \times 10^{-3}} = 0.986 \times 10^{-4}\text{m}$$

For the violet laser:

$$d = \frac{D}{\Delta y} = \frac{405 \times 10^{-9} \times 1}{4.38 \times 10^{-3}} = 0.925 \times 10^{-4}\text{m}$$

The average of these values is:

$$d = (0.97 \pm 0.03)\text{mm}$$

where the uncertainty in d has been estimated using $\frac{range}{n}$.

The value we have obtained is consistent with that given on the front of the double slit, to within the estimated precision of our measurement.